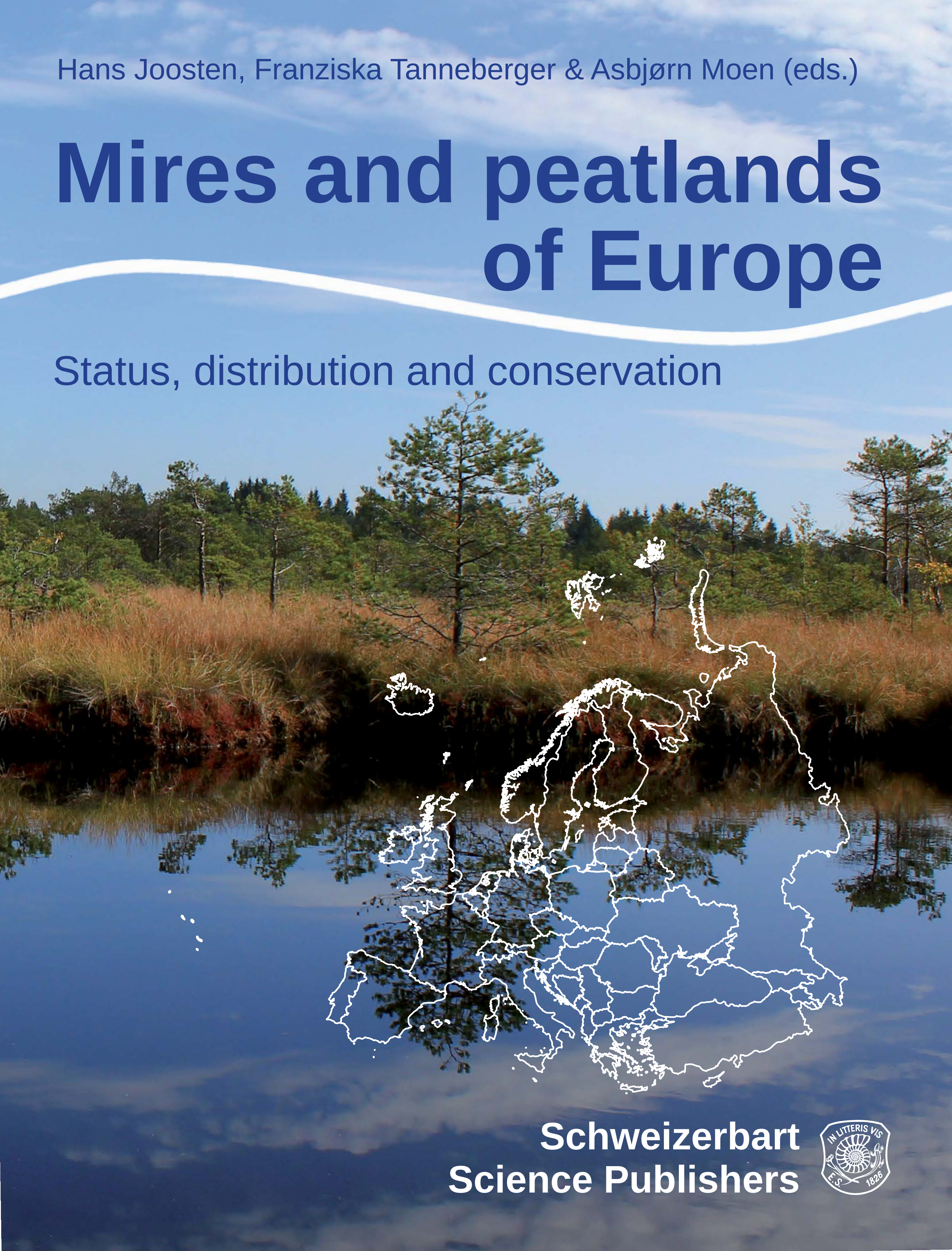
Hans Joosten, Franziska Tanneberger & Asbjørn Moen (eds.)

Mires and peatlands of Europe

Status, distribution and conservation



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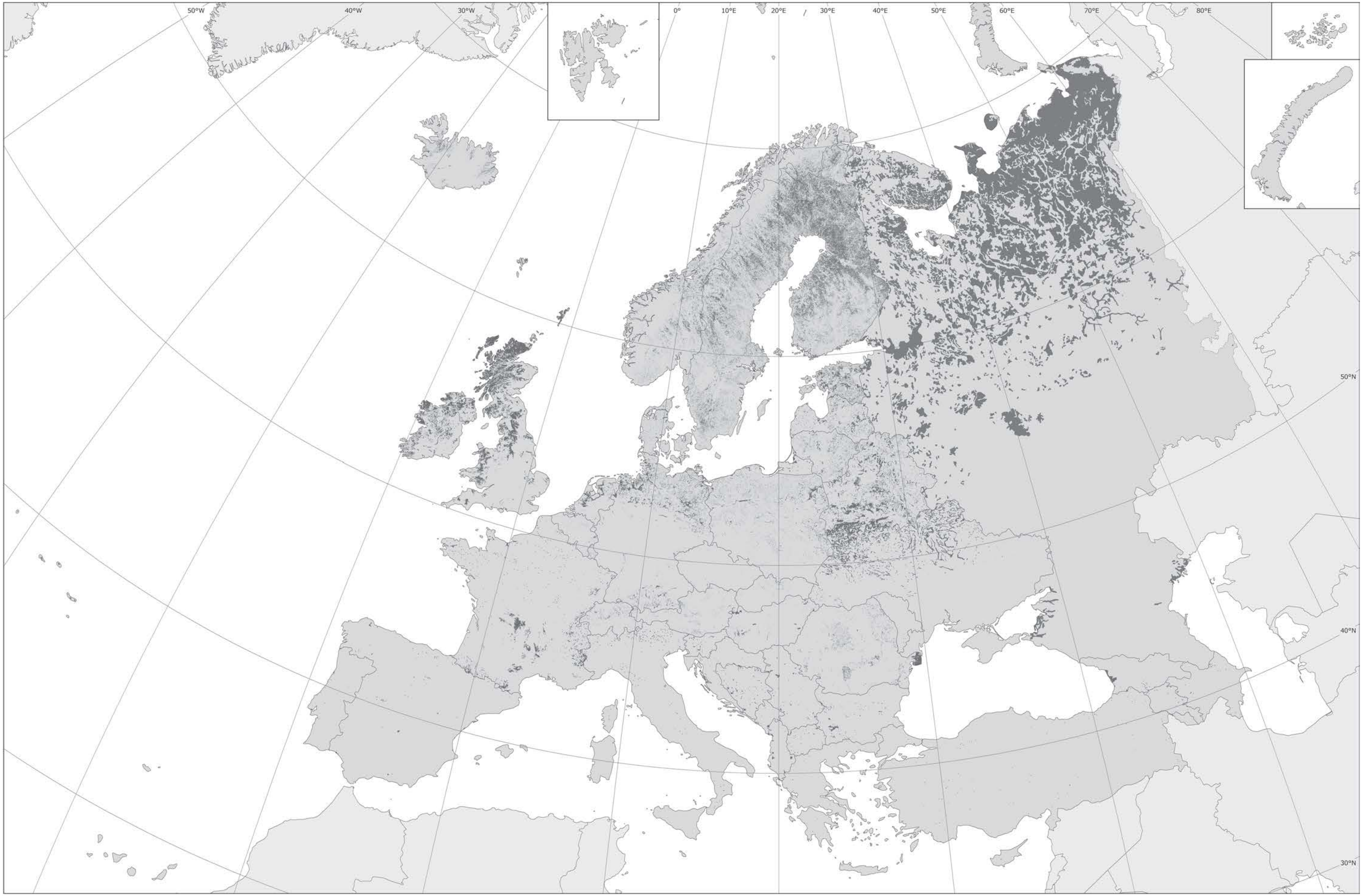

Fig. 4.9: Distribution of peatland/organic soil in Europe (see Chapter 4.4 for details).
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with contributions of 134 authors (see List of Contributors on page 723)

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Status, distribution and conservation

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Foreword by the Council of Europe

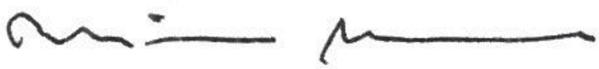
In 1979 the Council of Europe adopted the Convention on the Conservation of European Wildlife and Natural Habitats (or Bern Convention) as the first international treaty to protect species and habitats and to bring countries together to decide on how to take action to conserve nature. The Convention focused its attention on protecting endangered natural habitats of Europe and decided to pay particular attention to the conservation of peat lands, urging all European states – in its recommendation 3 (1984) – to draw comprehensive national inventories of this important ecosystem.

In 1980 the Council of Europe published Roger Goodwillie's 'European peatlands' in its series 'Nature and Environment'. This was the first Council of Europe report to concentrate on a European natural habitat type. This pioneer report took the issue of peatlands into the international political arena. It addressed 'ecosystem biodiversity', an issue that was taken up in 1992 by the Convention on Biological Diversity. Covering 17 countries of "western Europe", Goodwillie's 'European peatlands' was not equalled in its geographic coverage until 1994, when a new overview was drafted and presented by the International Mire Conservation Group during its Congress in Norway. That draft has now – more than 20 years later – resulted in this comprehensive book.

Since 1980, the face of Europe has significantly evolved. Council of Europe membership has substantially increased to cover all of Europe. Simultaneously, the appreciation of peatlands has grown all over Europe, be it as fascinating areas of wilderness, as treasures of biodiversity, as important constituents of conservation networks, and as providers of vital ecosystem services, not in the least as unchallenged stocks of carbon in the terrestrial biosphere. A new 'European peatlands' has been long overdue.

'Mires and Peatlands of Europe' is a resolutely European book about unity. It covers all countries of Europe and sets out the extent, distribution, variety, status and conservation of mires and peatlands. Written by 134 mire scientists, it gives credit to the enormous peatland diversity of Europe with respect to regional history, land use, language and culture without losing track of connections, communalities and unifying principles. People can only love and protect the nature they know, so this book is particularly relevant in times where climate change makes all governments and citizens aware of the challenges our natural habitats will be facing in the next decades.

I congratulate the International Mire Conservation Group on their achievement and I trust that this book will encourage continued conservation of our important common European natural heritage.



Thorbjørn Jagland
Secretary General of the Council of Europe

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Foreword by the International Mire Conservation Group

Conservation is all about context. It is impossible to know whether something is rare, distinctive, or characteristic unless one knows where it occurs and where it does not occur. Without such knowledge, conservation is to some extent ‘flying blind’. In the case of peatlands this has been made more difficult by the fact that peatlands are all too often overlooked and go unrecognised. Time and again they have been identified and misclassified as, for example, wet heath, alpine heath, moorland, wet grassland, wet woodland, swamp, or even merely wetland, thereby obscuring their fundamental character as peat-based systems. Even in areas as well-documented as Europe, this tendency has continued to distort the overall picture of peatland distribution and condition.

Consequently, in 1990 the IMCG, being the international network which seeks to provide a global context for the world’s peatland systems, decided to bring together an overview of European peatlands covering, for the first time, their distribution, type, and condition. The initial attempt at this overview, under the leadership of Michael Löfroth, largely involved the collation of several existing national peatland inventories. This exercise revealed, however, that not only were there issues of distinguishing peatlands from other habitat types, there were also significant differences between nations in the way that peatlands were described and their condition assessed, making it difficult to construct a coherent overview across the 22 countries then involved.

In taking responsibility for the second phase of this project, the present editors were therefore at great pains to seek a commonality of description across the national accounts in order to build up a coherent and consistent picture of the distribution, character, and condition of peatlands. In addition, the ambition of the project was expanded to embrace the entire continent of Europe, thus making it a much more ambitious project and a much greater challenge than was originally envisaged more than 25 years ago.

Moreover, in recent years and during the long gestation of this IMCG project, the global significance of peatlands for their carbon storage and wide range of other key ecosystem benefits has increasingly become acknowledged at the highest levels of international agreement, thanks in part to the efforts of the IMCG. The various initiatives and commitments arising from such global recognition, however, mean that questions of peatland distribution, character, condition, and context are becoming ever more important.

Publication of this present volume, describing the peatlands of an entire continent, is therefore particularly timely and extremely welcome. I am sure that this book will come to be seen as a baseline, a benchmark, a fixed point in time, against which all future measures of peatland wise use, sustainable management and conservation effort across the continent of Europe can be compared. It provides future generations with the means to assess whether the peatland resources of Europe are continuing to decline or whether, through concerted efforts to undo the damage of the past, Europe’s peatlands are being successfully restored to a state of active peat formation – a state which brings with it all the other ecosystem benefits associated with that most distinctive and peculiar of processes.

Richard Lindsay
Founder Member of the IMCG, and Chairman 1984–2000

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Table of Content

I. General Part

1 Introduction Part I

Hans Joosten, Franziska Tanneberger & Asbjørn Moen

'Sooner or later the big regional problems of peatland research must receive uniform treatment. Personally, I am not convinced that the time is yet right to begin the international effort. One could perhaps consider that the peatland researchers of various countries will for some time still be fully occupied with basic questions relevant to their regional peatland science, and that the viewpoints still need to mature. In any case one should not rush. Only gradually can the plan successfully develop. Should the seed already germinate in the near future, the young plant should be nursed meticulously, in order not to grow crookedly and one day to be able to bear those beautiful fruits it carries within itself rudimentarily.' (translated from von Post 1926, Some challenges of regional mire research).

During the 4th meeting of the International Mire Conservation Group (IMCG) in Dublin (Ireland) in 1990, it was agreed that European IMCG members (at that time representing ten West-European countries) should produce a detailed report on the mires in Europe. The last attempt to do so had been in 1980 when Roger Goodwillie had delivered such a review for "western" Europe for the Council of Europe (Goodwillie 1980). As coordinator of the work, Michael Löfroth (Sweden) was appointed. The early 1990s, with the changed political situation in central and eastern Europe, provided the interest and opportunity to cover the whole of Europe. The 5th IMCG meeting in Bern (Switzerland) in 1992 opened up possibilities for new personal transboundary contacts and many countries previously not represented in IMCG got engaged. Abstracts from 17 European countries were presented, and the 'European Mires Book' project was intensively discussed. A draft edited by M. Löfroth was presented including 16 European countries (Löfroth 1994), and many abstracts were published in the meeting's proceedings (Grünig 1994). The work continued and for the 6th IMCG meeting in Trondheim (Norway) in 1994 a new draft report was produced with chapters from 22 countries (Löfroth & Moen 1994): Austria, Belarus, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Iceland, Ireland, Italy, Latvia, Netherlands, Norway, Poland, Portugal, Russia, Spain, Sweden, Switzerland, and United Kingdom. The proceedings of the symposium (Moen 1995a) included a presentation of the project (Löfroth 1995) and descriptions of the diversity and conservation situation of mire ecosystems in various European countries.

The 1994/1995 publications were a major milestone towards a book covering mires in every country of Europe. They built on, and extended, earlier compilations (see also Chapter 4.8.1), especially:

- Von Bülow (1929): possibly the first publication presenting countrywise data on European mire distribution;
- Kats (1971) and Tyuremnov (1976): short descriptions of all European mire regions of the Soviet Union and an overview chapter about European peatlands;
- Goodwillie (1980): condensed descriptions of 17 "western" European countries;
- Carp (1980): wetland distribution assessments for all (at that time 31) European countries, building on the MAR and AQUA projects, mentioning peatlands in 12 countries;
- Gore (1983b): extensive descriptions of mires in five European countries/regions, including a classic English language presentation of mire distribution and diversity in the Soviet Union (Botch & Masing 1983);
- Moore (1984): extensive descriptions of mires in six European countries;
- Olenin (1988): descriptions and maps of peatlands in the European part of the Soviet Union and 26 other European countries;

In 1998–2000, a new attempt was started to finalise the European Mires Book, supported by the Global Peatland Initiative (GPI; Couwenberg & Joosten 1999b). In June 1999, responsibility for the entire initiative was transferred from Michael Löfroth (Sweden) to Hans Joosten (Germany). A small team from Greifswald University (Hans Joosten, John Couwenberg, Thomas Heinicke, Lebrecht Jeschke) could fill several gaps and a full draft was submitted in 2002 to the Global Peatland Initiative. A thoroughly edited, printed book, however, was still not achieved, and in the following years attention of IMCG work shifted to emerging new and pressing issues, e.g. trying to include peatlands in the United Nations Framework Convention on Climate Change (UNFCCC) architecture. Some of the advanced country chapter drafts were later published as separate papers. In parallel, several other regional overviews were produced, largely by members of the IMCG network:

- Lappalainen (1996): detailed presentations of 17 European countries and short summaries on an additional 13 European countries.
- Joosten & Clarke (2002): estimates of the peatland/mire area for all European countries/regions;
- Bragg (2003): reports on status and conservation of mires in 13 central and eastern European countries (funded by the Darwin Initiative, UK);

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- Bragg & Lindsay (2003): reports on eight countries covered in the Central and Eastern European Peatlands Project (CEPP);
- Nivet & Frazier (2004): a review of European wetland inventory information from 47 European countries (contribution to the Ramsar Convention on Wetlands' Global Review of Wetland Resources and Priorities for Wetland Inventory);
- Steiner (2005): extensive chapters about mires in nine European countries;
- Montanarella et al. (2006): area estimates and maps for the peatland area in 36 European countries (based on the 1:1,000,000 European Soil Database and a dataset of organic carbon content for the topsoils of Europe at 1km x 1km resolution);
- Institute of Biology RAS Karelian Research Centre (2006): 40 symposium papers on diversity, dynamics, carbon balance, resources, and conservation of mire ecosystems in the Russian Federation and Fennoscandia;
- Minayeva et al. (2009): reports on peatland diversity, extent, use, and conservation in 13 central and eastern European countries and the entire Russian Federation (using several drafts prepared for the European Mires Book);
- Joosten (2009b): estimates of the original and current mire/peatland area and drainage related greenhouse gas emissions in 51 European countries/regions.

Important information on the condition and conservation of mires in Europe is also presented in the excursion guides and proceedings of the IMCG field symposia (e.g. Eurola & Huttunen 1985, Grünig 1994, Moen 1995a, Lindholm & Heikkilä 2012; see also Box 6.2). Information on extent and drainage status of organic soils is furthermore – for most European countries – published in the annual UNFCCC National Inventory Submissions (NIS). Similarly, national reports published every three years for the Ramsar Convention Conference of Contracting Parties (COP) contain information on condition and protection of wetlands. For all European Union (EU) countries, extent and conservation status of mire-related Natura 2000 habitat types (see Chapter 2) are monitored and published for five year reporting periods (2001–2006, 2007–2012 etc.).

In 2013–2016, the final attempt to finish this book was undertaken and with an editorial team combining long-term experience and fresh energy, with enormous support of all 131 national authors, and with a dedicated mapping and language editing team (see Acknowledgements), the book has eventually been finished.

This book consists of two main parts. Part I contains six general chapters and Part II an introduction and 49 'country chapters'. Within Part I, Chapter 2 provides an extensive description of existing mire and peatland typologies. The variety in terms and typologies is an obvious problem when comparing mire information from different countries. Reaching agreement on a common terminology and understanding of different classification systems is a central aim of the IMCG work. The diversity in peatland-related terms is discussed in Chapter 3, where also a glossary is presented. The regionality of mires in Europe is extensively described in Chapter 4. Chapter 5 presents a summary on peatland use in Europe, and Chapter 6 reflects mire conservation activities in Europe.

Technical remarks

Nomenclature at the species and community level follows pan-European checklists:

- Seed plants and pteridophytes: Flora Europaea (Tutin et al. 1964–1993); species not included in Flora Europaea (except *Ranunculus/Coptidium*) were checked against The Plant List (2013) and are presented with the author name;
- Bryophytes: Mosses except for *Sphagnum* spp.: Hill et al. (2006); *Sphagnum* spp.: Flatberg (2013) and Kyrkjeeide et al. (2015) regarding *S. beothuk*; Liverworts: Grolle & Long (2000);
- Lichens: Santesson et al. (2004);
- Phytosociological units: Vegetation of Europe (EuroVeg-Checklist (Mucina et al. 2016).

In the reference list, all titles of publications are provided with an English translation. We have used the translation as provided in the original publication, even if not compliant with the concepts and terms used in this book (e.g. 'Kulczyński, S. (1949) Torfowiska Polesia. [Peat bogs of Polesie]'). If untranslated in the original publication, we have provided our own translation, using concepts and terms of Chapters 2 and 3. References published in non-Latin script are presented with both the transliterated author name and the author name in original script. Names of authors that have published both in English and in non-Latin script may appear differently in case their English language publications used other transliteration rules than this book. For example, 'Botch & Masing (1983)' are cited as in the original English language publication, but the same authors appear as 'Boch & Mazing (1979)' when transliterated from an originally Russian language publication.

In the book, text citations in the original language are presented in double inverted commas ("nomen"), whereas translations are in single inverted commas ('name'). All translations, unless otherwise specified, are made by the authors.

Maps have been prepared using generalised country border shape files (ESRI 2015), files from the European Environment Agency (EEA 2015), OpenStreetMap (OSM 2015), the Global Self-consistent, Hierarchical, High-resolution Geography Database (GSHHG 2015), and SRTM elevation data (Jarvis et al. 2008). See the introduction of Part II for explanations on country selection and borders. Depiction of borders is not authoritative.

2 Mire diversity in Europe: mire and peatland types

Hans Joosten, Asbjørn Moen, John Couwenberg & Franziska Tanneberger

2.1 Introduction

When comparing mires and peatlands from different countries, an obvious challenge lies in which types to distinguish and which terms to apply. A common typology and terminology has been a central aim of peatland science since its inception.

A multitude of environmental factors (e.g. source and type of water, climate, land setting, geological setting, nutrient availability, vegetation cover, peatland use in past and present) and their spatial and temporal interactions determine the enormous diversity of peatlands. As a result, numerous approaches to peatland classification have been developed over the course of time, reflecting the individual purpose of each classification system as well as local, regional, and historical aspects. Initially, peatlands were primarily classified from an economic and land exploitation perspective. Following the development of ecology, the 'ecosystem' (or 'biogeocoenosis') concept came more into focus, and subsequently the total landscape approach increasingly gained consideration. However, while classification systems tended to become more complex with continued scientific progress, simple systems have been perpetuated by tradition and practical use.

In this chapter we provide an overview of the various approaches to mire and peatland diversity and classification (see also Box 2.1). We pay particular attention to the history of the various concepts, emphasising persistent ideas that explain much of the current complexity and confusion. Further elaborations on terminology are provided in Chapter 3 of this book. The main regional approaches to mire classification are described in Chapter 4 and the country chapters.

2.2 Principles of classification

In this chapter we will elaborate on the theoretical principles of classification. What is classification and what do we mean when we write about classes and types? How do we classify and at which scale-level? We think it is important to focus on these questions and provide a theoretical background before we turn to existing peatland classification systems in the chapters that follow.

2.2.1 The purpose of classification and terminology

Classification is our most important instrument to handle information. Everything differs from everything else and so, in order to reduce this oversupply of data, we sort and group things into 'classes' (categories) that we make on the basis of similarities and dissimilarities. Each class must have properties that are shared by all of its members, but not by members of other classes. Which kind of likeness or difference is considered important, is determined by the purpose of the classification. Consequently, the classes distinguished by farmers, foresters, peat extractors, land use planners, teachers or conservationists often diverge.

The assignment of concrete mires and peatlands to a certain class is called 'identification'. Identification is only possible after the classes have been established and the characteristic properties have been defined. Identification and classification may become intertwined in an iterative process when concrete objects do not fit the existing classes and new classes have to be defined. In case the characteristic properties of a class are closely correlated, identification can restrict itself to the most obvious properties, the so-called 'indicators'.

Box 2.1: Mire classification and mire conservation

First, it is good to realise the dual relationship between mire classification and mire conservation. Classification pursues simplification, it seeks to condense the amount of *information* through a (conceptual) reduction of 'difference/diversity'. In contrast, conservation pursues the preservation of diversity. If a classification would proceed down to a level at which only two classes (e.g. 'bog' and 'fen') were left, it would be sufficient to conserve only two mires to preserve all perceived European mire diversity. Yet, we appreciate that everything differs from everything else if we observe it on a sufficiently fine scale.

Classification for conservation should therefore not simply pursue the reduction of data, but transform its oversupply into *useful* information. Consequently, classification for conservation must pay utmost attention to consistency and comprehensibility to allow a maximum of biodiversity to be appreciated.

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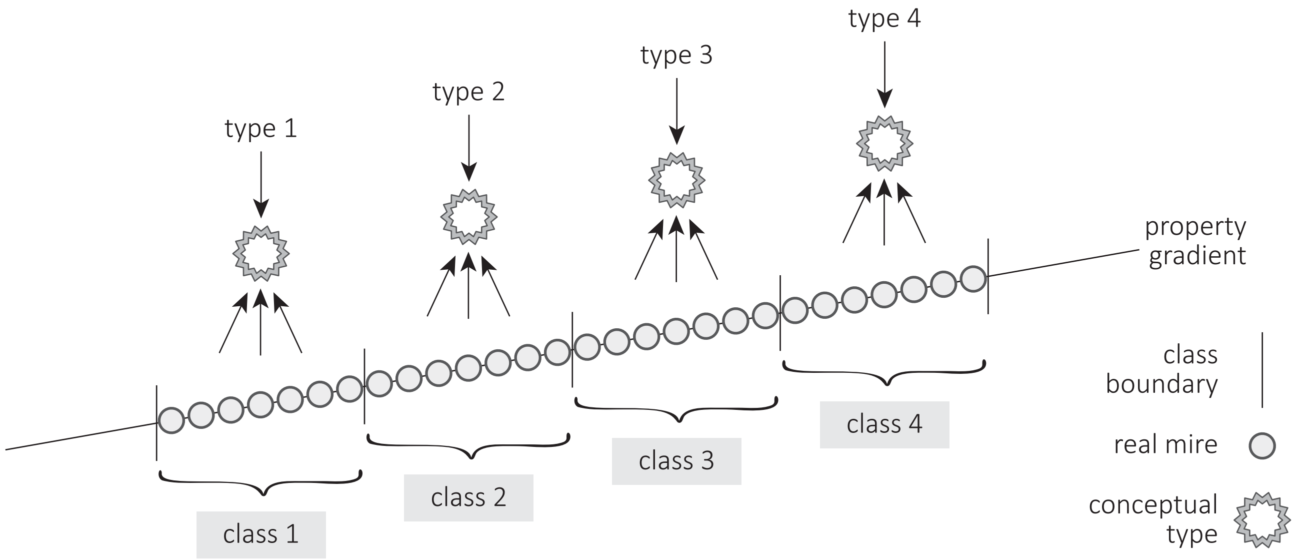


Fig. 2.1: The relation between typification and classification of real mires, mire classes, and mire types.

Mires exhibit a multitude of properties in continuous gradation. Drawing lines in such continuum leads to the question whether these boundaries really exist or whether they are arbitrary constructs conceived just for the sake of data reduction. To avoid the problem of vaguely defined boundaries, classification often uses 'types' to characterise classes. The major characteristics of real mires are brought together in a conceptual model (the 'type'), which is distinctly different from the types of other classes (Fig. 2.1). Whereas a class is defined by the boundaries, a type is defined by the ideal properties of a class. Types are important in understanding and ordering the diversity of mires and as a reference for identification. In the practice of mapping and statistics, however, real existing mires have to be assigned to a class, of which the boundaries are rarely as clear as the types suggest (Ramann 1907).

2.2.2 Classification and variables

Mire classification may be based on whatever properties mires may have (cf. Huxley 1869), i.e. on every variable (a property that 'may vary' from one item to another or from one time to another) and its variates (values, scores). The most common way of assessing difference is by expressing it as a distance on an axis. Many properties can be expressed as a numerical value on a scale, such as peat thickness, area, pH, N_C, water table depth, or degree of peat humification.

When scales have equal intervals, they allow for the calculation of aggregate properties, such as the arithmetic mean and its standard deviation, which are useful for describing a class or a type. Unequal intervals (generally) do not allow for a meaningful elaboration of aggregate properties. For example, as pH is expressed on a logarithmic scale, it makes no sense to derive an average pH of 5 from three samples with a pH of 3, 4, and 8 respectively. Because equal interval scales permit addition, subtraction, and the calculation of averages, they can be used to create compound measures, such as slope (m/m), relative cover (m^2/m^2), concentration (g/dm^3), hydraulic conductivity (m/day), and primary productivity ($g/m^2/yr$). Equal interval scales allow sorting of items according to which is greater or smaller. Such relationships are 'ordinal', because they specify the order of size, quantity, or magnitude among measured items. The term 'ordinal scale' is, however, in practice reserved for scales that *only* express the order of the measures, but not the magnitude of the difference. Ordinal measurement puts individuals in an order of importance, for example in the order of size, without paying attention to how large the individual differences are. Ordinal scales in peatland science include the scale of peat humification (decomposition) of von Post (1924) and the 'Zeigerwerte/ indicator values' of Central-European plants of Ellenberg (et al. 1991). Both von Post and Ellenberg have assigned a counting number (1–10, 1–9 or 12, respectively) to their scales to provide somewhat more information than a mere rank-ordering. Some of the Ellenberg Zeigerwerte-axes to some extent have an equal interval character (Såstad & Moen 1995, Ertsen et al. 1998, Klaus et al. 2012). Also the von Post scale shows 'a lucky choice of differentiation' (Overbeck 1975) with a strong linear correlation with a colorimetric proxy for decomposition (Overbeck 1947) and with bulk density (Päivänen 1973, Roßkopf et al. 2015).

The simplest way of measuring is categorical assessment, in which a decision is made whether an item belongs to a category or not (i.e. whether a variable has a value of '1' or 'zero'). For example, we can (after we have defined what a 'bog' is…) decide whether something is a bog or not a bog. Categories of this type are called nominal categories (from the Latin "nomen", meaning 'name'). Between nominal categories, there are no intrinsic relationships of 'greater than' or 'less than'. With increased knowledge, purely nominal categories may evolve to ordinal classes or even to classes on an interval scale. This happened, for example, in taxonomy with the development of cladistics, when pure morphologic criteria to distinguish species were replaced by evolutionary relationships and the differences between species became expressed on a scale of genetic dissimilarity. An example from the peatland world is found in the developmental sequence of raised bog types, where different morphological forms can be discerned in the order of age: the older ones have originated from the younger ones (Fig. 2.2, Chapter 2.6.3).

To arrive at a consistent classification it is essential to stick to the axis chosen. An axis (gradient) of trophy (Greek τροφή=food) that

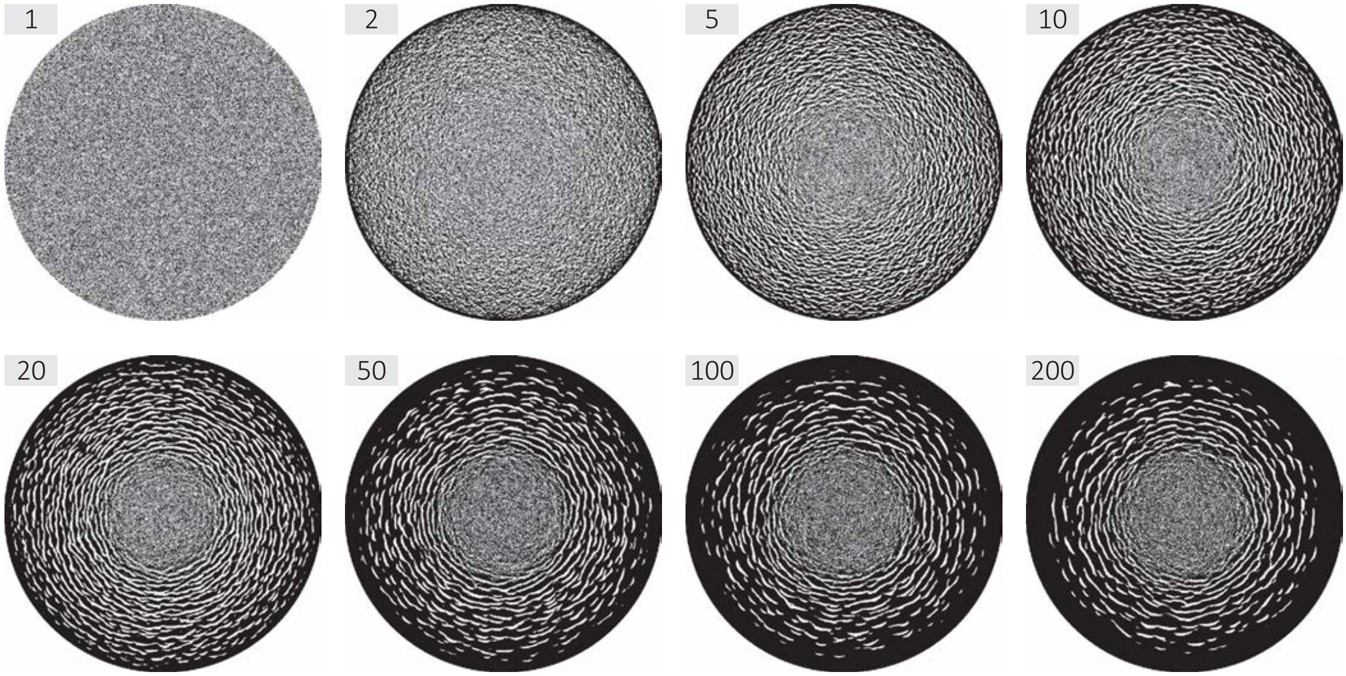


Fig. 2.2: A young bog (upper left) develops into an old bog (lower right) with more explicit expression of surface patterns. Black: hummocks, white: hollows. The time steps given in the upper left corner of the respective snapshots are of arbitrary length (Couwenberg & Joosten 2005).

encompasses the classes ‘eu-‘ (ευ=well), ‘meso-‘ (μεσο=medium), ‘oligo-‘ (οληγο=little), and ‘ombrotrophic’ (ομβρος=rain) (see Eurola et al. 1984) is confusing because the first three terms refer to the amount of available nutrients, whereas the latter term refers to their source. Precipitation is indeed generally extremely poor in nutrients, but in areas where the rain contains more nutrients (from volcanic tephras for example), such an approach will lead to identification problems (Damman 1995). In this case, a better term than ‘ombrotrophic’ would have been ‘peinotrophic’ (πείνος=starvation, cf. Walter 1977).

For a division into classes it is relevant whether the possible values of variables are discrete or continuous. The number of species in a peatland is discrete, for example, meaning it can be any whole number, but it can not be 1.5 or 1.9999. In contrast, peat depth is a continuous variable that can be expressed as 2.3, 2.44, or 2.6666 m, depending on the accuracy of measurement. In case of continuous variables the definition of classes is subjective. The discontinuities in discrete variables, on the other hand, provide more objective places for drawing class boundaries.

Some variables that are essentially continuous can nevertheless enable the objective definition of discrete classes, when the values are forced into prescribed ranges by thresholds and buffers. This applies, for example, to some extent to most peatland pH classes (cf. Sjörs 1950b), because these classes have rather strong chemical boundaries that are determined by various buffer ranges of carboxyl groups (-COO^-) of organic matter, aluminium compounds, cation exchange, and bicarbonate/carbonates respectively (Table 2.3, Stumm & Morgan 1981, Siegel et al. 2006).

Variables can be internal, i.e. be a property of the mire itself, or external, i.e. only measureable with respect to something outside the mire. The characteristic, name giving properties of a ‘mountain mire’ or a ‘valley mire’ are not determined by the mire itself but by its landscape setting. Also the criterion ‘source of the water’ (e.g. ombrogenous, soligenous, limnogenous, topogenous, cf. Sjörs 1948) is external, whereas the type of water flow in the mire (percolation, surface flow, acrotelm flow, cf. Succow & Joosten 2001, Joosten & Clarke 2002) is an internal characteristic. In general, internal features better describe the functioning of the peatland, whereas external ones better allow consideration of the landscape ecological context.

Classification along only one axis is called univariate. In practice, peatland classes are often sorted along two (bivariate) or more axes (multivariate**)**. Examples of bivariate peatland classification are the ‘Finnish mire site types’ (Chapter 2.4.7) of Ruuhijärvi (1983) along the axes of trophy and wetness (with a passive assignment of vegetation types), and the ‘ecological mire types’ (Chapter 2.4.8) of Succow (1988, Succow & Joosten 2001) along the axes soil pH and soil N_C (Nitrogen to Carbon ratio), the latter being a proxy for nutrient availability (Table 2.9). Examples of multivariate classification include coena (plant communities) in vegetation science, which actually involve as many axes as there are plant species. Peatland ‘vegetation forms’ (Succow & Joosten 2001), which aim at optimal site indication, are the outcome of a joint classification of vegetation and site variables and include a combination of two univariate interval axes (soil pH, soil N_C), one bivariate interval axis ‘degree of soil moisture’ (composed of springtime water table and annual water table range), and three nominal multivariate ‘axes’ (water quality type, water regime, and vegetation composition).

As the possible number of axes is next to unlimited and axes of continuous variables can be divided into unlimited interval classes, the total number of peatland types would be infinite, unless the variables are systematically associated with each other. Discovering such correlations is of utmost importance in deriving integrated mire types.

Box 2.2: Some basic concepts and terms

A **wetland** is an area that is inundated or saturated by water to the extent that its vegetation is dominated by plants that are adapted to life in anoxic soil conditions.

A **peatland** is an area with a naturally accumulated peat layer at the surface. The thickness of the peat layer is not fixed in this general definition as it varies between countries and interests. However, the maps and area statistics in this book are based on a minimum peat depth of 30 cm (unless otherwise noted).

Peat is a material that has accumulated in situ ('sedentarily') and consists of at least 30% (dry mass) of dead organic material.

A **mire** is a peatland with vegetation that forms peat.

A **swob** is a wetland with vegetation that may form peat.

Wetlands and swobs can occur both with and without peat and, therefore, may or may not be peatlands. In our definition, a mire is always a peatland. Mires are also wetlands, as peat is formed under waterlogged conditions. However, a peatland in which peat accumulation has stopped (e.g. as a result of drainage), is no longer considered a mire. When drainage has been severe, the peatland is no longer considered a swob or a wetland either. Figure 2.3 illustrates the relationship between the concepts.

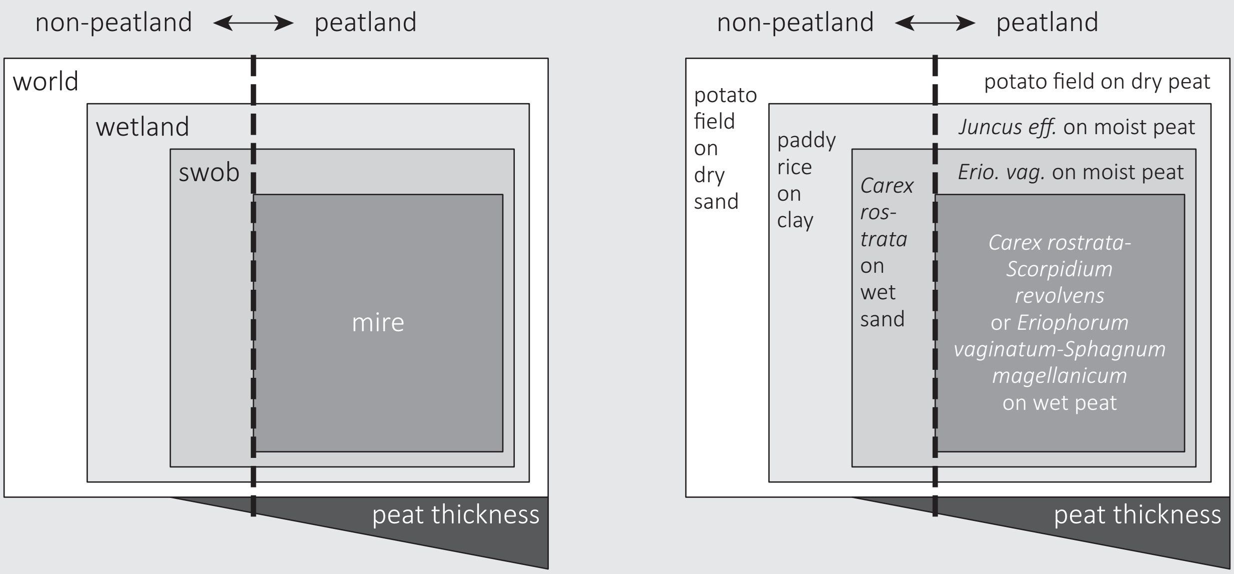


Fig. 2.3: Relationship between the nested concepts mire, swob, and wetland as used in this book (left) with examples (right; after Joosten & Clarke 2002). Wetlands and swobs may occur both as peatland and as non-peatland. Mires are always peatlands. The minimum peat thickness that differentiates between peatland and non-peatland (and thus also between mire and non-peatland swob) differs among countries/disciplines and over time. In the maps and area statistics in this book, we use a minimum peat depth of 30 cm (unless otherwise noted).

2.2.3 Resolution, hierarchy, and organisational level

Reality displays itself on various spatial scales. The differentiation between 'the forest and the trees' illustrates that these scales are not only a matter of looking into more detail, i.e. of resolution, but also of recognising various levels of organisation and complexity. Already in 1495 Albrecht Dürer painted the wet marginal 'lagg' zone and the elevated open dome as distinct components of one and the same bog (Photo 1).

The concept of organisational levels builds on hierarchy theory and implies that systems on a higher level contain and control systems on lower levels. The behaviour of the system can only partly be explained by the functioning of its subsystems: systems of a higher level also have 'emergent properties' that cannot be deduced a priori from the properties of the constituent parts (Klijn 1995). A brick, for example, does not provide shelter to human beings, a house (organised collection of bricks) does. The system, however, limits the degrees of freedom of its subsystems (cf. command structures, prey-predator relationships, social control mechanisms).

Each organisational level can be characterised by specific cybernetic properties, regulating and conducting flows of energy, matter, and information. The number of units increases downwards and the lower units are smaller, less complex, more dependent, and act on a shorter time scale. Higher levels tend to react more slowly than lower levels.

Self-organisation in mires clearly generates such organisational levels (Joosten 1993, Masing 1998, Couwenberg & Joosten 1999a, 2005).

In this book we deal with organisational levels in various ways. With respect to mire classification we distinguish between (1) 'point' (non-dimensional, 'topological') approaches that consider properties that are homogeneous in horizontal space ('site conditions') with variety

Table 2.1: Classification of “bogs” according to Boate (1652). Original text with our additions in [parentheses].

Type	Subtype	General and hydrological characteristics	Peat
dry, or red Bogs		the earth in them for the most part is reddish, and over-grown with Moss of the same colour	light, spungy, of a reddish colour, kindleth easily, and burneth very clear, but doth not last.
wet bogs, barren through superfluous moisture	grassy Bogs / Green-Bogs	looking fair and pleasant, as if they were dry ground [but] for the earth being very spongy can bear no weight … as well men as beast, assoon as they set foot on it doe sink to the ground, some knee deep, others to the wast, and many over head and ears. [The phenomenon that they] tremble for a great way [has given them the name of] Shaking-Bogs [and the smaller ones] Quagmires ordinarily … occasioned by Springs	heavy, firm, black, doth not burn so soon, nor with so great a flame, but lasteth a great while, and maketh a very hot fire, and leaveth foul yellowish ashes. It is the observation of women, that the linnen which is dryed by a fire made of this last sort of Turf, getteth a foul colour, be it never so white washed and bleeched, and groweth yellowish in that manner as that it can hardly be got out again.
	Watery-bogs	likewise clothed with Grass, but the water doth not sink altogether into them, … but remaineth in part standing on the top (in the same manner as in some of the Grassie-bogs, and in all the low Pastures and Meddows of Holland) by reason whereof these Bogs are not dangerous; for every one at the first sight may easily discern them from the firm ground	
	Miry-Bogs	consist of meer Mud and Mire, with very little or no grass upon them. These are commonly of a very small compass, whereas most part of the other two are of a notable extent, and some of several miles in length and breadth	
	Hassockie-bogs	[Their] ground being miry and muddy is covered over with water a foot or two deep … so as one would sooner take them for Loughs, were it not that they are very thick over-spread with little Tufts or Ilets, the which consisting of Reeds, Rushes, high sower Grass, and sometimes with little Shrubs, for the most part are very small, and have but a few feet in compass; some of them being of the bigness of a reasonable big chamber. These little Ilets or Tufts being so many in number, and spread over all the Bog, there remaineth nothing between them but great Plashes of water (in regard whereof these Bogs might well be called Plashy-Bogs) in some places wider, in others narrower, so as from the one men may well step or leap to the other; that which those who are expert in it know how to do very nimble, and so to run from one part of the Bog to another: For the roots of the Rushes, Reeds, and other things growing on those Tufts, are so interwoven, that they can easily bear a man who lightly treadeth upon them, although they have very little earth, and are wondrous spungy; so as they, when the water being drained, the Bog is dried round about, may easily be plucked from the ground.	

only in vertical strata (Chapter 2.4), and (2) ‘area’ (mosaic, ‘chorological’) approaches that consider properties that are heterogeneous in horizontal space (Chapters 2.5 and 4) (Zonneveld 1995, Joosten et al. 2001). The phytosociological hierarchy is dealt with in Chapter 2.4.6, whereas the hierarchy in mire structural and functional components (ero, feature, site, massif, and complex) is discussed in Chapter 2.7. We use the distribution of plant populations to define flora and vegetation regions on the level of the biome (Chapters 4.3 and 4.8), whereas vegetation types are used to distinguish mire types and mire regions (Chapters 4.3 and 4.5).

In this book we use five basic concepts and terms (Box 2.2). An extensive justification is provided in Chapter 3.2.

2.3 Early mire descriptions and classification

Mire classification must have originated within the everyday categorisation of land. Old ‘proto-language’ words that have developed into present-day peatland terms reflect the properties that were considered relevant (see Chapter 3). These properties include the instability and wetness of the soil (‘bog’, ‘swamp’), the shape and environmental setting (‘Hochmoor’, ‘Niedermoor’, ‘Flachmoor’), the presence of a special soil substance (‘fagne’, ‘moer’), or the characteristic colour (‘red’ bog). Use-oriented properties included the suitability for providing fodder (‘Grünlandmoor’) or sods for fuel (‘tourbière’, ‘torfeira’, ‘torfowiska’). Several of these properties were strongly correlated, which enabled one property to be used as an indicator for others. The other side of the coin was that variables were not clearly separated anymore so that with the development of separate scientific disciplines the same terms started to be used for different concepts.

John Leland, in his 1535–1543 ‘Itinerary in England and Wales’, was one of the first to distinguish various types of peatlands. He differentiated between fens (“fennes”) and bogs (“mores”), for example, when he described the landscape around the current Thorne and Hatfield Moors in the North of England: “The Quarters about Heatfeld be forest Ground, and though Wood be scars there yet there is great Plentie of red Deere, that haunt the Fennes and the great Mores thereabout” (quoted from Hearne 1768). The oldest systematic classification of “bogs” is that of Boate (1652, Table 2.1).

2.4 Topological classification

2.4.1 Introduction

Properties that are commonly used to classify mire sites include water table and its fluctuations, origin of the water, pH and base saturation of water and soil, nutrient availability, vegetation physiognomy and floristic composition, and peat stratigraphy. All these properties can be considered to be spatially non-dimensional, although some of them obviously occupy horizontal (vegetation) or vertical (water level, peat stratigraphy) space.

Such non-dimensional variables are suitable for classifying local mire spots and for describing assemblages (e.g. mosaics) of different spots in a large mire. When one property dominates the mire, it is often used to characterise the entire mire, even if the mire locally contains spots that are different, e.g. a eutrophic fen, a string-flark fen, or a palsa mire (Chapter 2.6.1).

2.4.2 Water table in relation to peat formation

Next to the decay-resistance of the dead plant material (Coulson & Butterfield 1978, Clymo 1983, Johnson & Damman 1993, Hartmann 1999), the presence of water is the most important factor controlling decomposition. The large heat capacity of water induces lower than ambient temperatures (Ball 2000), which impedes biological activity. More importantly, however, the limited diffusion rate of gasses in water (Denny 1993), in combination with fast microbial O_2 consumption, leads to anoxia. The lack of oxygen inhibits the activity of decomposing and decomposition-facilitating organisms, leading to the accumulation of peat (Clymo 1983, Moore 1993, Freeman et al. 2001, Koppisch 2001).

The groundwater table is defined as the highest level at which free (hydrostatic) water occurs in cavities in the peat (e.g. in a measurement tube; Sjörs 1948, Rydin & Jeglum 2013). Lower water tables in mires tend to result in a larger height of the vegetation, a larger productivity of vascular plants, and a faster rate of decomposition of dead plant material and peat. Because both production and decay are affected, the effect of a (limited) change in the water table on peat accumulation is not straightforward. Somewhat drier alder carrs, for example, may have a higher net peat accumulation rate than very wet ones, because with slightly lower water levels primary production increases faster than the rate of decomposition (Prager et al. 2006).

Already Boate (1652) noticed the importance of water in the origin of mires: "VEry few of the Wet-bogs in Ireland are such by any naturall property, or primitive constitution, but through the superfluous moysture that in length of time hath been gathered therein, whether it have its originall within the place it self, or be come thither from without. […] So that it may easily be comprehended, that whoso could drain the water, and for the future prevent the gathering thereof, might reduce most of the Bogs in Ireland to firm land". Boate (1652) furthermore described "bogs" from "places, where or through the situation of them, and by reason of their even plainness or hollowness, or through some other impediment, the water hath no free passage away, but remaineth within them, and so by degrees turneth them into Bogs".

Findorff (quoted in de Luc 1779) wrote about 'the water that generates the peat in these mires', and also Gough (1793) was aware of the intrinsic ties between water saturation and peat: "And, in fact, humidity is so necessary to the preservation of this kind of earth, that when it is exposed to air it loses its distinguishing properties, and is changed into mold." Crome (1812) expressed this idea even more explicitly: 'Water […] is always an essential condition for the formation of peat deposits; […] Without water absolutely no peat formation is possible!'.

On the other hand, there was also an early awareness that peat does not grow in water that is too deep (von Bose 1802), as was expressed by Cramer (1766): 'Rarely does one find peat on sites that are continuously deeply inundated […] It seems therefore that peat does not grow under water but only on such soils where water and air alternate'.

Lesquereux (1844) noticed that some peat deposits had been formed under water, whereas others are elevated over an only moistened soil without ever having been immersed. He thus distinguished between 'supra-aquatic or emerged mires', with which he meant the "hautes marais" (raised bogs), and 'infra-aquatic or submersed mires'. He noticed that the former could develop over the latter, but that every mire could be assigned to one of these two types.

Weber (1897) adopted the approach of Lesquereux (1844) and added 'semi-supra-aquatic' to describe alder and other carrs, while he reserved the term 'supra-aquatic' solely for ombrotrophic formations. Later he left this approach and categorised mire formations along the water level gradient limnic – telmatic – semiterrestric – terrestric (Weber 1902). While the latter classification has been widely adopted in modern mire science, the infra/supra-aquatic differentiation of Lesqeureux is hardly applied nowadays (cf. Háberová 2000), except when describing peat types and peat formation strategies (Succow & Joosten 2001). Kubiëna (1953) combined Weber's limnic and telmatic into one term 'subhydric'.

2.4.3 The origin of the water

All water on land ultimately originates from atmospheric precipitation. Water evaporated from the sea is originally pure. The dissolution of CO_2 makes atmospheric water somewhat acidic. In the air the water vapour condenses to liquid water, a process that is facilitated by aerosols (minuscule, dispersed fluid or solid particles). Close to the sea these aerosols include water particles that have been ejected into the atmosphere by bursting bubbles at the air-sea interface ('sea spray', Lewis & Schwartz 2004). In coastal areas precipitation thus contains the highest concentrations of sea-derived ions, such as Na and Cl, whereas Ca, Mg, and K supplied by soil dust show the highest concentrations in mid-continental precipitation water (Gorham et al. 1985, Damman 1995).

As soon as precipitation water enters the pedo- and lithosphere (soil, bedrock), its quality 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 mineral composition, pH, O_2 concentration, and temperature of the water change (Joosten & Clarke 2002). These changes may lead to various types of water discharging in a mire, which influence site conditions like pH and base saturation (Chapter 2.4.4), nutrient availability (Chapter 2.4.5), and temperature, and give rise to habitats of characteristic plant species (Chapters 2.4.7 to 2.4.9).

The differentiation of mire types according to the source of the feeding water was first recognised by Boate (1652), who described "Grassie-bogs, which ordinarily are occasioned by Springs" whereas "the Waterie and Hassockie-bogs... are in some places caused by the rain-water onely, as in others through brooks and rivelets running into them, and in some through both together; whereunto many times also cometh the cause of the Grassi-bogs, to wit the store of Springs within the very ground" (see Table 2.1).

Naismith (1807a,b) pointed out that "When the surface of a peat field is lower than the surrounding grounds, in times of rain, the water from the latter overflows the former, and the particles of the earths suspended in the water insinuate themselves among the fibres of the peat, altering its consistence more or less according to the proportion of the suspended earth. As the water is most loaded with earth when it arrives on the peat ground, the greatest quantity is deposited near the margin. There the alteration is greatest; the consistence becoming too solid, the peat-forming vegetables die; the peat ceases to augment its bulk; and vegetables, to which simple peat is not congenial, spring up. But the water, clearing as it advances, has less effect the farther it proceeds towards the interior of the field, so that the surface of a bed of peat frequently becomes higher towards the centre, where its natural tendency to swell is not suppressed, than on the margin where earth is deposited." In the centre of such peatland the ash content would thus be very low, as Naismith showed with a sample containing less than 1% (Gorham et al. 1985).

The most detailed early observations with respect to the effect of the source of water stem from Witte (after Lasius in Lesquereux 1847): 'The first peat forming plants, which vary according to the different nature of the mire subsoil, are decisive for the nature of the peat. Their production (both in terms of plant species as well as of the substances that they incorporate, change into new substances and deposit as future peat, as well as in terms of more or less rapid growth) depends essentially on the diverse nature and different origin of the water causing peat formation. The latter is either spring water, which occurs with very diverse mineral admixtures or pregnant with different gases, and either supports peat formation already at the source, or forms a stream that supplies the necessary water to the place of peat formation. Or, water collects from rainfall only, as in kettlehole mires that originated in the confluence of precipitation water from the surrounding heights and from the dead plant remains that were washed together. Or, the water causing mire formation has lost its way in the lowlands during floods and has remained there stagnant – or, finally, these three different forms of water supply act more or less together.'

The purely atmospheric origin of the water in raised bogs ("Vom Regen nur und Tau des Himmels ist es aufgewachsen" – 'from merely rain and dew of heaven has it grown') and its consequences for nutrient availability ("die Erde nährt es nicht" – 'it is not fed by Earth') was first recognised by Dau (1823, Fig. 2.8). Weber (1911) named the peat formed in such bogs "Regentorf" ('rain peat') or "ombrogener Torf" ('ombrogenous peat'). Mires solely fed by rain were called "ombrogene Moore" ('ombrogenous mires') by von Post & Granlund (1926) and "Niederschlagswassermoore" ('precipitation water mires') or shortly "Regenmoore" ('rain mires') by Ackenheil (1944). The plant species growing in bogs were called "Regenwasserpflanzen" ('rain water plants') by Witte (1847) and "Ombrominerobionten" by Ackenheil (1944).

Witte (after Lasius in Lesquereux 1847) classified peatland plants into "Quellwasserpflanzen" ('spring water plants'), "Regenwasserpflanzen" ('rainwater plants'), and "Sumpfpflanzen" ('swamp plants'): 'The first and last of these three classes basically form the foundation of all our peatlands. In bogs, however, they only extend to a certain height, namely as high as the water from ponding or the overgrown spring can reach. Once the mire reaches a specific height, the contribution of the original source of water stops, and only rainwater continues to exert an effect.' Weber (1911) called the peat formed in groundwater-fed mires "Grundwassertorf" ('groundwater peat') or "hydrogener Torf" ('hydrogenic peat'), whereas the mires were called "Mineralbodenwassermoore" ('mineral soil water mires') or shortly "Bodenmoore" ('soil mires') by Ackenheil (1944).

Ramann (1895–96) found conspicuous differences in the concentrations of Ca, Si, and total dissolved mineral matter between water from a *Sphagnum* bog and from a *Phragmites*-*Scirpus* dominated fen, which he ascribed to different proportions of the groundwater. Früh & Schröter (1904) provided a systematic overview of the differences between "Hochmoore" ('bogs') and "Flachmoore" ('fens'), in which they linked the source of the water (telluric versus atmospheric) to its quality. They noted that whereas 'fens' were always and only linked to telluric water supply, 'bogs' were influenced by water that is poor in mineral substances, which was supplied by the atmosphere, but could – especially on carbonate poor soil – also be provided by telluric water (cf. Wheeler & Proctor 2000).

The vegetation of mires influenced by mineral soil water ('fens') appeared to be more species rich than that of mires fed by rain water alone ('bogs'), with specific species (the 'fen indicator plants' of Sjörs 1948) differentiating the former from the latter. Obligatory 'bog' species appeared to be very rare: most species (at least all vascular plant species) growing in bogs were also found in poor and extremely poor fens (Du Rietz 1954).

In the older literature the 'bog' concept often also included mire parts influenced by acid mineral soil water (see e.g. Früh & Schröter 1904 above) as well as nutrient-rich fen parts hydrologically connected to purely rain-fed parts (Kästner & Flössner 1933). Thunmark (1940, 1942) narrowed down the border between 'bog' and 'fen' using the change in microbial communities in relation to the "Mineralbodenwassergrenze" ('mineral soil water limit'), i.e. the highest level the mineral soil water reached. The "Mineralbodenwassergrenze" concept strongly stimulated research into the exact boundary between bog and fen, especially in Sweden, where Du Rietz noticed a similarly sharp change in macrovegetation (review in Du Rietz 1954). As the mineral soil water limit was in the field identified as the occurrence of the most advanced exclusive fen species, Sjörs (1946, 1948) proposed to replace Thunmarks expression "Mineralbodenwassergrenze" with the phytosociological concept "kärrväxtgränsen" ('fen plant limit', cf. the "Euminerobiontengrenze" of Ackenheil 1944). As bogs and fens also have many species in common (that logically are thus also 'fen plants'), Du Rietz (1950) alternatively proposed the more exact "exclusive fen plant limit".

After Witting (1949) had shown that the mineral soil water limit usually lies at c. 1 mg Ca l^{-1} or slightly lower, Du Rietz (1954) proposed to use the concept "Mineralbodenwassergrenze" only in case the limit had been indicated by chemical analysis and to use the term "Mineralbodenwasserzeigergrenze" ('mineral soil water *indicator* limit') in cases this limit is only indicated by "Mineralbodenwasserzeiger" ('mineral soil water *indicators*'), i.e. the most advanced exclusive fen species.

The concept of "Mineralbodenwasserzeigergrenze" has later been questioned by Wheeler & Proctor (2000, see also Proctor 2013), who argue that the boundary is not sharp. However – except for highly oceanic areas in western Europe – the distinction is the least ambiguous, and all other differences between mire vegetation types are less sharp (e.g. Sjörs 1948, Malmer 1962, Økland et al. 2001, Sjörs

& Gunnarsson 2002). Also from a worldwide perspective, this border is accepted as a major ecological limit in mire ecology (e.g. Damman 1995, Rybníček & Yurkovskaya 1995, Glaser 1987, 1992a,b, Glaser et al. 1981, 1990, 2004a). The boundary is very sharp for Ca concentration (2 mg l^{-1}) and usually sharp for pH (4.2, although it can be 4.3 with low Ca concentrations or 4.4 in extreme maritime settings where high rainfall washes the peat of organic acids).

The difference in water chemistry and vegetation led to the classification of mires into two main groups based on the source of the pore water:

- 'Ombrogenous': sites that only receive water from precipitation; and
- 'Geogenous' (minerogenous): sites that also receive water that has been in contact with the Earth, i.e. the mineral soil or substratum (cf. Sjörs 1948).

The further subdivision of geogenous mires (which are not merely fed by atmospheric water) goes back to von Post (1926) and von Post & Granlund (1926) who distinguished between "topogenous" (= 'originated as a function of place') and "soligenous" (= 'originated as a function of soil') mires. The origin of topogenous mires, according to von Post (1926) 'can be deduced from topographic conditions only'. Topogenous mires are largely independent of climate, and 'develop from terrestrialising lakes or river valleys, or at springs'. Groundwater-fed valley mires and spring mires were thus explicitly considered to be topogenous (cf. the calcareous spring mire Källmosskupol in Fig. 35 of von Post & Granlund 1926). In soligenous mires, peat formation is not only 'induced and continued' by direct precipitation, but also by "zulaufendes Meteorwasser aus dem umgebenden Terrain" ('meteoric water flowing in from the surrounding terrain', von Post 1926, cf. Witte in Lesquereux 1847). Similarly, von Bülow (1929) differentiated between 'purely climate-dependent peat deposits', 'climate- and topography-dependent peat deposits', and 'climate-independent peat deposits'.

The distinction between topogenous, soligenous, and ombrogenous in the original sense was attractive because it allowed distinguishing climatic mire regions. Ombrogenous peatlands solely depend on precipitation and their geographic distribution is clearly determined by climate. Soligenous mires (*sensu* von Post) are climate dependent as well. On the one hand they occur in areas where rainfall is so abundant that in a sloping landscape run-off from the mineral surroundings prevents the development of ombrogenous mires. On the other hand they are found in regions where precipitation is insufficient to allow ombrogenous mire development, but where low temperatures limit evaporation to such an extent that a waterlogging of the surface can occur even on sloping ground (Granlund 1932). The topogenous mire region is defined as being neither ombrogenous, nor soligenous. It starts where climatic dryness prevents the development of ombrogenous and soligenous peatlands (von Post 1926, Granlund 1932).

In 1948, Hugo Sjörs coined the term 'geogenous' to combine the concepts 'topogenous' and 'soligenous'. Furthermore, he introduced the term 'limnogenous' to express soil wetness (or "wet of soil" as he named it in his English summary) that is "caused by inundation or permanent influence of water from rivers and lakes". Simultaneously, he redefined the concepts 'soligenous' and 'topogenous' in terms of hydrotopography and water movement. Thus, in Sjörs's understanding soil wetness is topogenous when "the mineral soil water surface causing wet of soil is approximately horizontal" and thus stagnant, and soligenous when "the mineral water surface causes wet of soil while still in motion", i.e. when the water table is sloping. This redefinition led to a typological switch of spring-fed mires from topogenous to soligenous. Later the term soligenous has also been used to denote mires fed by artesian water alone (cf. Masing 1975, Boch & Mazing 1979, Wołejko 2000). In current European mire science the concepts 'topogenous' and 'soligenous' are thus used in (at least) three different ways (as also the country chapters in this book illustrate). The approach of Sjörs (1948) is in science the most commonly used, whereas the recent EUNIS classification follows the von Post (1926) definition (Chapter 2.4.9).

Joosten & Clarke (2002) suggested to focus the terms more on the source of the water instead of on the genesis of the peatland. They proposed to refrain from using the term 'topogenous', to use 'soligenous' in the original meaning of von Post to mean 'originating from the soil', and to use 'lithogenous' for describing water originating from the deeper substratum. To accommodate for peatlands that receive a substantial part of their water supply from the sea (e.g. peat accumulating mangroves and salt marshes) they proposed the term 'thalassogenous'. They thus arrived at the following subdivision of 'geogenous':

- soligenous – originating from precipitation and near-surface run-off;
- lithogenous – (also including limnogenous) also originating from deep groundwater; and
- thalassogenous – also originating from the sea.

Equivalent to 'ombrogenous' and 'geogenous' the terms 'ombrotrophic' and 'minerotrophic' (e.g. Verhoeven 1992), 'ombrogenic' and 'minerogenic', and 'ombrophilous' and 'minerophilous' (Greek φίλος=friend) are used (e.g. Sienkiewicz & Kloss 1985). The Scandinavian tradition uses '-genous' ('-originated from') for geological/hydrological concepts and '-trophic' ('-fed by') for geographical/biological concepts (Moen 1995a). We use the suffix '-genous' for water, nutrients, and peat and the suffix '-trophic' for site conditions and vegetation. In this sense ombrogenous water feeds ombrotrophic vegetation that grows under ombrotrophic site conditions and produces ombrogenous peat. A mire and a peatland can be both '-genous' or '-trophic' depending on whether reference is to the geological deposit or to the ecosystem.

It is important to note that all these terms refer to the origin of the water, not necessarily to its quality: geogenous water or minerotrophic mires do not necessarily have to be rich in minerals and ombrogenous water not necessarily poor.

Next to the terms 'atmotrophic' (fed by 'mist, vapor')/'atmocline' ('mist, vapor'-like water quality), 'lithotrophic' (fed by 'stone')/'lithocline', and 'thalassotrophic' (fed by 'sea')/'thalassocline' (van Wirdum 1991, 1993), van Wirdum (1979) introduced the term 'poikilotrophic' (fed by 'various kinds' = alternately by precipitation and ground- or surface water).

Parallel to 'ombrophilous', Kulczyński (1949) introduced the concept 'rheophilous' to describe mires that are fed by flowing water, because – as he noted – 'Flowing water acts like an increase of nutrient content, stagnant water like a decrease' (Ramann 1911). The phenomenon had earlier been described by Weber (1902), who had observed that 'the lush woodland of the Rugulner Rülle thrives on poor moss peat and in contact with water that is always nutrient poor', leading him to the conclusion 'that the presence of a particular vegetation is by no means always dependent on the chemical composition of the soil and of the water, but may depend to a much greater extent on the movement of the water'. The terms 'rheophilous' and 'rheotrophic' (cf. Moore & Bellamy 1974) are also used as a synonym for soligenous sensu Sjörs or geogenous (cf. Gore 1983c).

Rudolph (1928) and Fægri (1935) introduced the concept of soli-ombrogenous and ombro-soligenous mires, respectively, to describe mires consisting of combinations of ombrogenous and soligenous parts (sensu von Post 1926). Ombro-soligenous mires often occur at higher altitudes.

Within one and the same mire, various types of discharge water may lead to a clear zonation of vegetation composition, productivity, and physiognomy (Oswit 1968,

Table 2.2: Mean pH, total concentration, and relative importance of major cations in peatland waters in Sweden (modified from Gorham 1955; names of peatland types after Gorham 1955).

Peatland type	Number of samples	pH	Na + K + Mg + Ca (mg l^{-1})	Relative proportion (% of total concentration of these elements)			
				Na	K	Mg	Ca
Raised bog	43	3.9	3.3	58	11	15	16
Extreme poor fen	15	4.3	4.4	45	5	12	38
Poor fen	16	5.0	6.4	46	7	20	28
Transitional poor fen	8	5.9	9.7	24	2	10	64
Rich fen	4	6.1	10.9	29	3	9	59
Transitional rich fen	5	6.5	28.8	12	1	4	59
Extreme rich fen	7	7.5	53.4	10	1	8	81

Table 2.3: Distribution of pH values in water from different kinds of mire communities in the poor-rich gradient of Scandinavian mire vegetation classification (names of mire types after Sjörs 1950b; modified after Shotyk 1988 and based on Sjörs 1950b).

Mire type	Number of samples	pH range	Buffer mechanism	
Moss	130	3.7–4.2	Carboxyl groups of organic matter	
Extreme poor fen	116	3.8–5.0		Aluminium compounds
Transitional poor fen	35	4.8–5.7	Cation exchange	
Intermediate fen	86	5.2–,6.4		
Transitional rich fen	80	5.8->7.0	Bicarbonate	
Extreme rich fen	8	~7.0-~8.4	Carbonates	

Pałzcyński 1984, Wassen & Joosten 1996, Wassen et al. 2002, Schipper et al. 2007). Over time, changes in hydrochemical conditions commonly result in a succession from groundwater to exclusively rainwater-fed vegetation (Lasius in Lesquereux 1847, Ramann 1895, Bellamy & Rieley 1967, Walker 1970, Granath et al. 2010, Tahvanainen 2011); changes in the opposite direction occur only rarely (Hughes & Dumayne-Peaty 2002, Michaelis 2002, Hájková et al. 2012a).

2.4.4 pH and base saturation

An important variable in mire ecology is the 'acidity', or – more correctly – the pH, i.e. the activity of hydrogen ions in the water (Kotilainen 1927). In general, the pH of peatland waters is controlled by the capacity for acid production (from the decomposition of organic matter) on the one hand, and the supply of bases (from ground or surface water) on the other hand. *Sphagnum* dominated mires produce organic acids with strongly acidic functional groups, whereas organic acids derived from sedges or brownmosses have weaker acidity and are less capable of neutralizing the bases transported into the peatland by groundwater. The different acids stabilise the discrete ranges in pH among different peatland types across the boreal zone (Siegel et al. 2006).

For an extensive discussion on the factors affecting the pH of peatland waters, the history of peatland pH research, and the methods and pitfalls of pH measurement in peatlands, see Shotyk (1988).

Few direct effects exist between pH and vegetation, but the indirect effects are numerous. Already Sprengel (in Lesquereux 1847) had observed that 'the vegetation becomes more diverse, the more spring water (which is rich in mineral forms) penetrates the peat deposit.' pH is tied directly to base saturation (Shotyk 1988, Table 2.2), i.e. to the proportion of exchange sites in the soil that are occupied by cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}). Plants may displace these cations with hydrogen cations (H+) making them available for uptake. pH also strongly influences the solubility and availability of other nutrients (phosphate, nitrate, ammonium) and toxic elements (aluminium).

Consequently, base saturation and pH correlate well with species composition (Yelpat'evskiy et al. 1974, Wheeler & Shaw 1995, Hájková et al. 2004, Tahvanainen 2004) and pH is a reliable indicator of the so-called poor-rich gradient in vegetation (Du Rietz 1949, Sjörs 1950b, Box 2.3) – not surprisingly as this gradient is in part defined by the presence and absence of calcareous water (Du Rietz 1949). Sjörs (1946) observed 'a striking parallelism between pH and the composition of vegetation', although the pH ranges of the groups show considerable overlap (Sjörs 1950b, Malmer 1962, 1986, Sjörs & Gunnarsson 2002, Table 2.3). Standardised soil pH classes form an important axis in the classification of 'vegetation forms' (Chapter 2.4.8).

2.4.5 Nutrient availability

Nutrient availability and associated productivity has traditionally been given much weight in the classification of mires because it directly relates to potential land use. The main separation of peatlands in bogs and fens on the basis of their different water sources has its logical consequences for water chemistry, including the availability of plant nutrients. The ombrogenous water supply of bogs normally results in nutrient poverty, whereas the geogenous (minerogenous) supply of fens may lead to a wide range of nutrient conditions, from nutrient poor to nutrient rich.

Although the concept of trophy is commonly associated with limnology, it was actually C.A. Weber (1902, 1907b) who introduced the terms “oligotroph” or “nährstoffarm” (‘nutrient poor’), “mesotroph” or “mit mittlerem Nährstoffgehalt” (‘with medium nutrient concentration’), and “eutroph” or “nährstoffreich” (‘nutrient rich’) to describe the nutrient content of peats in ‘bogs’, ‘transitional mires’, and ‘fens’, respectively.

The concepts oligo-, meso-, and eutrophic have been formalised in a scale that uses the ratio of nitrogen and carbon in the soil (N_C ratio, also expressed as C/N ratio). Together with pH, this formalised N_C ratio is used to delineate mire sites in the classification of ‘vegetation forms’ (Chapter 2.4.8).

The traditional differentiation in poor and rich fens (Chapter 2.4.4) refers to water chemistry (pH), not to the nutrient status. There is some confusion on this matter and the terms oligo-, meso-, and eutrophic are often used to denote the pH gradient in mires (e.g. Eurola 1962, Eurola et al. 1984, Bradis & Andriyenko 1974).

2.4.6 Vegetation composition

Stenius (1742) was the first to describe the difference between bog and fen vegetation, whereas Linnaeus (1751b) provided lists of plant species by which fens (“paludes”) can be clearly differentiated from bogs (“caespitosae paludes”). His pupil Kalm presented the best vegetation descriptions of fens (Kalm 1746) and bogs (Kalm 1753) in the 18th century as well as the first quantitative vegetation analyses. The scientific study of the indication value of species and vegetation started with the 1810 contest question of the Royal Holland Society of Sciences and Humanities: ‘to what extent can be judged about the fertility of cultivated and unused lands by way of the plants that grow there spontaneously?’, which was won by Crome (1812).

Witte (after Lasius in Lesquereux 1847) classified peatland plants into spring water, rainwater, and swamp species.

Vegetation composition has always been important in mire classification as vegetation is a useful indicator of at least three main ecological factors that are relevant for land use: base-richness, nutrient availability, and moisture conditions (Wheeler & Proctor 2000, Kotowski et al. 2016).

The base saturation gradient refers to pH and the abundance of ions in the groundwater and provides the basis for the differentiation of poor to extremely rich fens (Chapter 2.4.4). Nutrient availability separates plant species according to their ability to acquire and use nutrients (Aerts & de Caluwe 1994) and – via productivity – to compete for light (Kotowski & van Diggelen 2004). Less productive vegetation in general supports higher species diversity and conservation efforts therefore commonly focus on nutrient poor mires (Wheeler & Shaw 1991, Wassen et al. 2005). Moisture conditions affect the duration and frequency of anoxic conditions in the upper soil layers and interfere with nutrient availability: low water tables enhance peat mineralisation and the release of nutrients, and the soil redox potential determines the form in which nutrients are available (e.g. N) and whether they are available at all (e.g. P).

Because of the high indicator value of plants, the classification of mire vegetation has received ample attention. The level of detail of mire vegetation classification by far exceeds that of most other mire ecosystem components. Still, differences in vegetation play an important role in describing mire diversity on a regional, European scale (Chapter 4).

In spite of the importance of vegetation, no unified approach to classification of mire vegetation exists in Europe, because in different countries different ‘schools’ have developed. The different approaches found across countries relate to differences in 1) species richness between these countries, 2) mire diversity and abundance, 3) anthropogenic impact, and 4) the goals of classification.

Two main ways have commonly been used to translate concrete plant communities into abstract units. The classification of vegetation (syntaxonomy) assembles communities into hierarchical classes (associations, alliances, orders, and classes) purely on the basis of floristic composition and community characteristics, whereas the ordination of vegetation (gradient analysis) links floristic composition and community characteristics to environmental variables and distinguishes non-hierarchical units (Whittaker 1973). The Central and Southern European approach represents the first type, the Scandinavian approach the latter. The original Finnish approach was based on a combination of physiognomy/ecology and plant communities, but has developed towards the two main systems (Chapter 2.4.7). National/local variations to all these systems are discussed in the country chapters.

In central and southern Europe mires cover rather small areas, the large majority of which is heavily impacted by human activities, and the present-day plant cover mainly consists of anthropogenic ‘replacement communities’. In a regional context mires are regarded as azonal (Ellenberg 1988) and of minor interest. However, mires are also seen as unusual phenomena, relics of former times, and with environmental conditions supporting special species, communities, and ecosystems (Rybníček 1984, 1985). Most mire ecosystems in central and southern Europe are indeed species rich, which allows differentiating communities by characteristic species of vascular plants.

The Central and Southern European approach to vegetation classification is largely based on the work of Braun-Blanquet (1921, 1928) on plant sociology and syntaxonomy. His system of vegetation classification inspired numerous studies on the classification of mire vegetation all over Europe (e.g. Osvald 1923, Rudolph 1928, Nordhagen 1928, 1936, 1943, Paasio 1933, Tüxen 1937, Tsinzerling 1938, Paul & Lutz 1941, Dahl 1957, Rybníček 1964, 1974, 1984, Aletsee 1967, Moore 1968, Neuhäusl 1972, Oberdorfer 1977, 1983, Tyler 1979, Dierssen 1982, 1996, Masing

1982, Hájek et al. 2008, Graf et al. 2010, Chytrý 2007–2013, Jiménez-Alfaro et al. 2012). Within central and southern Europe eventually two schools developed: the Zürich-Montpellier school (e.g. Braun-Blanquet 1964) and the Central-European phytosociological school (e.g. Rybníček 1985, Ellenberg 1988). The two schools have shared two important principles: 1. The floristic composition as the main basis for the delimitation of units and 2. The hierarchic classification in associations, alliances, orders, and classes based on an inductive synthesis of relevés (systematic descriptions of sample plots) in form of tables (Rybníček 1985).

Until World War II, the two Central and Southern European schools were often regarded as one and the same, but later they developed into different directions. The Zürich-Montpellier school has its origins mainly in the western Alps and in the (sub)mediterranean, i.e. in regions with a very rich flora of vascular plants and with clear-cut (often anthropogenic) boundaries between plant communities. As a result the concepts of 'character species', 'differential species', and fidelity of species to associations were developed. In other parts of central Europe, where vegetation was less species rich, phytosociologists deviated from these basic concepts of the Braun-Blanquet approach, especially with respect to the principle of the fidelity of character species (van der Maarel 2005).

Nowadays, European mire vegetation has been systematically classified following the Central and Southern European approach and the resulting vegetation types have been correlated to site conditions (cf. Oberdorfer 1992, Dierssen 1996, Mertz 2000, Chytrý 2007–2013). Ellenberg & Leuschner (2010) describe for central Europe (out of a total of 53 classes and 177 alliances) two classes and 14 alliances of 'the most typical' mire vegetation units. These classes, however, exclude spring fen vegetation, transitional types to heathland, and fen forests. Based on Mucina et al. (2016, cf. Peterka et al. 2016) we arrive for all major peat accumulating vegetation types in Europe at a total of 11 classes, 24 orders, and 46 alliances (Table 2.4). Also this list is not exhaustive, because also other plant communities (of salt marshes, snow beds, heathlands, grasslands, and broadleaf forests) may locally be peat forming.

In Britain, mire classification advanced slightly separated from the developments on the continent. After his pioneering work in 1911, Tansley (1939) presented in 'The British Islands and their vegetation' an overview of vegetation types, using a phytosociological approach, but not strictly the Braun-Blanquet (1928) system. The work of Tansley was followed by e.g. McVean & Ratcliffe (1962), Birks (1973), and Birse (1984); see Chapter United Kingdom. Work on the 'National Vegetation Classification' (NVC) started in 1975 and resulted in five volumes of 'British Plant Communities' (Rodwell 1991-2000), including a 'Phytosociological conspectus'. The classification criteria somewhat differ from the more formal Braun-Blanquet system, but a hierarchy with Classes, Orders, and Alliances is presented, with common names with the Braun-Blanquet system. The NVC has been of great importance for the development of the European classification system of mires (EUNIS, cf. Chapter 2.4.9), presented in e.g. Rodwell et al. (2002), Schaminee et al. (2014), Peterka et al. (2016), and Mucina et al. (2016).

In northern Europe, especially in the boreal zone, mires are often the dominant and most diverse ecosystems and thus important for regional differentiation. In these northern regions mires are in general less species rich than further south, especially with respect to vascular plants. A few species dominate and the same species may occur in many different communities. Phytosociologists in northern Europe thus faced the problem of how to classify species poor vegetation with few or no character species. Nordhagen (1936, 1943) and others developed a typology in which the entire species assemblage (including mosses and lichens), the dominant species, and the cover of all species are used to classify vegetation. The basic classification units (sociations/associations) are rather narrowly delineated to better reflect ecological conditions. This 'Nordic' system was included as a part of the Central European system (e.g. Nordhagen 1943, Dahl 1957, Kielland-Lund 1981; see also Dierssen 1982).

The Scandinavian approach to mire vegetation classification has strongly been influenced by Tuomikoski (1942) and Sjörs (1948), who related the diversity in vegetation to 'gradients', using the distinction between ombrotrophic ('bog') and minerotrophic ('fen') as the main variance. Within the ombrotrophic realm a differentiation is made between the mire expanse (which includes the hummock-mud-bottom gradient) and the ombrotrophic margin (which is usually covered with low *Pinus sylvestris*). Within the minerotrophic realm a differentiation is made in three axes of local variation: poor-rich, expanse-margin, and hummock-mud-bottom (Fig. 2.4, 2.5, Box 2.3). A fourth gradient is the regional variation of mires (see Chapter 4).

During the subsequent decades the gradient approach has been used by most Scandinavian mire ecologists and clustering and ordination of vegetation relevés have underlined the existence of these gradients (e.g. Pakarinen 1976, Økland 1990a). Studies on the distribution of species, vegetation types, and ecological variables (pH, nutrients etc.) along the gradients are published in e.g. Sjörs (1948, 1983), Persson (1961, 1962), Malmer (1962, 1985), Sonesson 1970a,b), Tyler (1979), Moen (1985, 1990), Singsaas (1989), Nordbakken (2001), Sjörs & Gunnarsson (2002), and Moen et al. (2012). See also Rydin et al. (1999) and Table SWE-1 in Chapter Sweden.

The ecological niche of individual species may differ regionally. In markedly oceanic areas (e.g. in Britain and western Norway), for example, *Carex pauciflora* and *Narthecium ossifragum* occur under ombrotrophic conditions, whereas in more continental regions they require mineral soil water influence (Moen et al. 2012, cf. Glaser 1992a). Large differences in the occurrences of species also exist between north and south. *Pinguicula vulgaris* and *Scirpus cespitosus* ssp. *cespitosus*, for example, are listed as 'specialists' of base-rich fens in central Europe (e.g. Jiménez-Alfaro et al. 2014), whereas they occur in both bogs and fens in boreal oceanic areas. Common mire species that are calcicole in the central European Western Carpathians show a distinct preference for acidic conditions in Bulgarian mires (Hájek et al. 2009).

Multivariate analysis of the vegetation of undrained mires was initiated by Tuomikoski (1942). Nowadays, computer programmes like Tabord (van der Maarel et al. 1978), TWINSPAN (Hill 1979, Hill & Šmilauer 2005), and JUICE (http://www.sci.muni.cz/botany/juice/) facilitate the multivariate analysis of large numbers of relevés and the compilation of classification tables. Jiménez-Alfaro et al. (2014), for example, used some 7,000 plot samples in their analysis of base-rich fen vegetation across Europe. During the past decades, the

Table 2.4: A hierarchical phytosociological classification of mire vegetation in Europe. Compiled by Michal Hájek and Asbjørn Moen; based on Mucina et al. (2016).

Class	Order	Alliance	Characterisation
Oxycocco-Sphagnetea Br.-Bl. et Tx. ex Westhoff et al. 1946	Sphagnetalia medii Kästner et Flössner 1933	Oxycocco microcarpi-Empetrion hermaphroditi Nordhagen ex Du Rietz 1954 nom. conserv. propos.	Bog hummock and wooded bog vegetation; boreal non-oceanic regions
		Sphagnion medii Kästner et Flössner 1933	Bog lawn and carpet vegetation; nemoral-boreonemoral non-oceanic regions
	Erico-Ledetalia palustris Tx.1937	Oxycocco-Ericion tetralicis Nordhagen ex Tx.1937	Bog and poor fen hummock (partly tree-covered) and lawn; nemoral-boreal oceanic regions
		Ericion tetralicis Schwickerath 1933	Oceanic dwarf shrub mire vegetation, transitional to heathland; nemoral-boreal oceanic regions
Scheuchzerio palustris-Caricetea fuscae Tx. 1937	Scheuchzerietalia palustris Nordhagen ex Tx. 1937	Scheuchzerion palustris Nordhagen ex Tx. 1937	Mainly carpet of bog and poor fen; wide distribution
	Caricetalia davallianae Br.-Bl. 1950 nom. conserv. propos.	Caricion davallianae Klika 1934	Short sedge rich fen; nemoral-boreal zones
		Caricion atrofuscae-saxatilis Nordhagen 1943	Short sedge extremely rich fen; alpine and upper boreal zones
		Caricion viridulo-trinervis Julve ex Hájek et Mucina in Theurillat et al. 2015	Short sedge rich fen of halophytic dune slack in atlantic seabords
	Caricetalia fuscae Koch 1926	Drepanocladion exannulati Krajina 1933	Arctic-alpine fen/tundra with thin or no peat
		Caricion fuscae Koch 1926 nom. conserv. propos.	Mire margin, short sedge poor/intermediate fen
		Sphagno-Caricion canescentis Passarge (1964) 1978 nom. conserv. propos.	*Sphagnum*-dominated, poor fen; nemoral-boreal zones
		Festucion frigidae Rivas-Mart. et al. 2002	Poor spring and fen vegetation; South-west-Europe
		Anagallido tenellae-Juncion bulbosi Br.-Bl. 1967	Rich/intermediate oceanic fen; Iberian Peninsula
		Caricion intricatae Quezel 1953	Rich/intermediate fen; Mediterranean (Corsica)
		Narthecion scardici Horvat ex Lakusic 1968	Rich/intermediate fen; Mediterranean (Balkans)
	Sphagno warnstorfii-Tomentypnetalia Lapshina 2010	Sphagno warnstorfii-Tomentypnion nitentis Dahl 1956	Mire margin/low hummock, intermediate-rich fen; mainly boreal/subalpine and alpine zones
		Caricion stantis Matveyeva 1994	Mainly rich fen; arctic zone
		Stygio-Caricion limosae Nordhagen 1936	Carpet and mud-bottom of rich fen; wide distribution
		Saxifrago-Tomentypnion Lapshina 2010	Brownmoss moderately rich fen; boreal continental region
Phragmito-Magnocaricetea Klika in Klika & Novak 1941	Phragmitetalia Koch 1926	Phragmition communis Koch 1926	Reed and tall sedges of freshwater wetlands; nemoral-southern boreal (submontane) zones
		Typhion laxmannii Nedelcu 1968	Upper littoral reed fen; continental sections
	Nasturtio-Glycerietalia Pignatti 1953	Glycerio-Sparganion Br.-Bl. & Sissingh 1942	Stream reed beds; nemoral zone
	Magnocaricetalia Pignatti 1953	Magnocaricion elatae Koch 1926	Mesotrophic tall sedge fen; nemoral zone
		Magnocaricion gracilis Gehu 1961	Eutrophic tall sedge fen; nemoral zone
	Bolboschoenetalia maritimi Hejny in Holub et al. 1967	Scirpion maritime Dahl et Hadač 1941	Maritime (brackish)-water reed beds; mainly nemoral oceanic regions

Class	Order	Alliance	Characterisation
Littorelletea uniflorae Br.-Bl. et Tx. ex Westhoff et al. 1946	Littorelletalia uniflorae Koch ex Tx. 1937	Sphagno-Utricularion T. Müller et Görs 1960	Pools in poor fen; wide distribution
		Scorpidio-Utricularion minoris Pietsch 1965	Pools in rich fen; wide distribution
Montio-Cardaminetea Br.-Bl. et Tx. ex Klika et Hadač 1944	Montio-Cardaminetalia Pawlowski et al. 1928	Mniobryo-Epilobion hornemanni Nordhagen 1943	Soft, cold water; boreal, alpine and arctic northern Europe
		Cardamino-Montion Br.-Bl. 1926	Soft, cold water; subalpine-alpine belts in central-western Europe
		Swertio perennis-Anisothecion squarrosi Hadač 1983	Cold water springs; montane belt of central Europe
		Epilobio nutantis-Montion Zechmeister 1994	Cold water springs; submontane and montane belts of western Europe
		Cratoneurion commutati Koch 1928	Cold water springs with calcareous water; wide distribution
	Cardamino-Chrysosplenietalia Hinterlang 1992	Caricion remotae Kästner 1941	Wooded poor springs; mainly in submontane-montane regions in southern Europe
Alnetea glutinosae Br.-Bl. et Tx ex Westhoff et al. 1946	Alnetalia glutinosae Tx. 1937	Alnion glutinosae Malcuit 1929	Wooded regularly flooded fen/swob; mainly nemoral-submontane/southern boreal regions
	Salici pentandrae-Betuletalia pubescentis Clausnitzer in Dengler et al. 2004	Salici pentandrae-Betulion pubescentis Clausnitzer in Dengler et al. 2004	Wooded birch/bay willow rich fen; nemoral-boreal outside the most oceanic regions
	Sphagno-Betuletalia pubescentis Scamini et Passarge 1959	Betulion pubescentis Lohmeyer et Tx. ex Oberd. 1957	Wooded birch poor fen; nemoral-boreal regions
Franguletea Doing ex Westhoff et Den Held 1969	Salicetalia auritae Doing 1962	Salicion cinereae T. Müller et Görs ex Passarge 1961	Fen scrub/woodland; mainly nemoral in oceanic regions
		Alno incanae-Salicion pentandrae K.-Lund 1981	Fen scrub/woodland; mainly poor-/intermediate, boreal regions
Vaccinio-Piceetea Br.-Bl. in Br.-Bl. et al. 1939	Ledo palustris-Laricetalia gmelinii Ermakov in Ermakov et Alsynbayev 2004	Empetro-Piceion obovatae Morozova et al. 2008	Wooded mires with long-frozen soil/permafrost; northern boreal continental regions
	Vaccinio uliginosi-Pinetalia sylvestris Passarge 1968	Vaccinio uliginosi-Pinion sylvestris Passarge 1968	Open pine woods in poor fen/bog vegetation; boreal-nemoral non-oceanic regions
	Eriophoro-Piceetalia abietis Passarge 1968	Eriophoro-Piceion abietis Passarge 1968	Spruce woods in poor fens; boreal-nemoral non-oceanic regions
	Calamagrostio purpureae-Picetalia obovatae Lapshina 2010	Calamagrostio canescentis-Piceion abietes Solomeshch in Willner et al. 2015	Herb and grass dominated spruce woodlands; boreal non-oceanic regions
Molinio Arrhenatheretea Tx. 1937	Molinietalia caeruleae Koch 1926	Molinion caeruleae W. Koch 1926	Anthropogenic grasslands/fens; mainly nemoral oceanic regions
		Calthion palustris Tx. 1937	Herb rich anthropogenic grasslands/fens; mainly nemoral region
Juncetea maritimi Br.-Bl. in Br.-Bl. et al. 1952	Juncetalia maritimi Br.-Bl. ex Horvatic 1934	Juncion maritimi Br.-Bl. ex Horvatic 1934	Salt marshes transitional to fens, thin or no peat; mediterranean and nemoral atlantic coast
Festuco-Puccinellietea Soó ex Vicherek 1973	Scorzonero-Juncetalia gerardii Vicherek 1973	Juncion gerardii Wendelberger 1943	Saline grasslands/fens with thin or no peat; from atlantic coast to continental Russia

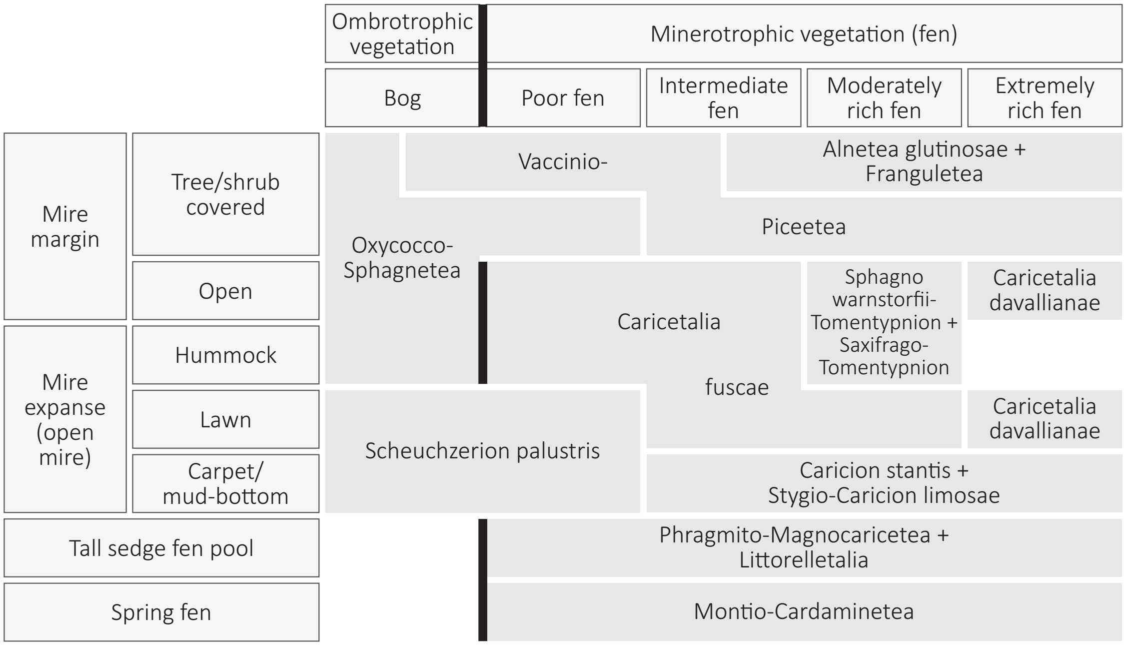


Fig. 2.4: The distribution of the main phytosociological mire vegetation units in Europe (Table 2.4) over the three main local gradients in mire vegetation of the Scandinavian approach (Box 2.3; excluding anthropogenic fen grasslands, wet heathlands, and halophytic vegetation).

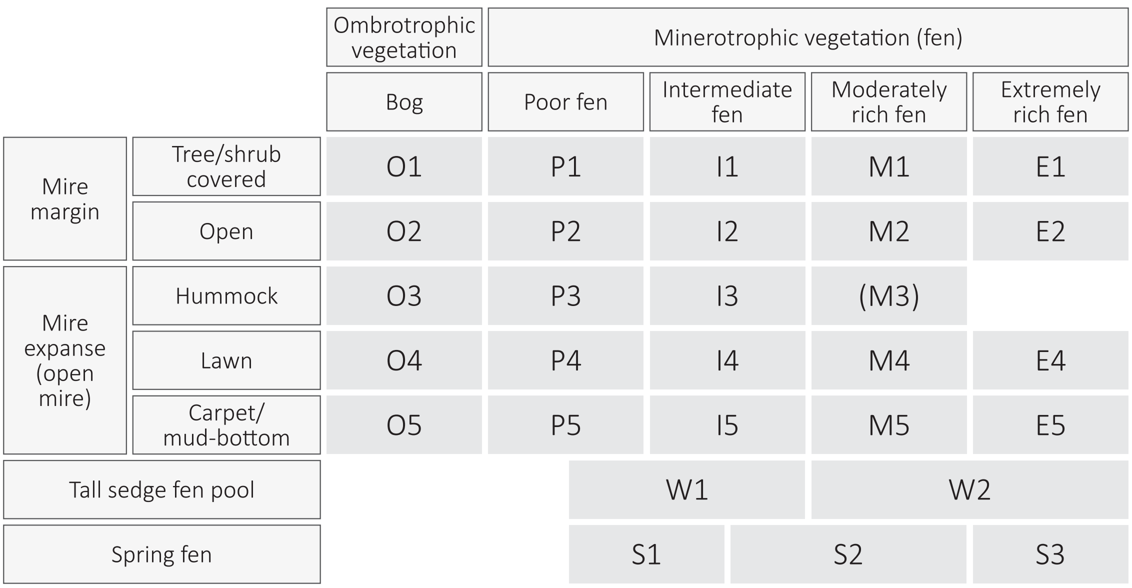


Fig. 2.5: Schematic presentation of 29 units of mire and spring vegetation in central Norway, defined along the three gradients in mire vegetation (Box 2.3; revised after Moen 1990).

vast majority of descriptive studies in mire ecology have made use of such multivariate methods. Modern technologies and advances in software development like the TURBOVEG database management system (Schaminée et al. 2009) have eroded the difference between classification and ordination methods and schools. Furthermore, databases have been established that provide an overview of existing vegetation data in different parts of the world (e.g. the Global Index of Vegetation-Plot Databases, www.givd.info). A European Mire Vegetation Database has been established at Masaryk University, Brno, Czech Republic (Landucci et al. 2015, M. Hájek pers. comm.).

Russian vegetation classification developed from forest inventory at the end of the 18th century (Dokhman 1973). Plant communities were classified according to dominant species and their position in the landscape (Mirkin & Naumova 1999). In the early 19th century, the first studies on the vegetation of mires, meadows, and pastures were performed in the area surrounding St. Petersburg and published by G.N. Engelman in his ‘Theoretical and practical guidelines for habitat drainage’ (1810) and his

Box 2.3: The three gradients of the Scandinavian approach to mire vegetation classification

1 Poor-rich. This gradient reflects differences in available ions (H^+, Ca^{2+}, Mg^{2+}, K^+, Na^+) that determine differences in the distribution of plant species (Chapter 2.4.4). Bogs are at the extreme end of the gradient, with few species and extreme poverty in minerals and a pH of c. 4. Generally no grass species occur in natural bog vegetation, except for *Molinia caerulea*, which grows in bogs that are highly oceanic or subject to high atmospheric deposition. *Carex limosa* and *C. pauciflora* are the only sedge species growing under ombrotrophic conditions. Fens are divided into four main types: poor, intermediate, moderately rich, and extremely rich, each characterised by a variety of species, especially bryophytes. The terms 'poor' and 'rich' refer to 'richness in indicator species', not to the absolute number of species (Sjörs 1948). The subdivision of the gradient and the names of the types have varied somewhat over time (cf. Du Rietz 1949, 1954, Sjörs 1948, 1950a,b, Table 2.2 and 2.3) but have meanwhile stabilised in the typology mentioned above. The poor-rich gradient concept seems to be applicable across the entire circum-boreal and circum-arctic belt. Similar ranges of species richness and water chemistry have been described for bog, poor fen, rich fen, and extremely rich fen in North America (Sjörs 1963a, Glaser 1987, 1992b, Glaser et al. 2004a).

Peatmosses (*Sphagnum* spp.) dominate bogs and poor fens, whereas 'brownmosses' (e.g. *Campylium stellatum* and *Scorpidium* spp.) dominate the rich fens (Table 2.5). Hájek et al. (2006) additionally differentiate between extremely rich and calcareous fen, the latter being characterised by specific species, the deposition of tufa (travertine, terrestrial chalk), and consequently extremely high pH and electro-conductivity.

2 Hummock-mud-bottom. Most mires have an uneven surface and vegetation composition differs between height levels in relation to differences in moisture conditions, water table fluctuations, and firmness of the peat. In bogs, the 'hummocks' are generally dominated by *Calluna vulgaris* and other dwarf shrubs, with *Sphagnum* spp. (e.g. *S. fuscum*) in the bottom layer. The '*Calluna* limit' is often used to separate hummocks from other features in the hummock-mud-bottom gradient. The 'lawns' are firm to walk on and often dominated by *Narthecium ossifragum* and *Scirpus cespitosus* ssp. *cespitosus*. In contrast, footprints leave marks in 'carpets', which are characterised by moisture-demanding species like *Carex limosa*, *Drosera* spp., *Rhynchospora* spp., *Scheuchzeria palustris*, and *Sphagnum cuspidatum*. The 'mud-bottoms' are characterised by bare peat and a poor bearing capacity. An example of the distribution of species along the hummock-mud-bottom gradient in boreal mires is presented in Table 2.6.

3 Mire expanse-mire margin (open mire-wooded/shrub-covered mire). The mire expanse includes a large group of species that avoid thin peat and proximity to dry ground. Ombrotrophic bogs with thick peat are often regarded as being entirely covered by mire expanse vegetation (Sjörs 1948), but bog vegetation may – similar to the vegetation of minerotrophic mires – also be separated into mire expanse and mire margin (Moen 1990). Many species, such as *Alnus* spp., *Picea abies*, *Salix* spp. and herbs like *Filipendula ulmaria* and *Ranunculus acris*, are absent from the open expanse and common in mire margins and are also found in woodland or grassland vegetation on mineral ground (Moen 1990). Shallow and mineral-rich peat, good access to nutrients, plenty of shade, and fluctuating groundwater tables in summer define the mire margin and its vegetation. The distribution of boreal mire plant species over the mire expanse-mire margin gradient (cf. Tables 2.5 and 2.6) is presented in Chapter Norway (Table NOR-1).

'Brief guidelines for study and maintenance of meadows and pastures' (1818). As meadow vegetation is difficult to classify by dominants because of its seasonal and annual dynamics, Engelman introduced the concept of 'plant mixtures': comprehensive species groups to characterise vegetation types and ecological conditions of non-forested habitats, including mires. He was the first to introduce a typology of mire massifs in Russia, which he distinguished by the level of paludification (the thickness of 'soft matter') and the prevailing vegetation type (e.g. moss mires, sedge mires, birch mires, and alder mires). He mapped plant communities within the mire massifs, indicating 'plant mixtures' with special symbols, but without drawing explicit boundaries between them in order to emphasise the vegetation continuum.

At the end of 19th and the beginning of the 20th century, vegetation classification in Russia had been systemised and presented in numerous local and regional studies and inventories (Aleksandrova 1969, 1978). The 'fitotsenoz'/фитоценоз (phytocoenosis) developed as the basic object and the 'formatsciya'/формация (formation) as its basic classification unit, which after the 3rd Botanical Congress (1910) was renamed to 'assotsiatsiya'/ассоциация (association) in accordance with international practice. This term has been applied ever since in Russia. More than 50 years of discussion followed on the definition of the association, on its identification in the field, on syntaxonomic nomenclature, and on the principles of the hierarchy of classification units.

Rabotnov (1979) described the three main directions that developed in Russian vegetation classification and

Table 2.5: Distribution of boreal mire plant species over the bog-poor fen-rich fen vegetation gradient in central Norway. Modified after Moen (1990). Black=common, grey=rare or scattered, white=absent or casual.

Species	Ombro-trophic	Minerotrophic vegetation			
		Poor	Inter-mediate	Moderate rich	Extreme rich
Melampyrum pratense, *Rubus chamaemorus*, *Cephalozia* spp., *Cladopodiella fluitans*, *Dicranum leioneuron*, *D. undulatum*, *Gymnocolea inflata*, *Mylia* spp., *Sphagnum balticum*, *S. capillifolium*, *S. majus*, *S. rubellum*, *S. russowii*, *S. tenellum*, *Straminergon stramineum*, *Warnstorfia fluitans*	Black	Black	Grey		
Carex pauciflora, *Eriophorum vaginatum*, *Rhynchospora alba*, *Scheuchzeria palustris*, *Vaccinium* spp., *Aulacomnium palustre*, *Sphagnum angustifolium*, *S. austinii*, *S. papillosum*, *S. pulchrum*	Black	Black	Black	Grey	
Andromeda polifolia, *Carex limosa*, *Drosera anglica*, *D. rotundifolia*, *Erica tetralix*, *Huperzia selago*, *Myrica gale*, *Narthecium ossifragum*, *Scirpus cespitosus* ssp. *cespitosus*, *Vaccinium microcarpum*, *V. oxycoccos*	Black	Black	Black	Black	Black
Carex canescens, *C. echinata*, *C. magellanica*, *C. rotundata*, *Cornus suecica*, *Juncus filiformis*, *Trientalis europaea*, *Sphagnum angermanicum*, *S. annulatum*, *S. centrale*, *S. molle*, *S. riparium*		Black	Black		
Carex lasiocarpa, *C. nigra*, *C. panicea*, *C. rostrata*, *Equisetum fluviatile*, *Eriophorum angustifolium*, *Menyanthes trifoliata*, *Molinia caerulea*, *Potentilla erecta*, *Odontoschisma elongatum*		Black	Black	Black	Black
Carex livida, *Viola palustris*, *Cinclidium subrotundum*, *Dicranum bonjeanii*, *Sphagnum platyphyllum*, *S. subfulvum*, *S. subnitens*, *S. subsecundum*, *S. teres*, *Warnstorfia sarmentosa*, *W. exannulata*, *W. tundrae*			Black	Black	
Carex chordorrhiza, *C. demissa*, *C. dioica*, *Equisetum palustre*, *Euphrasia frigida*, *Hammarbya paludosa*, *Juncus stygius*, *Pedicularis palustris*, *Pinguicula vulgaris*, *Rhynchospora fusca*, *Scirpus hudsonianus*, *Selaginella selaginoides*, *Succisa pratensis*, *Utricularia* spp., *Aneura pinguis*, *Loeskypnum badium*, *Paludella squarrosa*, *Sphagnum contortum*, *S. warnstorfii*			Black	Black	Black
Parnassia palustris, *Saussurea alpina*, *Tofieldia pusilla*, *Campylium stellatum*, *Lophozia borealis*, *Plagiomnium ellipticum*, *Scorpidium revolvens*, *S. scorpioides*, *Tomentypnum nitens*			Grey	Black	Black
Bartsia alpina, *Carex appropinquata*, *C. buxbaumii*, *C. flava*, *C. heleonastes*, *C. pulicaris*, *C. saxatilis*, *Crepis paludosa*, *Dactylorhiza incarnata*, *Eleocharis quinqueflora*, *Eriophorum latifolium*, *Pedicularis oederi*, *Thalictrum alpinum*, *Triglochin palustris*, *Bryum pseudotriquetrum*, *Calliergon giganteum*, *C. richardsonii*, *Calliergonella cuspidata*, *Cinclidium stygium*, *Meesia triquetra*, *M. uliginosa*, *Plagiomnium elatum*, *Pseudocalliergon trifarium*, *Rhizomnium magnifolium*, *R. pseudopunctatum*				Black	Black
Carex atrofusca, *C. capillaris*, *C. capitata*, *C. hostiana*, *C. lepidocarpa*, *C. microglochin*, *Dactylorhiza cruenta*, *D. pseudocordigera*, *Gymnadenia conopsea*, *Juncus castaneus*, *J. triglumis*, *Kobresia simpliciuscula*, *Listera ovata*, *Salix myrsinites*, *Saxifraga aizoides*, *Schoenus ferrugineus*, *Catascopium nigritum*, *Cratoneuron* spp., *Ctenidium molluscum*, *Fissidens adianthoides*, *F. osmundoides*, *Lophozia rutheana*					Black

their numerous modifications are described in detail by Aleksandrova (1969). Basically, approaches differed with respect to the object of classification. The pure dominant approach was dictated by foresters and focuses on the 'biogeocoenosis' in which plant species are essentially used only for naming. The ecological-floristic approach was mainly developed for meadows and takes into account the ecological indicator value of species; it aims at classification of ecotopes or habitats as indicated by the phytocoenosis. The third approach is a purely floristic modification of the Braun-Blanquet approach, and the only one to focus solely on classifying plant associations.

Russian syntaxonomy has had a strong phytophylogenetic basis, reflecting the origin and development of phytocoenoses (Pachoskiy 1891, Sukachev 1915). The main syntaxonomical system used by Russian geobotanists since the 1930s integrates various approaches and was elaborated for mires by Tsinzerling (1938) to include the following hierarchical units:

- Association (with subassociations as ecological modifications);
- Group of associations;
- Formation;
- Group of formations;
- Class of formations;
- Type of vegetation.

Table 2.6: Distribution of boreal mire plant species over the hummock-mud-bottom vegetation gradient in central Norway. Modified after Moen (1990). Black = common, grey = rare or scattered, white = absent or accidental.

Species	Hummock	Lawn	Carpet	Mud-bottom
Calluna vulgaris, *Empetrum* spp., *Pinguicula villosa*, *Pinus sylvestris*, *Vaccinium uliginosum*, *Dicranum undulatum*, *Pleurozium schreberi*, *Racomitrium lanuginosum*, *Sphagnum capillifolium*, *S. fuscum*, *S. russowii*, *Cladonia arbuscula*, *C. rangiferina*, *C. stellaris*	black			
Betula nana, *Melampyrum pratense*, *Rubus chamaemorus*, *Aulacomnium palustre*, *Dicranum bonjeanii*, *Mylia* spp., *Ptilidium ciliare*, *Sphagnum subfulvum*, *S. warnstorfii*, *Tomentypnum nitens*	black	black		
Andromeda polifolia, *Drosera rotundifolia*, *Erica tetralix*, *Eriophorum vaginatum*, *Vaccinium microcarpum*, *V. oxycoccos*, *Dicranum leioneuron*, *Sphagnum magellanicum*, *S. papillosum*, *S. rubellum*	black	black	black	grey
Bartsia alpina, *Carex canescens*, *C. capillaris*, *C. echinata*, *C. flava*, *Dactylorhiza pseudocordigera*, *Kobresia simpliciuscula*, *Listera ovata*, *Molinia caerulea*, *Narthecium ossifragum*, *Saussurea alpina*, *Schoenus ferrugineus*, *Succisa pratensis*, *Thalictrum alpinum*, *Tofieldia pusilla* , *Fissidens adianthoides*, *F. osmundioides*, *Loeskypnum badium*		black		
Carex atrofusca, *C. demissa*, *C. dioica*, *C. hostiana*, *C. lepidocarpa*, *C. nigra*, *C. panicea*, *C. pauciflora*, *Dactylorhiza incarnata* ssp. *cruenta*, *D. incarnata* ssp. *incarnata*, *Eriophorum latifolium*, *Euphrasia frigida*, *Myrica gale*, *Parnassia palustris*, *Pinguicula vulgaris*, *Scirpus cespitosus* ssp. *cespitosus*, *S. hudsonianus*, *Selaginella selaginoides*, *Campylium stellatum*, *Lophozia borealis*, *L. rutheana*, *Sphagnum contortum*, *S. papillosum*, *S. platyphyllum*, *S. subnitens*, *S. subsecundum*, *S. teres*		black	black	
Carex lasiocarpa, *C. rostrata*, *C. saxatilis*, *Drosera anglica*, *Eleocharis quinqueflora*, *Equisetum palustre*, *Eriophorum angustifolium*, *Menyanthes trifoliata*, *Pedicularis palustris*, *Phragmites australis*, *Triglochin palustris*, *Aneura pinguis*, *Cladopodiella fluitans*, *Scorpidium revolvens*, *Sphagnum balticum*, *S. compactum*, *S. pulchrum*, *S. tenellum*		black	black	black
Carex chordorrhiza, *C. limosa*, *C. heleonastes*, *Hammarbya paludosa*, *Rhynchospora alba*, *Scheuchzeria palustris*, *Utricularia* spp., *Calliergon giganteum*, *C. richardsonii*, *Cinclidium stygium*, *Cladopodiella fluitans*, *Gymnocolea inflata*, *Pseudocalliergon trifarium*, *Scorpidium scorpioides*, *Sphagnum annulatum*, *S. cuspidatum*, *S. lindbergii*, *S. majus*, *S. riparium*, *Warnstorfia exannulata*, *W. fluitans*, *W. sarmentosa*			black	black
Carex livida, *Juncus stygius*, *J. triglumis*, *Lycopodiella inundata*, *Rhynchospora fusca*, *Utricularia intermedia*, *Fossombronia foveolata*, *Siphula ceratites*			grey	black

The association is the basic classification unit and can be subdivided into subassociations on the basis of small ecological differences (for example more or less wet). In the USSR, the name of an association was either formed by adding suffixes to species names or by simply combining species names (as in Scandinavian nomenclature). The first approach was common in the 'dominant' classification approaches; the second in the ecological-floristic approach.

Formations are groups of associations with the same dominants in the main layer. They carry the life form in their name (for example spruce forests, *Sesleria* meadows, or sedge-*Sphagnum* mires).

With respect to mire vegetation, classification is heavily oriented on the landscape and driven by hydrology. Consequently, units have a very strong topological and ecological background, but dominants have been used to classify associations as well. Tsinzerling (1938) distinguished mire vegetation types based on a combination of various vegetation-ecological life forms (trees, shrubs, herbs, mosses, lichens, liverworts, and algae, emphasising hydro- and psychrophily (water and cold loving, respectively)) and ordered each type into one of the trophic groups 'eutrophic', 'mesotrophic', 'oligotrophic', or 'eurytrophic'. Communities with a common life form are then united (e.g. those with an absolute dominance of *Scheuchzeria* and an underdeveloped or absent moss layer into the formation Scheuchzerieta palustris).

Mire classification systems based on such vegetation-ecological life forms (Table 2.7) were widely used by Soviet botanists (overview in Boch & Mazing 1979). In recent times, vegetation classification based on the Central and Southern European approach is gaining popularity.

2.4.7 Physiognomy and Finnish mire site types

The main purpose of the Finnish mire classification system was to assess the suitability for forestry. The system was developed by the Finnish forest and mire ecologist A.K. Cajander and has dominated mire vegetation classification in Finland until present (Lindholm 2013). Cajander considered vegetation types as useful indicators of forest productivity, because 'all sites with the same plant community are in biological sense rather equal'. Furthermore, he observed that 'in general the Nordic mires are compared with forests and meadows much less influenced by human culture; the struggle between plants has been able to proceed here with less disturbance, and the mire types

Table 2.7: Main types of mire vegetation for the East-Baltic mire province (after Boch & Mazing 1979, see Typical raised bog region, East-Baltic subregion in Chapter 4.8.7) as an example of Russian vegetation classification.

Type I. Гидрофильно древесная растительность (Hydrophilic tree vegetation)
1. Alneta glutinosi
Type II. Мезогидрофильнодревесная растительность (Mesohydrophilic tree vegetation)
1. Betuleta pubescentis
Type III. Психрофильнодревесная растительность (Psychrophilic tree vegetation)
1. Piceeta abietis (in swobs)
2. Pineta sylvestris (in swobs)
Type IV. Гидрофильнотравяная растительность (Hydrophilic graminoid vegetation)
1. Phragmiteta australis
2. Scheuchzerieta palustris
3. Menyantheta trifoliatae
4. Cariceta limosae
5. Cariceta rostratae
6. Cariceta lasiocarpae
7. Calamagrostideta neglectae
Type V. Гидрофильнокустарниковая растительность (Hydrophilic shrub vegetation)
1. Saliceta cinereae
Type VI. Психрофильнокустарничковая растительность (Psychrophilic dwarf shrub vegetation)
1. Calluneta vulgaris and others
Type VII. Гидрофильномоховая растительность (Hydrophilic moss vegetation)
1. Drepanocladeta fluitantis
2. Drepanocladeta exannulati
3. Calliergoneta gigantei
4. Calliergoneta straminei
5. Sphagneta fusci
6. Sphagneta magellanici
7. Sphagneta angustifolii
8. Sphagneta fallaxi
9. Sphagneta majoris
10. Sphagneta cuspidati
11. Sphagneta rubelli
12. Sphagneta nemorei
13. Sphagneta subsecundi
Type VIII. Психрофильномоховая растительность (Psychrophilic moss vegetation)
1. Polytricheta communis
2. Polytricheta stricti

are therefore generally more sharply developed compared with most other vegetation types' (Cajander 1913).

In his book on forest types Cajander (1909) had already subdivided the mires of Finland in 'four natural groups', namely 'forest mires', 'shrub mires', 'transitional/flat mires' and 'low mires, quagmires, and sedge fens'. His subsequent mire site typology (Cajander 1913) distinguished as main types: "Bruchmoore" ('forest mires'), "Reisermoore" ('dwarf shrub mires'), "Braunmoore" ('brown mires'), and "Weissmoore" ('white mires') primarily based on a combination of physiognomic criteria and with further subdivisions on the basis of plant cover (Table 2.8). Cajander's mire typology was an early form of ecosystem classification with site types characterised by both vegetation and environmental conditions.

Table 2.8: Mire typology of Cajander (1913). Species names – except in names of vegetation types – are adapted to modern nomenclature.

I			"Weissmoore" ('white mires'): treeless, generally more or less wet and quaking peatlands without moss hummocks, poor in shrubs; the moss vegetation, as far as present, mainly consists of peatmosses (*Sphagnum*)
	A		'Terrestrialisation white mires': at the margin of lakes and flowing carbonate-poor water, where nutrient supply is guaranteed by flooding or flowing water
		a	'Quaking mires': very wet, generally strongly quaking mires with a more or less incomplete moss layer but abundant graminoids and herbs, subdivided into four types on the basis of different vegetation (*Scirpus*/*Phragmites*, *Equisetum fluviatile*, *Carex rostrata*, and herbs such as *Menyanthes*, *Calla*, *Potentilla palustris*, *Lysimachia thyrsiflora*)
		b	'Flooded mires': meadow-like mires at the margin of slowly flowing water (e.g. with *Carex curta*)
		c	'Tussock mires': with the graminoids having a more or less pilar-like form which is most wide at the top (*Eriophorum vaginatum*)
		d	'Overgrow mires': extremely quaking lake margin mires that float more or less freely on the water, subdivided into two vegetational types (*Menyanthes* and *Sphagnum* esp. *riparium*)
	B		'Real white mires': with an (almost) complete *Sphagnum* cover and only few graminoids and herbs
		a	'Tall sedge mires': very wet and rather quaking, with generally a full cover of *Sphagnum* and rather abundant tall sedges, subdivided into four types on the basis of the dominant Cyperaceae species (*Carex rostrata*, *C. lasiocarpa*, *C. limosa*, and *Eriophorum angustifolium*)
		b	'Short sedge mires': not very wet, only slightly quaking, with a full moss cover and a low open graminoid vegetation, consisting of two vegetation types (*Eriophorum angustifolium* and *Carex pauciflora*)
		c	'*Sphagnum fuscum* white mires': wet to rather wet with abundant or dominant *Sphagnum fuscum* and more dwarfshrubs (*Andromeda*, species of the former genus *Oxycoccus*, *Chamaedaphne*, *Ledum*, *Betula nana*, *Calluna* etc.) than in other 'white mires' subdivided into four subtypes ('colourful': with a mosaic of *S. fuscum* and *S. angustifolium* and other *Sphagnum* species, *Calluna*-*Eriophorum angustifolium*, *Betula nana*-*Eriophorum vaginatum*, and *Rubus chamaemorus*-*Eriophorum vaginatum*)
	C		'Rimpi-like white mires': with an extremely gentle slope and very nutrient poor water persisting at the surface for the entire or most of the summer and always with very light yellow or brownish *Sphagnum* species (like *S. papillosum*, *S. majus*, *S. lindbergii*). The peat in the uppermost layers is only very weakly humified
		a	'*Sphagnum papillosum* mires': with a more or less closed moss cover, often almost exclusively consisting of *Sphagnum papillosum*; with three subtypes (*Scirpus cespitosus*, *Carex pauciflora*, and *C. lasiocarpa*)
		b	'Pool mires': in and along pools and hollows with a rich and complete cover of soft and (because of algae) slippery *Sphagnum* mosses (*S. majus*, *S. cuspidatum*, *S. jensenii*, *S. lindbergii*), with four subtypes (*Eriophorum vaginatum*, *Rhynchospora alba*, *Scheuchzeria palustris*, and *Carex limosa*)
		c	'Rimpi (flark) mires': similar to the latter groups but with insignificant or absent moss cover. Subdivided into five subtypes (*Molinia*, *Scirpus cespitosus*, sedge-rimpi, mud-bottom, and spring mud-bottom)
	D		'String mires': combinations of elongated rimpi- and narrow moss-rich white mire stripes, not yet sufficiently investigated
	E		'Spring white mires': with numerous springs, species rich with many 'brown mire' species because of exfiltrating mineral rich water
II			"Braunmoore" ('brown mires'): treeless, normally more or less quaking mires without moss hummocks. The moss cover mainly consists of so called brownmosses; richer in graminoid and herb vegetation than the 'white mires'
	A		'Terrestrialisation mires': differing from IA by the more species rich vegetation with typical 'brown mire' species and by the almost total absence of *Sphagnum*
		a	'Quaking mires': only known by Cajander as 'brown mires' from North-Russia, not from Finland
		b	'Overgrow mires': extremely quaking lake margin mires
	B		'Real brown mires': more or less wet mire with an uninterrupted, fresh green cover of brownmosses
		a	'*Drepanocladus* mires': rather analogue to the 'large sedge white mires', but *Sphagnum* species replaced by species of the former genus *Drepanocladus*, esp. *Hamatocaulis vernicosus*; can be subdivided in, among others, *Carex diandra*, *C. heleonaste,* and *C. dioica* mires
		b	'*Paludella* mires': somewhat drier than the *Drepanocladus* mires and similar to the 'short sedge white mires', with a moss layer dominated by *Paludella squarrosa*
		c	'*Tomentypnum nitens* mires': somewhat similar to the *Sphagnum fuscum* white mires with abundant *Tomentypnum nitens* and often abundant *Carex dioica* or more rarely *Scirpus hudsonianus*
	C		'Rimpi brown mires': completely analogue to the rimpi white mires, subdivided into six types (*Scirpus hudsonianus*, *Scirpus cespitosus*, *Carex chordorrhiza*, *C. livida*, *C. lasiocarpa*, and *C. limosa*)
	D		'String brown mires': completely analogue to the string white mires

III			“Reisermoore” (‘dwarf shrub mires’): little or hardly quaking mires, generally (substantially) drier than white mires, with a vegetation generally rich in dwarf shrubs, a moss layer consisting of *Sphagnum* species, and almost always some forest growth, prevailingly consisting of more or less crippled *Pinus*
	A		‘Paludified forests’: with a rather thin peat layer (often < 30 cm), subdivided in ‘Rääseikkö-forests’ (on poor morainic soil with badly growing *Picea*, *Pinusaea* and *Betula* and a closed moss layer), ‘Vesikangas-forests’ (on poor stagnating soils with water trickling over the surface and with somewhat crippled *Pinus* and a closed moss layer of mainly *Polytrichum commune*), ‘Räme-kangas-forests’ (rather dry, poor heath forests on permeable soil, paludified by groundwater rise, with forest mosses and *Sphagnum* and rich in dwarf shrubs), and a combination of the two latter subtypes that develop into real dwarf shrub mires
	B		‘Real dwarf shrub mires’: with a generally rather deep peat layer, with a rather flat surface and a full cover of moss vegetation mixed with lichens
		a	‘Swamp forest-like shrub mires’: highly productive and characterised by the rich occurrence of *Vaccinium myrtillus*; subdivided into ‘proper swamp forest-like dwarf shrub mires’ (with very often rather closed *Picea* stands with many peatmosses) and ‘*Vaccinium vitis-idaea* mires’ (with pine and some spruce),
		b	‘*Andromeda* mires’: typical *Pinus* dwarf shrub mires rich in *Vaccinium myrtillus*, *Ledum* or *Chamaedaphne*, subdivided into *Vaccinium uliginosum* mires (with closed *Sphagnum* cover), *Ledum* mires (with open, low pine forest and often pure stands of *Ledum palustre*), *Chamaedaphne* mires (with abundant *Chamaedaphne* but also other dwarf shrubs and *Rubus chamaemorus*), *Andromeda* mires (rather wet, like strings in aapa-mires), and *Betula nana* mires
		c	‘Heath mires’: rather dry with (very) crippled tree growth, subdivided into *Calluna* mires (rather dry, with open moss cover, rich in *Calluna vulgaris* with other dwarf shrub species in variable proportions) and *Sphagnum fuscum* dwarf shrub mires (open, very crippled pine forest with closed *Sphagnum fuscum* cover)
	C		Combinations of white mires and dwarf shrub mires as hollows/pools and hummocks, respectively
		a	‘Expanse mires’: most completely developed on the expanse of raised bogs, subdivided into ‘expanse heath mires’ (with *Calluna* hummocks) and ‘expanse *Sphagnum fuscum* mires’ (with *Sphagnum fuscum* dwarf shrub hummocks)
		b	‘Cottongrass / dwarf shrub mires’: a combination of dwarf shrub mire and *Eriophorum vaginatum* white mire, subdivided in cottongrass / heath mires (consisting of *Calluna* mire or *Sphagnum fuscum* mire and *Eriophorum vaginatum* stands), cottongrass / *Andromeda* mires (with very low hummocks), and cottongrass / *Vaccinium vitis-idaea* mires (without hummocks, with well-growing *Pinus*)
		c	‘Sedge / dwarf shrub mires’: combinations of dwarf shrub mire and more or less wet, water soaked white mire with prevalent sedge vegetation
	D		‘Brown mire / dwarf shrub mires’: a very diverse group of combinations of brown mire and dwarf shrub mire
IV			“Bruchmoore” (‘swamp mires’): forested mires with *Picea* or deciduous tree species (*Betula*, *Fraxinus*, *Ulmus*), typically with *Polytrichum commune* and *Sphagnum wulfianum*, always with flowing water
	A		‘Grove-like swampforests’: with mixed tree stands (*Picea*, *Betula*, *Populus*) with abundant shrubs (e.g. *Prunus padus*, *Frangula alnus*, *Rubus idaeus*, *Ribes nigrum*, *Viburnum opulus*, *Daphne*, and various *Salix* species) and very rich in species of moss, graminoids and herbs
	B		‘Common carrs’: characterised by a more or less closed mat of *Polytrichum commune*, without deciduous trees but with more or less abundant dwarf shrubs (*Vaccinium myrtillus*, *V. vitis-idaea*)
	C		‘Normal swamp mires’: with generally an abundant and closed moss cover of mostly *Sphagnum*, subdivided into *Vaccinium vitis-ideae* swamps (the most productive; a dense and very dark forest with abundant dwarf shrubs), *Rubus chamaemorus* swamps (with abundant *Rubus chamaemorus*), *Equisetum sylvaticum* swamps, and *Equisetum palustre* swamps (rather wet at spring rivulets)
	D		‘Herb and grass swamps’: generally wetter than the former types with more clearly flowing water, subdivided into ‘fern swamps’ (with *Athyrium filix-femina*, *Dryopteris carthusiana* and others), ‘common herb and grass swamps’ (with *Calamagrostis purpurea* ssp. *phragmitoides* and *Deschampsia cespitosa*, *Carex curta*, *C. rostrata*, *C. globularis*, *Phragmites australis*, *Molinia caerulea*, etc. and the herbs *Calla palustris*, *Potentilla palustris*, *Lysimachia thyrsiflora* and more), and *Equisetum fluviatile* swamps (with often rather pure *Equisetum* stands)
	E		‘Cottongrass swamps’: intermediate between normal swamps and cottongrass- and tall sedge white mires, with a subdivision according to wetness in ‘slightly wet normal swamp mires’ (with rather good *Betula-Picea* forest), ‘proper cottongrass swamps’ (wet cottongrass white mire with hummocks of *Polytrichum commune*) and ‘swashing swamps’ (extremely wet with almost completely dead tree stands)
	F		‘Willow floodplains’: with dense brushwood of *Salix* and *Betula nana*, subdivided in ‘common willow floodplains’ (with many graminoid and herb species) and ‘zsombék’ brushwood (with abundant *Carex nigra* and *C. cespitosa*)
	G		‘White mire swamps’: intermediate between white mires and swamp mires; subdivided in *Phragmites* swamps (bordering white mires, at springs and rivulets, with abundant *Phragmites* and often *Carex lasiocarpa*), ‘sedge swamps’ (*Salix* or *Betula* bushes with a white mire vegetation but without *Phragmites*), and ‘*Menyanthes* swamps’ (rich in *Menyanthes*)
	H		‘Brown mire swamps’: bordering between brown mires and swamp mires (rather rare and little studied), with a subdivision in a combined and an intermediate form

Cajander's typology was applied and further developed by his students (e.g. Aario 1932, Auer 1920, 1922, 1927, Backman 1919, Kotilainen 1927, Kujala 1921, Lukkala 1931, Lumiala 1937, Paasio 1933, 1936, Tanttu 1915, and Warén 1926). Of main importance for the development of Cajander's mire typology were the studies of Tuomikoski (1942) on forested mires. The later studies simplified the typology; 'flooded swamps' and 'spring mires' were given the same status as the original four main types (Eurola et al. 1984).

Under increased influence of international studies in mire ecology, a new generation of Finnish mire researchers (e.g. Ruuhijärvi 1960, Eurola 1962) adapted the typology to comply with the concepts of ombrotrophy and minerotrophy and with the three main ecological gradients of the Scandinavian classification (Sjörs 1948, Box 2.3, Ruuhijärvi 1983, Eurola et al. 1984). Ruuhijärvi & Lindholm (2006) presented a diagram of 39 mire site types based on the three gradients (Table FIN-1 in Chapter Finland) with obvious similarities to hierarchical phytosociological (Fig. 2.4) and Scandinavian mire type classification (Fig. 2.5). However, in modern Finland the basic features of the mire site typology of Cajander are still used, both in applied surveys and in basic botanical/ecological research (e.g. Pakarinen & Ruuhijärvi 1978, Heikkilä 1987, Pakarinen 1995, Vasander 1996, Ruuhijärvi & Lindholm 2006).

2.4.8 Ecological mire types and the vegetation form concept

As vegetation correlates well with site conditions, it provides biological indicators for mapping site conditions in the landscape (Cajander 1913, Mueller-Dombois & Ellenberg 1974, Wamelink et al. 2005). The 'vegetation form concept' (Schlüter 1979, Koska et al. 2001) has been developed for these practical purposes and combines a classification of vegetation and environmental conditions (e.g. soil moisture, nutrient availability, pH) with the ecological niches of plant species. The classification into vegetation forms uses a multidimensional subdivision of phytosociological associations by differential species (Moravec 1975, Peppler 1992) but ultimately only depicts site conditions.

Phytosociological units (associations and higher units) with their character species (Braun-Blanquet 1932) often show insufficient correlation with site conditions to use them for detailed bioindication (Egler 1954, Ellenberg 1956, Klötzli 1972, Leser 1997, Mueller-Dombois & Ellenberg 1974, Schlüter 1981, Witte 1998). On the other hand, concrete vegetation patches often have insufficient character and differential species to assign them to a sharply defined lower hierarchical syntaxon. Therefore Ellenberg (1956) proposed to use in their place, at least within a limited region, non-hierarchical vegetation units on the basis of sociological species groups to indicate environmental conditions. These thoughts were combined with elements of landscape ecology (Neef 1967) and forest ecology into the concept of the vegetation form by Schlüter (1979, 1981) and Kopp (1979).

Succow (1988) elaborated the vegetation form concept for mires and named the resulting units 'ecological mire types' (Table 2.9). The system was advanced by Koska et al. (2001a) who also expanded it to include drained peatlands (Succow & Joosten 2001). A recent practical application of the concept is the GEST (Greenhouse gas Emission Site Types) approach to assess greenhouse gas emissions from peatlands using vegetation as a proxy (Couwenberg et al. 2011).

2.4.9 Habitat types

A classification system that over the past decades has gained importance in Europe is the habitat classification system of the European Nature Information System (EUNIS, http://eunis.eea.europa.eu/), which – aside from Canary Islands and Madeira – covers the same geographic area as this book. EUNIS is maintained by the European Environment Agency (EEA), an agency set up to provide independent information on the environment to policy makers and the general public. Currently, the agency has 33 member countries, including the 28 European Union member states together with Iceland, Liechtenstein, Norway, Switzerland and Turkey, Albania, Bosnia and Herzegovina, Republic of Macedonia, Montenegro, Serbia as well as Kosovo are 'cooperating countries'.

EUNIS defines a habitat as "a place where plants or animals normally live, characterized primarily by its physical features (topography, plant or animal physiognomy, soil characteristics, climate, water quality, etc.) and secondarily by the species of plants and animals that live there". It uses a scale that is comparable with vegetation classification in traditional phytosociology, but also assembles frequently-occurring combinations or mosaics of individual habitat types into 'habitat complexes' (Davies et al. 2004). The classification of habitat types is strictly hierarchical. There are ten 'level 1' categories (A Marine habitats, B Coastal habitats, C Inland surface waters, D Mires, bogs and fens, E Grasslands and lands dominated by forbs, mosses or lichens, F Heathland, scrub and tundra, G Woodland, forest and other wooded land, H Inland unvegetated and sparsely vegetated habitats, I Regularly or recently cultivated agricultural, horticultural and domestic habitats, and J Constructed, industrial and other artificial habitats). The category 'D Mires, bogs and fens' is defined as follows: "Wetlands, with the water table at or above ground level for at least half of the year, dominated by herbaceous or ericoid vegetation. Includes inland saltmarshes and waterlogged habitats where the groundwater is frozen" (Davies et al. 2004).

This definition makes no reference to peat or peat forming vegetation, and explicitly excludes 'waterlogged habitats dominated by trees or large shrubs'. Because of its name, category D is often considered to cover all types of mires and peatlands. In reality, however, all level 1 categories may include peatland and most of them may include mire, which is insufficiently recognised and frustrates mire and peatland statistics. Within category D, habitats are separated on the basis of the source of water supply: "completely or primarily ombrogenous (rainwater only) or other sources which are combinations of ombrogenous, soligenous (run-off), and topogenous (groundwater) but where the ombrogenous water supply is of less importance". (It is noteworthy that the terms 'soligenous' and 'topogenous' are used following the definition of von Post 1926, and not that of Sjörs 1948,

Table 2.9: Ecological mire types in northern Germany and their characteristic plant species (after Succow 1988, Joosten & Clarke 2002).

Ecological mire type	Site conditions	Oligotrophic acid	Mesotrophic acid	Mesotrophic subneutral	Mesotrophic calcareous	Eutrophic	Salt influence
	Vegetation	**Peat-moss-cotton-grass-dwarf shrub-communities**	**Peat-moss-sedge-communities**	**Brown-moss-sedge-communities**	**Brown-moss-saw-grass-black rush communities**	**Tall sedge & reed communities, alder swamps**	
	pH_{KCl}	2.5–4.8	2.5–4.8	4.8–6.4	6.4–8.0	3.5–8.0	
Species	**C/N_{peat}**	50–33	33–20	33–20	33–20	20–10	
Calluna vulgaris, *Empetrum nigrum*, *Erica tetralix*, *Ledum palustre*, *Melampyrum pratense* ssp. *paludosum*, *Vaccinium myrtillus*, *V. uliginosum*		■					
Andromeda polifolia, *Drosera intermedia*, *Eriophorum vaginatum*, *Lycopodiella inundata*, *Rhynchospora alba*, *Scheuchzeria palustris*		■	■				
Calla palustris, *Deschampsia flexuosa*, *Juncus bulbosus*, *J. filiformis*, *Luzula pilosa*, *Ranunculus flammula*, *Salix aurita*, *Veronica scutellata*			■				
Drosera rotundifolia, *Pinus sylvestris*		■	■	■			
Calamagrostis stricta, *Carex curta*, *C. echinata*, *C. lasiocarpa*, *C. nigra*, *Dryopteris cristata*, *Eriophorum angustifolium*, *Juncus acutiflorus*, *Menyanthes trifoliata*, *Potentilla palustris*, *Viola palustris*			■	■			
Carex appropinquata, *C. diandra*, *C. dioica*, *Dactylorhiza incarnata*, *D. majalis* ssp. *majalis*, *Juncus acutiflorus*, *Liparis loeselii*				■			
Molinia caerulea		■	■	■	■		
Carex limosa, *Drosera anglica*, *Hammarbya paludosa*		■	■		■		
Cardamine pratensis, *Carex panicea*, *Cirsium palustre*, *Galium uliginosum*, *Lychnis flos-cuculi*, *Potentilla erecta*, *Rumex acetosa*			■	■	■		
Betula humilis, *Briza media*, *Carex buxbaumii*, *C. flacca*, *C. hostiana*, *C. pulicaris*, *Dianthus superbus*, *Epipactis palustris*, *Juncus subnodulosus*, *Laserpitium prutenicum*, *Linum catharticum*, *Polygala amara*, *Salix repens*, *Selinum carvifolia*, *Serratula tinctoria*, *Succisa pratensis*				■	■		
Cladium mariscus, *Dactylorhiza majalis*, *Eriophorum latifolium*, *Gymnadenia conopsea*, *Juncus alpinus*, *Ophrys insectifera*, *Parnassia palustris*, *Pinguicula vulgaris*, *Polygonum bistorta*, *Primula farinosa*, *Schoenus ferrugineus*, *Tetragonolobus maritimus*, *Utricularia vulgaris*					■		
Carex acuta, *C.cespitosa*, *C. paniculata*, *C. vesicaria*, *Cicuta virosa*, *Circaea* × *intermedia*, *Hottonia palustris*, *Lathyrus palustris*, *Lemna minor*, *Oenanthe fistulosa*, *Phalaris arundinacea*, *Senecio paludosus*, *Teucrium scordium*, *Thalictrum flavum*, *Typha angustifolia*						■	
Carex elata			■	■	■	■	
Alnus glutinosa, *Calamagrostis canescens*, *Juncus effusus*			■			■	
Agrostis stolonifera, *Cardamine palustris*, *Equisetum fluviatile*, *Lycopus europaeus*, *Lysimacia thyrsiflora*, *Lythrum salicaria*, *Mentha aquatica*, *Peucedanum palustre*, *Salix cinerea*, *Thelypteris palustris*			■	■		■	
Caltha palustris, *Carex acutiformis*, *C. disticha*, *Iris pseudacorus*, *Myosotis scorpioides*, *Ranunculus lingua*, *Rumex hydrolapathum*, *Sium latifolium*, *Stellaria palustris*, *Typha latifolia*				■		■	
Phragmites australis			■			■	■
Juncus articulatus, *Pedicularis palustris*, *Valeriana dioica*				■	■		■
Carex viridula Michx., *Eleocharis quinqueflora*, *Scirpus lacustris* ssp. *tabernaemontani*, *Triglochin palustris*					■		■
Aster tripolium, *Blysmus rufus*, *Centaurium littorale*, *Eleocharis uniglumis*, *Festuca rubra* ssp. *littoralis*, *Juncus gerardi*, *Oenanthe lachenalii*, *Plantago maritima*, *Ruppia maritima*, *Salicornia europaea*, *Samolus valerandi*, *Scirpus maritimus*, *Triglochin maritima*							■

Table 2.10: Example of EUNIS habitat types on level 3 with respect to level 2 category 'D2 Valley mires, poor fens and transition mires' (European Environment Agency 2016b). Names as in original list.

D2.1 Valley mires D2.11 Acid valley mires D2.12 Basic and neutral valley mires D2.2 Poor fens and soft-water spring mires D2.21 *Eriophorum scheuchzeri* fens D2.211 Alpide cottonsedge lake girdles D2.212 Boreal *Eriophorum scheuchzeri* fens D2.22 *Carex nigra*, *Carex canescens*, *Carex echinata* fens D2.221 Peri-Alpine black-white-star and tall bog sedge fens D2.2211 Subalpine black sedge fens D2.2212 Central Alpine tall bog sedge fens D2.222 Sub-Atlantic black-white-star sedge fens D2.2221 Sub-Atlantic *Carex* acidic fens D2.2222 Sub-Atlantic *Carex*-*Juncus* acidic fens D2.2223 Sub-Atlantic *Carex*-*Sphagnum* fens D2.2224 Sub-Atlantic *Carex*-*Juncus*-*Sphagnum* fens D2.2225 Sub-Atlantic *Agrostis*-*Sphagnum* fens D2.223 British black-white-star sedge acidic fens D2.224 Pyrenean black sedge acidic fens D2.225 Iberian black sedge acidic fens D2.226 Peri-Danubian black-white-star sedge fens D2.2261 Carpathian black-white-star sedge acidic fens D2.2262 Dinaric black-star sedge acidic fens D2.2263 Rhodopide black-star sedge acidic fens D2.2264 Peri-Pannonic black-white-star sedge fens D2.2265 Balkanic black-star sedge fens D2.2266 Moeso-Macedonian black-star sedge fens D2.23 Apennine acidic fens D2.24 *Carex intricata* pozzines (wet depressions surrounding glacial lakes) D2.241 Nevadan Borreguile fens D2.242 Corsican intricated sedge pozzines D2.243 Nebrodi pozzines D2.25 *Trichophorum cespitosum* and *Narthecium ossifragum* acidic fens D2.251 Perialpine deergrass acidic fens	D2.252 Pyrenean deergrass and bog asphodel acidic fens D2.253 Cantabrian deergrass and bog asphodel acidic fens D2.254 Middle European deergrass and bog asphodel acidic fens D2.255 Corsican deergrass fens D2.26 *Eriophorum angustifolium* fens D2.27 Dunal sedge acidic fens D2.28 Illyrio-Moesian acidic fens D2.281 Pelagonide fens D2.2811 Pelagonide bog-asphodel fens D2.2812 Pelagonide Macedonian sedge fens D2.282 Montenegrine willemetia fens D2.283 Illyrian sedge-beak-sedge fens D2.29 Boreal acidic sphagnum fens D2.291 Boreal *Eriophorum vaginatum* sphagnum fens D2.2911 *Eriophorum vaginatum*-*Carex pauciflora* sphagnum fens D2.2912 *Eriophorum vaginatum*-deergrass-sphagnum fens D2.2913 Boreal stiff sedge-sphagnum fens D2.292 Boreal purple moorgrass-deergrass fens D2.2921 Boreal purple moorgrass-deergrass-sphagnum fens D2.2922 Boreal purple moorgrass-deergrass-brown moss-sphagnum fens D2.293 Boreoalpine *Sphagnum lindbergii* mires D2.2931 Sedge and cottongrass boreoalpine *Sphagnum lindbergii* mires D2.2932 Deergrass boreoalpine *Sphagnum lindbergii* mires D2.2A *Myrica gale* scrub on poor fens D2.2B Caucasian acidic fens D2.2C Soft water spring mires D2.2C1 Soft water bryophyte springs D2.2C11 Montane soft water moss springs D2.2C12 *Philonotis*-*Saxifraga stellaris* springs D2.2C13 *Pohlia* springs D2.2C14 Boreoalpine soft water hepatic springs D2.2C15 Britannic *Anthelia* springs D2.2C16 Boreal meadow springs D2.2C17 Soft water lichen springs D2.2C18 Permafrost seeps D2.2C2 Bittercress springs D2.2C3 Oro-Mediterranean soft water spring mires	D2.3 Transition mires and quaking bogs D2.31 *Carex lasiocarpa* swards D2.311 Brown moss slender-sedge swards D2.312 Sphagnum slender-sedge swards D2.313 Brown moss-sphagnum slender-sedge swards D2.32 *Carex diandra* quaking mires D2.33 *Carex rostrata* quaking mires D2.331 Acidocline bottle sedge quaking mires D2.332 Basicline bottle sedge quaking mires D2.3321 Basicline sphagnum-bottle sedge quaking mires D2.3322 Brown moss-bottle sedge quaking mires D2.34 *Carex limosa* swards D2.341 Brown moss-mud sedge swards D2.342 Sphagnum-mud sedge swards D2.343 Boreal mud sedge swards D2.35 *Carex chordorrhiza* swards D2.36 *Carex heleonastes* swards D2.37 *Rhynchospora alba* quaking bogs D2.38 *Sphagnum* and *Eriophorum* rafts D2.39 *Menyanthes trifoliata* and *Potentilla palustris* rafts D2.391 Boreo-nemoral bog bean and marsh cinquefoil rafts D2.392 Oroboreal bog bean-sphagnum rafts D2.393 Boreoalpine dwarf willow quaking bogs D2.394 Boreal bogbean-brown moss carpets D2.395 Boreal cowbane-willowherb-*Calliergon* quaking bogs D2.396 Fennoscandian *Paludella* spring bogs D2.3A *Calla palustris* mires D2.3B Brown moss carpets D2.3C *Eriophorum vaginatum* quaking bogs D2.3D *Molinia caerulea* quaking bogs D2.3E *Calamagrostis stricta* quaking bogs D2.3F *Scirpus hudsonianus* (*Trichophorum alpinum*) quaking bogs D2.3G Iberian quaking bogs D2.3H Wet, open, acid peat and sand, with *Rhynchospora alba* and *Drosera* D2.3H1 Nemoral bare peat communities D2.3H2 Boreal mud-bottom communities

see Chapter 2.4.3.) All level 1 categories are subdivided into level 2 categories, which, for example, for category D include D1 Raised and blanket bogs, D2 Valley mires, poor fens and transition mires, D3 Aapa, palsa and polygon mires, D4 Base-rich fens and calcareous spring mires, D5 Sedge and reedbeds, normally without free-standing water, and D6 Inland saline and brackish marshes and reedbeds. Level 2 is again subdivided into a large number of level 3 categories (example in Table 2.10).

EUNIS builds upon previous initiatives of habitat classification in Europe, like the CORINE Biotopes Project (Devillers et al. 1991) and its successor, the Palaearctic habitat classification (Devillers & Devillers-Terschuren 1996). The EUNIS system uses a phytosociological classification system, and Rodwell et al. (2002) published a cross-reference between EUNIS and phytosociological definitions of vegetation types, which was updated in Schaminée et al. (2014). However, a single EUNIS unit may include vegetation types belonging to multiple alliances and single alliances may be found in multiple EUNIS units. A main problem in comparing classification systems is that the EUNIS classification (like the system of Bohn et al. 2000–2004, see Box 2.4) mixes various classification approaches, like for example hydromorphic units (e.g. palsa mires) and vegetation types (e.g. rich fen and poor fen).

The EUNIS is used for environmental reporting and assistance within the Natura 2000 process and coordinated with the Emerald Network of the Bern Convention. Natura 2000 is the European Union system for creating a network of special areas of conservation under the EU Birds and Habitats directives (Chapter 6). The Habitats Directive (more formally known as Council Directive 92/43/EEC on the Conservation of natural habitats and of wild fauna and flora) is a European Union directive adopted in 1992 as an EU response to the Bern Convention. It is one of the two EU directives in relation to wildlife and nature conservation, the other being the Birds Directive. The Habitats Directive aims to 'maintain and restore, at favourable conservation status, natural habitats and species of wild fauna and flora of Community interest' and protects some 220 habitat types and 1,000 species listed in the directive's annexes (cf. Table 2.11). For each of these types, information on their distribution is available (Chapter 4).

It should be noted that the Natura 2000 habitat type classification system (Table 2.11) only covers the habitat types of 'Community interest' and does not present a complete typology of all habitats in the EU. Like Bohn et al. (2000–2004) and EUNIS, the Habitats Directive uses units that are based on different criteria (vegetation, distribution, and hydromorphology). Although detailed criteria exist for their identification, different countries and federal states within the EU interpret the various habitat types in a very different way. 'Active raised bogs' (7110), for example, are interpreted by some as only including the hydromorphic mire type 'raised bog' (see Chapter 2.6.3), whereas others include under '7110' all areas with vegetation belonging to the Oxycocco-Sphagnetea (Table 2.4). Interpretation of 'transition mires and quaking bogs' (7140) is internationally and regionally very diverse and in their national manuals countries define different and different numbers of indicator species. Within Germany the various federal states use very different indicator species for 7140, with numbers of indicator species varying from 7 to 141 (Joosten & Greiser 2015).

2.4.10 Peat types and stratigraphy

Mires that differ with respect to water supply, hydrological regime, and vegetation also develop different peat types with different physical and chemical properties. This relationship was already recognised in the earliest peatland studies. Rennie (1807), for example, gave a detailed overview on how his scientific predecessors had distinguished various kinds of peat on the basis of colour, density, fibrousness or compactness, and botanical composition, and linked these different qualities to the origin of the peats.

Von Bose (1802) recognised that peats may differ in properties according to 'the diverse species of plants that make up the single parts of the peat and that may differ strongly dependent on the location of the peatlands, the admixtures of various additional substances, like wood, reed, strange soil types, the older or younger age of the peatlands and the consequent more or less disintegration of their components' as well as 'their location, whether they lay close to the sea, and therefore by their regular flooding are provided with more salty and earthy parts…or in areas with many iron and copper ores that by

Box 2.4: Mires in the 'Map of the Natural Vegetation of Europe'

The extensive mapping project of the vegetation of Europe (Bohn et al. 2000–2004, 2005) depicts the potential distribution of the main natural plant communities in Europe, corresponding to current climatic and edaphic conditions. The map shows c. 700 units included in 19 vegetation formations (based on physiognomic-ecological features). Five of these formations are called azonal, including Mires (formation S), Tall reed and sedge swamps (R), and Fen and swamp forest (T, including degraded raised bogs). The formations are further classified into a hierarchy of subgroups based on species composition and abiotic conditions. Rybníček & Yurkovskaya (1995) and Rybníček (2004, 2005) describe the mire system and mire units used in the project.

Mires (formation S) are subdivided into three main groups (Ombrotrophic mires, Ombro-minerotrophic mires, and Minerotrophic mires), nine groups, and 26 mapped units. Four mire types are included in formation R and seven in formation T, bringing the total to 37 mapping units of mires/peatlands. Also other formations may include mires, like Arctic tundra and alpine vegetation (B) and Atlantic dwarf shrub heath (E). All these units have a detailed description of ecological conditions, including statistics (number of polygons and area covered). The largest mire unit is 'Fennoscandian aapa mire complexes' with 48,000 km^2, followed by 'palsa mires', 'Eastern raised bogs', and 'alder carrs'. The latter covers 33,000 km^2 in 219 mapped polygons and seems to be one of the most heterogenous mire units mapped, occurring all over Europe. The smallest mire units are the 'Mediterranean alder carrs', covering 30 km^2 in three polygons, and the 'Colchic fen' with 91 km^2 in one polygon. Many units (and reported ecological and geographic variants) represent mire types that have a distinct regional distribution, and the maps of the 37 mire units make this work invaluable for elaborating mire regions in Europe (Chapter 4). However, the criteria for separating units and the quality of the maps vary. Some countries are well covered, others are lacking completely. Some units are defined by vegetation (e.g. Calcareous brown-moss fen), others are pure hydromorphic units (e.g. Palsa mires), or combinations of vegetation, hydromorphology and regionality (e.g. *Sphagnum fuscum* raised bog complexes in the boreal zone).

Table 2.11: Mire-related Natura 2000 habitat types (i.e. habitat types listed in the Council Directive 92/43/EEC (Habitats Directive) Annex I, after European Commission 2013). In parentheses the approximate equivalent under EUNIS habitat classification (Council of Europe 2015) is given.

Code	Name
1340	Inland salt meadows (D6.1)
1410	Mediterranean salt meadows (Juncetalia maritimi) (D6.2)
1530	Pannonic salt steppes and salt marshes (E6.2)
4010	Northern Atlantic wet heaths with *Erica tetralix* (F2.2)
6410	*Molinia* meadows on calcareous, peaty or clayey-silt-laden soils (Molinion caeruleae) (E3.5)
6460	Peat grasslands of Troodos (E3.1)
7110	Active raised bogs (D1.1)
7120	Degraded raised bogs still capable of natural regeneration (D1.1)
7130	Blanket bogs (D1.2)
7140	Transition mires and quaking bogs (D2.3)
7150	Depressions on peat substrates of the Rhynchosporion (D2.3)
7160	Fennoscandian mineral-rich springs and springfens (D2.2)
7210	Calcareous fens with *Cladium mariscus* and species of the Caricion davallianae (D5.2)
7220	Petrifying springs with tufa formation (Cratoneurion) (D4.1)
7230	Alkaline fens (D4.1)
7240	Alpine pioneer formations of the Caricion bicoloris-atrofuscae (D4.2)
7310	Aapa mires (D3.2)
7320	Palsa mires (D3.1)
91D0	Bog woodland (G1.5)
91E0	Alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior* (Alno-Padion, Alnion incanae, Salicion albae) (G1.1)

provision of their ochre also contribute much to the refinement of the peat, or whether they stand more or less under water, or for example receive water inflow from adjacent fresh springs, or even are at times flooded by adjoining rivers.'

The earliest classification of peat was based on properties relevant for energy generation. The first examples in this respect go back to Boate (1652, Table 2.1) and Degner (1729/1731); in his classification Degner already referred to chemical studies and properties.

Later, peat types were further classified on the basis of the origin of the feeding water (e.g. "Regentorf" – 'rain peat' – or "ombrogener Torf" – 'ombrogenous peat', Weber 1911), their degree of decomposition (cf. black peat, grey/white peat – von Post scale, von Post 1924), nutrient content and acidity (oligotrophic, mesotrophic, eutrophic, see Chapter Ukraine), ash / organic matter content (cf. Halbtorf, Volltorf, Reintorf, Succow & Stegmann 2001b), pedogenic alteration (cf. the German Ried, Fen, Mulm, Zeitz & Stegmann 2001; the Polish moorsh types, Okruszko & Ilnicki 2003), fibre content (fibric, hemic, sapric), and other characteristics (Fuchsman 1980, Andriesse 1988, Succow & Stegmann 2001b).

A large number of plant species (sedges, grasses, *Sphagnum* and other mosses, woody plants) may contribute to peat formation, and as a result also a wide variety of 'botanical' peat types can be distinguished (e.g. 71 types in Tołpa et al. 1967; Troels-Smith 1955, Jasnowski 1959, Grosse-Brauckmann 1962a,b, Tobolski 2000, Succow & Stegmann 2001a, Luthardt et al. 2011).

Peatland sites and massifs can be classified according to the peat types they contain. Also in this respect different approaches persist. Some countries relate the name of the site/massif to the peat type at the surface of the peatland, whereas others use the prevailing peat type in the peat deposit. A peatland with a layer of bog peat over a thicker layer of fen peat will thus be called a bog in one country, where the top peat layer is used as the critical feature, whereas it will be called a fen in another country, where the peat that dominates the stratigraphy is the decisive criterion. In a 'mixed' peatland various peat types occur but none is dominant.

2.4.11 Peat accumulation and peatland degradation

Over the past decades, the classification of peatlands into 'living' and 'dead' or 'degraded' ecosystems has gained popularity. Distinguishing peatlands with active peat formation ('mires') is useful, because peat forming ecosystems differ strongly from non-peat forming ecosystems (including degrading peatlands), especially with respect to their climatic and hydrologic regulation functions, biodiversity, and in the provision of a range of other ecosystem services (Bonn et al. 2016).

Already Schoockius (1658), in the first scientific book about peatlands, differentiated between uncultivated and wild "rouwe veenen" ('raw peatlands') and "afghetapte Venen" ('drained peatlands'), whereas Findorff (1764) called the former 'wild peatlands' or peatlands in "heiler Haut liegend" ('lying in pristine skin'). In times when peat constituted the prevailing source of energy in various countries, the differentiation between sites with and without peat accumulation, also after peat extraction, was relevant for estimating the sustainability of the resource. Schoockius (1658), for example, devoted an entire chapter to the question "An materia cespititia efossa, progressu temporis restaurari possit" ('Whether excavated peat material can over time be restored?') and this question was in the following centuries repeated in almost every book on peatlands.

Also in the discussion on the origin of peat the question of 'dead or alive' was addressed, asking whether it should be seen as a lifeless mineral or a growing organism or ecosystem. Anderson (1794, see also Rennie 1807) differentiated between 'quick moss' (cf. quicksand) and 'dead moss': "Quick moss is a solid compact body which in its ordinary state is without fissures of any sort. It readily absorbs water to a certain degree, which it retains so strongly as never to be found dry, except when much exposed to the sun or air, in very particular situations. In the common state in which it is found, it is a soft substance that may be easily penetrated, and of course it can seldom be trod upon, when moist, with safety, by any animal; for if the surface be once broken it is incapable of making a sufficient resistance to bear its weight, so as to form a most dangerous kind of bog. It also resists the passage of water through it, so as to retain it as an impermiable reservoir. […] When it has been once thoroughly dried, peat, like clay that has been burned, is no longer capable of being reduced to its former state of quick moss; and in this sense it may be said to be as effectually dead as an animal after it has been deprived of life […]; it is indeed precisely the substance universally known in all peat countries, and distinguished in Aberdeenſhire by the name of dead moss."

A typology of peatland degradation stages to assess the potential for restoration was presented by Schumann & Joosten (2006; Joosten 2016, see also Dommain et al. 2010) who distinguished six stages of degradation based on the progressive deterioration of the more important and inert mire functional components. Bruneau & Johnson (2014) differentiated between 'active', 'degraded', 'bare', 'archaic', and 'wasted or lost' peatlands on the basis of differences in structure, vegetation, management, water table, and organic matter dynamics.

Anderson (1794) also deliberated how fast 'quick moss' would grow: "Again, no opinion is more generally received in peat countries, than that moss grows in certain circumstanses very rapidly … Of this fact, for some years after I went to Aberdeenshire, I did not entertain a doubt – yet I can now without any hesitation aver, that after thirty years very careful attention, I have not been able to discover one single instance in which I could say I had seen a single inch of moss produced upon the surface, in the manner in which it is in general understood to grow, though I have seen and examined many hundreds of acres of those mosses that are generally called growing mosses in that country.

I would not from this wish to be understood to say that moss never does grow. From the strong fact I have just stated, it seems to be undeniable that moss must have been gradually produced, and therefore the probability is that it still continues to grow. I would only mean to say, either, that the circumstances that favour the generation of moss have not occurred in the cases that have fallen under my observation, or that its growth is so very slow, or the accretion is produced in such a manner as not to be perceptible on the surface in the period of time that my observations have been continued."

As peat accumulation is a subtle process with large annual variation (Alm et al. 1999, Roulet et al. 2007, Frolking et al. 2014) it is – without direct long-term observational studies or extensive palaeoecological analysis and dating (Joosten 1995b) – difficult to determine whether an ecosystem is actually peat accumulating. A first indication for peat formation is the presence of peat. This requirement is necessary, but not sufficient, because the peat may also have formed during an earlier period. Satisfactory indicators of peat formation are the prevalence of plants whose remains are also found in the uppermost peat, together with almost permanently waterlogged conditions.

It should be noted that there may also be areas in a mire where no actual peat accumulation takes place or where peat is degrading like in pools and mud-bottoms (Lundqvist 1951, Sjörs 1963a, Foster et al. 1988, Pelletier et al. 2014, 2015). However, the active peat formation at the surface that defines a mire as a 'living peatland' should be assessed as a significant process at the landscape scale.

2.5 The classification of mire areas and patterns

2.5.1 Principles and history

Next to 'point' properties, mire classification obviously also considers spatial aspect of mires and their components. In early works different 'forms' were described in a 'geographic' or 'territorial' context; later, these units were increasingly interpreted in terms of their 'functions' ('pattern and process', cf. Watt 1947, van Leeuwen 1966, Bormann & Likens 1979, Ivanov 1981), and their functional interconnectedness was analysed in hierarchically organised levels of scale.

Weber (1902) systematically described the Augstumal raised bog as consisting of separate but interrelated entities: the plateau, bog pools, stream valleys, marginal slope, and surroundings of the raised bog, respectively. On a smaller scale level he described various shapes and forms of hummocks and hollows. Cajander (1913) noticed that "Grossmoore" ('large mires') are 'composed of a large number of different mire types, which stand in an occassionally quite intimate interdependency to one eachother.' Abolin (1914) was the first to propose special terms for the mire landscape units on different hierarchical levels (Masing 2001) and assigned the terms эпитипы ('epitypes') to the larger heterogeneous areas and эпиморфы ('epimorphs') to the smaller homogeneous units constituting them. Since then, the spatial units have been variously classified and variously named.

The term 'mire complex' was first used by Cajander (1913), who noted: 'The small primary mires that have originated either through terrestrialisation of lakes or through paludification of marshes or of ordinary forest soil may expand in every lateral direction, eventually causing the formation of very large mires. It is also very common that several, often even many mires combine to form very large mires. […] Hereafter such "Grossmoore" will be called 'mire complexes', irrespective of whether they have originated from simple lateral expansion and consequent internal differentiation, or from the merging of numerous isolated primary mires.' Cajander (1913) himself recognised the dualism of the term: 'I have indeed certain doubts about the use of the term 'mire complex' for the first mentioned category, to which especially the raised bogs (sensu stricto) belong; on the other hand, also the raised bogs constitute a complex of various mire types, although the complex has originated in a different way than the mires of the second category'.

Aario (1932) used the terms "Kleinformen" ('small forms', like hummock and hollow), "Formenteile" ('form parts' like plateau, rand, and lagg) and "Grossformen" (like relief following, flat, or domed mires). Sjörs (1948) proposed a similar sequence, which he named "myrstruktur" (translated in English by him as 'mire feature'), "myrelement" ('mire site'), and "myrkomplex" ('mire complex'). His 'complex' follows the same concept as that of Cajander (1913) by covering both the single massif and a conglomerate of various massifs. The latter differentiation was explicitly made by E.A. Galkina, who had worked with aerial photography for geobotanical mapping since the 1930s; she used her knowledge to solve military and civil supply problems during the Leningrad blockade of World War II. After the war she published a classification of mire landscape structures visible from the air with three scale levels: (i) микроландшафт ('microlandscape', i.e. the level of 'mire site'), (ii) мезоландшафт ('mesolandscape', i.e. the level of 'mire massif'), and (iii) макроландшафт ('macrolandscape', i.e. the level of a 'complex of mire massifs', Galkina 1946). Galkina's ideas were widely accepted among Soviet Union mire researchers. However, the terms met with criticism because of their 'hybrid', partly German origin (Masing 1998), moving Galkina (1963) to rename the microlandscape to болотная фация ('peatland facies'), the mesolandscape to болотное урочище ('peatland tract') or mire 'massif', and the macrolandscape to система болотных урочищ ('system of peatland tracts').

Similar approaches with four levels, often with different names for the names of the units, have been used by e.g. Ivanov (1975/1981: microrelief/microform, microtope, mesotope, macrotope), Moen (1985: feature, site, synsite, complex), Lindsay et al. (1988: microform, microtope, unit, complex), and Økland (1989b: feature, segment, synsegment, complex). Eventually, Mazing (1974, Masing 1984: microform, site/association complex, complex/massif, system, and region) added a higher level, the 'region' and also recognised – from a vegetational point of view – two lower levels: the 'coenotic' and the 'microcoenotic'. Masing worked out this 'multilevel approach' in a variety of publications, with a last overview presented in 1998.

Here the following standard terms are used: mire feature (nanotope, Chapter 2.5.3), mire site (microtope, Chapter 2.5.4), mire massif (mesotope, Chapter 2.6), mire complex (macrotope, Chapter 2.7), and mire region (supertope, Table 2.12). The highest level, the mire region, is dealt with in Chapter 4.8. Below the nanotope level we furthermore distinguish the 'ero' or 'picotope' (Chapter 2.5.2).

Important functional linkages between organisational levels (Table 2.12) are found in the hydraulic conductivity – which determines to what extent water flow is obstructed – and the storage capacity – which determines how much water can be stored in a given volume. To guarantee peat growth the water table in a peatland must almost always be high; drops in the water table should not be too strong and not persist for too long. Consequently, hydraulic conductivity must be small (at least in inclining mires) to limit lateral and downward water losses, whereas storage capacity must be high to guarantee that – also when lateral and downward losses are minimised – water tables remain high inspite of inevitable water losses through evapotranspiration.

Both hydraulic conductivity and storage capacity are determined by the size and arrangement of void spaces in the sense that larger voids lead to larger conductivity and larger storage capacity, and smaller voids to the opposite (Couwenberg & Joosten 1999a). (Note that the porosity of peat is dynamic and that pores expand and contract in response to changing water pressure, cf. Hemond & Goldman 1985, Edom 2001, Glaser et al. 2004b, Fritz et al. 2008). Hydraulic conductivity and storage capacity thus both depend on the 'porosity' of the peat, but whereas low conductivity requires small pores, high storage capacity requires large ones. A peatland can only exist when these two contrasting requirements are sufficiently optimised across all levels of organisation (Fig. 2.6, Table 2.12). Higher order patterns of more and less 'open' elements are made up of more or less open elements at lower organisational levels. At the same time, optimisation at the higher level constrains and determines the development of elements at the lower level (the shape of the mire determines the position and extent of the sites, both these higher levels determine the position and shape of the features, and together the higher levels eventually even determine the physiognomy of individual moss plants). Resulting feedback loops make mires into highly self-organising entities (Couwenberg & Joosten 1999a, 2005).

2.5.2 Mire eros (picotope)

The lowest level of organisation is the picotope with the finest structural and functional elements, the eros: the plant tissue (which obstructs water flow, contains cation exchange sites, and releases organic acids) and the plant internal and external pore space (which can store water). The ero consists of a moss or vascular plant with its biotic companions and symbionts. Different species have different growth rates, vitality, and density, and consequently have different effects on other plants in their competition for space, light, and nutrients. The ero is determined by the water table, water table fluctuations, and water flow. In return, the ero feeds back on water table level and water flow by its shape, texture, and density as determined by vegetative reproduction, branching, and spreading (Smolyanitski 1977, Masing 1984, Panov 2012). These interdependencies are particularly clear in case of *Sphagnum* (Clymo & Hayward 1982, see Chapter 4.5, Box 4.1).

2.5.3 Mire features (nanotope)

The nanotope is the level of organisation of the mire features, the most important elementary parts of the peatland surface, which consists of microrelief elements and the associated plant communities. A wide range of microrelief forms are distinguished (Sjörs 1948, 1983).

A hummock is a roundish or elongated small elevated area; a hollow a lowered area. Hollows are often subdivided in lawn, carpet, and mud-bottom on the basis of different plant communities (Sjörs 1948). A string (or ridge) is an elevated and elongated area perpendicular to the slope of a mire, a flark (or rimpi) a similar lowered area. The term flark is restricted to lowered geotrophic areas (Sjörs 1946), the term string/ridge may apply to both geo- and ombrotrophic areas. The term

Table 2.12: Preferred names (as proposed by the IMCG Workshop on Global Mire Classification, Greifswald, 1998), synonyms in literature, indicative size, structural, compositional, and functional diversity, and examples of elements that obstruct and store water on the various mire organisational levels (after Cajander 1913, Aario 1932, Sjörs 1948, Galkina 1946, Ivanov 1975/1981, Masing 1974, 1984, 1998, Moen 1985, Lindsay et al. 1988, Økland 1989a,b, Yurkovskaya 1995, Couwenberg & Joosten 1999a, Joosten et al. 2001). The 'tope' concept expresses that on that respective level more attention is paid to external than to internal differences.

Organisational level	Component	Synonyms	Size (m^2)	Structural diversity	Compositional diversity	Functional diversity-	Obstructing element	Conducting and storing element
0.		–	10^{-8}	Porosity	Various types of tissue	Plant growth, cation exchange, release of organic acids	Plant tissue	Pore structure
1.Picotope	Mire ero	Elementary particle, subfeature, nanoform	10^{-2}	Single plant, moss clone, peat column, life strategies	Lithology, species, palaeoecological archive value	Capillarity, peat accumulation	Plant	Open water
2. Nanotope	Mire feature	Microform, microrelief, element, subelement, structure	10^{-1}-10^{1}	Water table height, water quality, ecological mire type	Microrelief elements, synusia	Primary production, water table fluctuations, competition, greenhouse gas emissions	Lower acrotelm, catotelm	Upper acrotelm
3. Microtope	Mire site	Facies, type, unit, element, segment, Kleinform, mikrolandšaft	10^{1}-10^{6}	Microtopography, peat depth	Sigmetum, vegetation mosaic, vegetation form	Transmissivity, surface water flow, differential peat accumulation	Hummock, string, kermi	Hollow, pool, flark
4. Mesotope	Mire massif	Complex, synsite, unit, Grossform, mesolandšaft, synsegment	10^{2}-10^{7}	Macrorelief, hydrogenetic mire type	Microtope and vegetation zonation, mire stratigraphy	Oasis-effect, differential peat accumulation, lateral matter transformation	Rand	Flush, rull, plateau
5. Macrotope	Mire complex	Massif system, coalescence, makrolandšaft	10^{5}-10^{9}	Extent, degree of heteronomy	Assembled mire massifs and emergent mire sites, macrostratigraphy	Mire expansion and initiation, mesoclimate regulation	Bog massif	Fen matrix
6. Supertope	Mire region	District, province, rayon	$>10^{9}$	Ecological infrastructure	Diversity in mire types, metapopulation	Mesoclimate regulation		

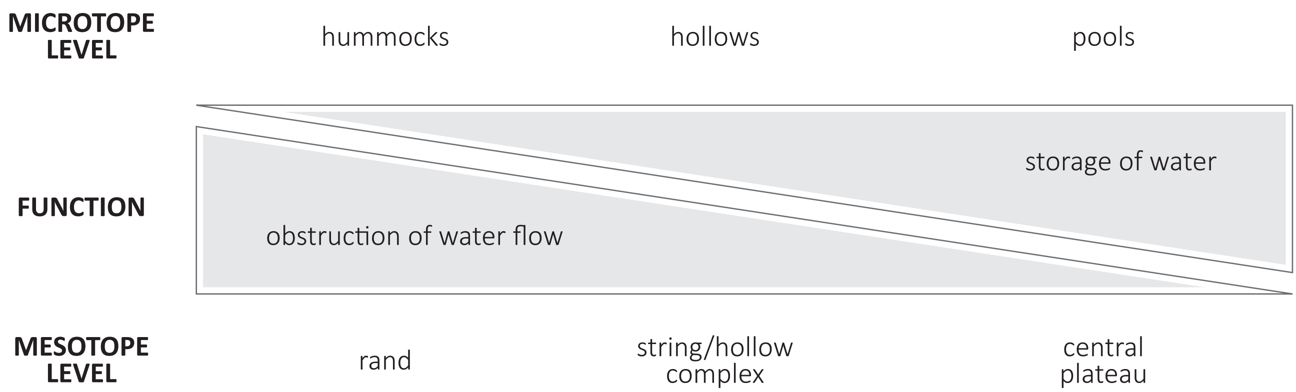


Fig. 2.6: 'Function-sharing' of nanotopes (on the microtope level) and microtopes (on the mesotope level) in hydrological self-regulation of a bog (Baumann 2006, modified from Couwenberg & Joosten 1999a).

for an elongated ombrotrophic depression is elongated hollow. A pool is an open water depression that has developed in the peatland; a distinction is made between hollow pools and flark pools. A tarn is a primary open water depression, i.e. a remnant of a lake that already existed before the peatland had established. A swallow hole is a vertical hole in the peat connected to a subterranean drainage system. An islet hummock is a single ombrotrophic mound situated in a flat fen (also called 'miniature bog'). An erosion channel results from water, ice, and wind erosion and also from trampling; a hag top is a free-standing remaining part of the original mire surface (most often a bog) around which the peat has eroded away.

Linnaeus (1751a) already described hummocks as typical for bog surfaces and provided lists of the characteristic plants of Swedish bog hummocks in Skåne (southern Sweden), including *Calluna vulgaris* and the lichen *Cladonia rangiferina*. *Sphagnum* mosses were described as the main plants occupying the spaces between the hummocks. Other species reported include *Rubus chamaemorus*, *Vaccinium oxycoccos*, *Andromeda polifolia*, *Eriophorum*, *Vaccinium myrtillus*, and *Scirpus cespitosus* as an abundant species, whereas some bogs were described as overgrown with low pines. Linnaeus speculated on winter flooding being the cause of the origin of hummocks and noted that hummocks do not arise where standing water persists after winter. The presence of tree stumps he said would favour the development of hummocks.

Von Meidinger (1775) suspected another origin of hummocks: 'Wild and undrained peatlands are weak and swampy most of the year. One encounters many hummocks here, which originate from the loose earth: the cattle tread on the surface of the mire, especially in the outer parts, which results in the weak adjacent parts being pressed up, bringing all these hummocks about'.

Surface patterns, often arranged perpendicular to the slope, belong to the most striking features of mires from the boreal to the meridional zone (Gams & Ruoff 1929, Sjörs 1961, Aartolahti 1965, Ivanov 1981, Glaser 1999). Various explanations for this phenomenon have been proposed (Auer 1920, Seppälä & Koutaniemi 1985), ranging from solifluction (von Post & Sernander 1910, Weber 1910), fissuring (Pearsall 1956), frost action (Sjörs 1961), differential thawing of surface elements (Auer 1920), differences in local rates of peat accumulation (Alexandrov 1988, Foster et al. 1988), litter transport (Tanttu 1915, Sakaguchi 1980), flooding along the contour interval (Boatman & Armstrong 1968, Glaser et al. 1981, 2004a, Boatman 1983), to the patterns simply reflecting underground relief (Auer 1920, Radforth 1969).

Recently, peatland feature and pattern development have been linked to general theories on spatial patterning (Rietkerk & van de Koppel 2008). Some approaches are based on the feedback mechanisms between hydrological and biological processes (Swanson & Grigal 1988, Couwenberg 2005), others suggest that biotic processes such as different growth and decay rates between *Sphagnum* species are responsible for nanotope development (Nungesser 2003). Rietkerk et al. (2004) and Eppinga et al. (2008) ascribe regular maze patterning in very flat peatland to evapotranspiration driven nutrient enrichment in hummocks and consequent higher rates of peat accumulation. Eppinga et al. (2009) suggest that various combinations of biotic processes, hydrology, nutrient availability, and peat accumulation rates may result in similar surface patternings.

Some of the most convincing explanations for the origin of striping patterns (cf. Proctor 2013) focus on the feedback mechanisms that exist between the vegetation, peat, and water (Swanson & Grigal 1988, Couwenberg 2005, Couwenberg & Joosten 1999a, 2005). Most clearly, these can be observed in *Sphagnum* dominated systems, where differences in local water tables lead to intra- and interspecific changes in the mosses (Beijerinck 1934, Früh & Schröter 1904, Overbeck & Happach 1957, Green 1968, Ilomets & Paap 1982, Clymo & Hayward 1982, Hayward & Clymo 1983, Masing 1984, Panov 1991) and in decomposition rates (Ivanov 1981, Clymo & Hayward 1982, Grigal 1984, Wallén et al. 1988, Rochefort et al. 1990, Vitt 1990, Hogg 1993). These modifications change the hydraulic properties of the uppermost mire layer, which in turn alter the local water table levels. On drier sites hummocks develop with a typically lower hydraulic conductivity than the hollows that develop on wetter sites (Ivanov 1981, cf. Belyea & Clymo 2001).

In sloping mires, where substantial lateral water flow takes place through the uppermost layer of peat and vegetation, the presence of a hummock leads to a rise in the water table upslope, creating wetter conditions that stimulate the development of hollows (Malmström 1923). In contrast, hollows with their higher hydraulic conductivity will drain upslope areas, creating drier conditions that stimulate the development of hummocks. Finally, a striping pattern of hummock strings and hollow flarks aligned perpendicularly to the slope results.

Using spatially explicit computer simulations, Swanson & Grigal (1988) showed that such a dependency of vegetation and surface elements on water table, combined with a difference in hydraulic conductivity of the elements, will lead to the formation of striping patterns on an inclined surface when the water flux is sufficiently large. Revisiting this model, Couwenberg (2005) showed that it may also account for the meandering and merging of the striping patterns as it is observed in natural systems. Furthermore, the model revealed that the formation of the striping patterns is controlled by positive feedback mechanisms, which means that a striping pattern either develops or not, but never only partly or extremely vaguely. These modelling approaches are certainly not exhaustive (as reality is more complex), but seem to provide an adequate explanation for some of the more striking features such as string-flark striping patterns. Furthermore such simulation models generate hypotheses and search images that can be tested against field observations and data.

Research on pools on patterned peatlands has a long tradition. A historic perspective as far back as the 17th century is offered by Gorham (1953) and more recently by Tallis (1983), Seppälä & Koutaniemi (1985), Sjörs (1999), and Glaser (1999).

2.5.4 Mire sites (microtope)

Mire features unite to form a mire site with fairly homogeneous hydrological conditions at a larger scale level. Mire sites are composed of two or more kinds of features which are repeated in indefinite numbers and alternate more or less in the same way all over the site (Sjörs 1948), but also a single, large feature can form a mire site. A fully-developed mire generally consists of various mire sites, like the lagg (the fen strip separating the bog from the surrounding mineral soil), a fen soak (a strip of fen between bog units), the bog expanse, often with hummock-hollow or string-pool complex, and the marginal forest of a raised bog (Weber 1902, Masing 1972, 1984, Overbeck 1975, Ivanov 1981).

Varenius (1650) was the first to classify mire massifs by their site characteristics: "Paludes duplices sunt. Quadam uliginosa & mixta quasi substantia ex aqua & terra constant, ita ut vestigia hominum non ferat vel sustineat. alia parva stagna vel aquarum collectiones habent, hinc inde parvis terra sicca extantibus portionibus." ('There are two types of mires. Some are swampy and their substance consists of a sort of mixture of water and earth, so that it does not carry nor support the footsteps of humans. Others have small pools or collections of waters, from which dry land protrudes in small portions'.)

King (1685) described how "Every *red Bog* has about it a deep marshy floughy ground, which they call the *bounds* of the *Bogs*". Findorff (1764) made a clear distinction between the sloping dwarf shrub dominated margin of a bog and its flatter centre where individual moss and dwarf shrub covered hummocks occur only sparsely. De Luc (1775–1779) already described the pulsating character of mire features (cf. Barber 1981):'The surface of the mires is generally covered partly by heather and shrubs, partly by marsh plants. In dry years the woody plants expand, in humid years the waterplants. In this way ever alternating layers of both these types of plants originate and are more and more compressed and eventually form the black, firm and combustible matter of the peat, which is crisscrossed by fibers and roots.'

Venema (1855, Fig. 2.7) noticed how the form of hummocks changed across the pristine Bourtanger bog: 'the mire does not form a smooth plane, but [...] is covered by small elevations, which are called hummocks or heads. In the centre these hummocks are of very little significance, usually not more than 0.5 'palm' [hand] above the mire. They run with a very small angle up and down and the profile is therefore somewhat undulating. Far from the centre the hummocks become higher, with steeper slopes both up and down. The highest they are at the margins, where they not rarely arise to 5–6 palms above the peat, and often from above they show a larger plane than where they rest on the peat soil.'

Traditionally, peatland features and site types have been explained by (i) biotic processes (e.g. the regeneration complex theory of Osvald 1923, cf. Walker and Walker 1961, Casparie 1969, Barber 1981), (ii) frost and ice action, and (iii) gravity (Moore & Bellamy 1974, see Chapter 2.5.3). Modelling the distribution of mire sites on a domed bog (cf. Fig. 2.2), Couwenberg & Joosten (2005) found that on steep domes with limited precipitation input, the entire surface of the bog is taken up by one site type, solely consisting of hummocks. The combination of an all hummock rand and a central expanse with randomly arranged hummocks and hollows seems to be restricted to rather flat domes with limited precipitation. On somewhat steeper domes and with higher precipitation, a zone with string-hollow patterning occurs as a band between the outer all-hummock rand and the central expanse. With very large amounts of rain and/or on very flat domes, the expanse features an all-hollow area. Larger differences in hydraulic conductivity between the hummock and hollow vegetation/peat led to more sharply defined patterns both on the mesotope and on the microtope level. The longer persistence of (impervious) ice in hummocks/strings compared with hollows probably causes the more explicit surface patterning of peatlands in the boreal zone (cf. concentric and eccentric bogs, string-flark mires) compared with more southern zones. An increase in the amount of recharge leads to an increase in the amount of wet elements, i.e. to the appearance of wetter types of microtopes and an increase in their extent. Such shifts have been described by Osvald (1925a), Ruuhijärvi (1960), Eurola (1962), Aartolahti (1965), Damman (1977), Glaser & Janssens (1986), Glaser (1992a), and Seppä (1996). Associated changes in peat composition have been correlated with changes in the wetness of the climate (cf. de Luc 1775–1779, Weber 1902, Casparie 1969, 1972, Barber 1981, Charman & Chambers 2004).

Mire sites can be classified according to various criteria, including the type of mire massif supporting the site, the location of the site on the massif, the properties of the site itself, the vegetation structure of the site (simple, mosaic, patched, complex), and the type and depth of the underlying peat (Galkina et al. 1974). Some of these criteria concern the current developmental stage of the site (e.g. the vegetation), whereas others also include the developmental history (e.g. peat stratigraphy).

2.6 The classification of mire massifs (mesotope)

2.6.1 Principles of mire massif classification

A mire massif (unit at the mesotope level of organisation) is the basic geographic unit of mire classification on the landscape scale. It represents a stand-alone mire area whose properties are determined by the shape of the basin and the consequent hydrological dynamics, as reflected in the distribution of vegetation, surface structures, and peat deposits (Galkina et al. 1974, Abramova et al.1974). In its simplest form, a mire massif is on all sides surrounded by non-mire, i.e. by mineral soil or water, but in many cases single mire massifs are joined in a mire complex (Chapter 2.7), so that a single mire massif may also border other mire massifs.

The origin of a mire massif may lie in a single point, or in a larger homogeneous area where peat started to grow simultaneously, or in a group of depressions in which individual mires developed but rapidly expanded and grew together, after which the united mire body developed as a single entity.

A mire massif typically consists of a characteristic combination of mire sites. Yet, mire massifs may be comprised of only one site as well, like a flat fen or a sloping fen.

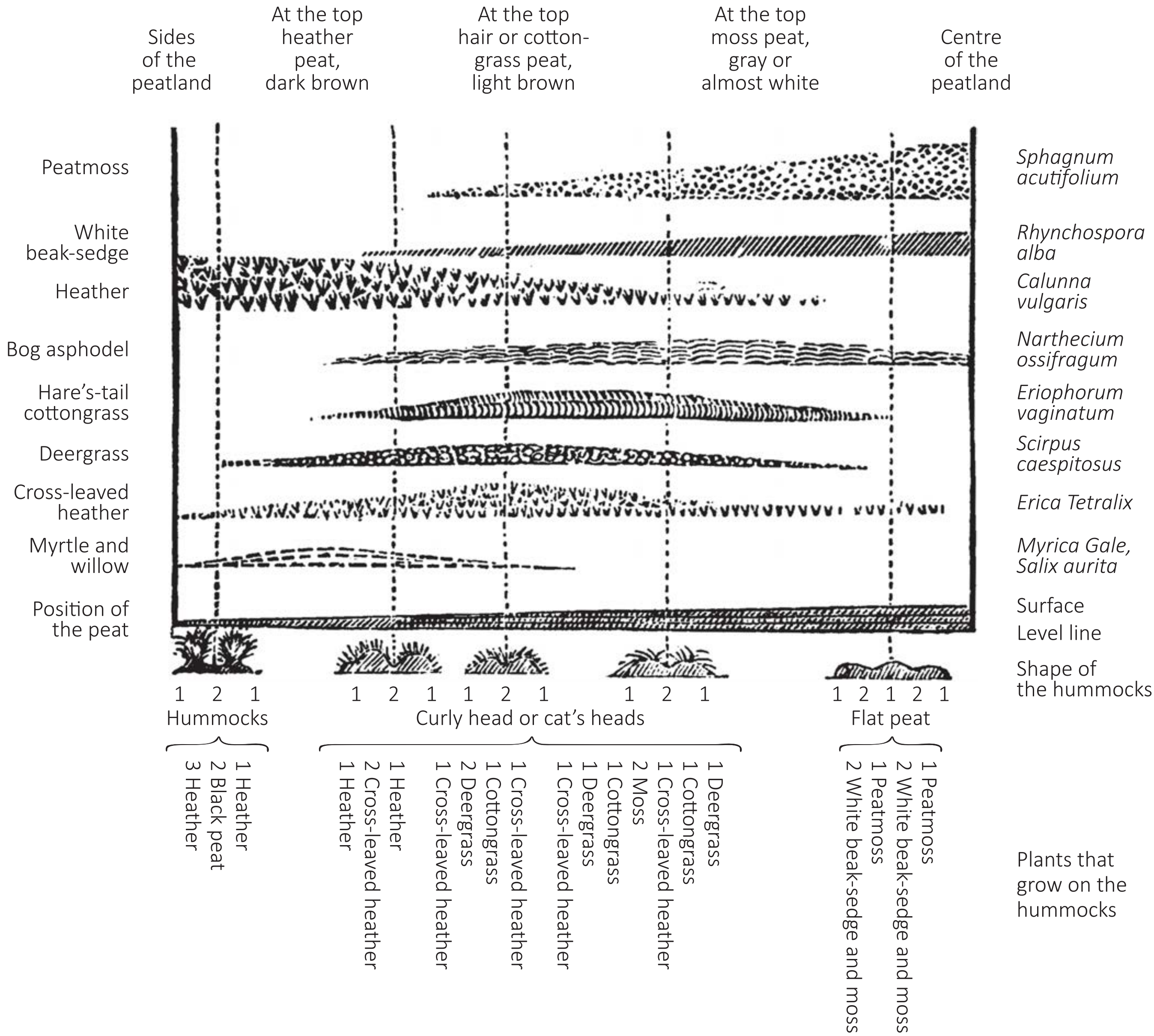


Fig. 2.7: Schematic presentation of the distribution of mire features, sites, and species across the Bourtangermoor (after Venema 1855).

Mire massifs can be classified according to various principles (Table 2.13, Fig. 2.9). The first group of classifications extrapolates a dominant characteristic on the point or site level to give a name to the entire mire massif (see Chapter 2.4). The second group considers chorological properties, such as location, the shape of the mire, the patterning of surface elements, the role of water, and developmental stage. In the following, we discuss topographic (geomorphic), morphic/hydromorphic, hydrogeomorphic, and hydrogenetic mire classification approaches that are often used in Europe. These classification approaches run largely parallel with the main properties that Galkina et al. (1974) saw as relevant for the classification of mire massifs:

1. The geological and geomorphological characteristics and origin of the basin in which the massif has developed;
2. The type of water flow and its change over time;
3. The developmental stage in the successional sequence from 'eutrophic' to 'oligotrophic';
4. The developmental stage in a series in which mire massif types change into each other;
5. The specific expression of this developmental stage as determined by local environmental conditions.

Properties 2–5 are most clearly manifested in vegetation cover and peat deposits.

Historically – but also at present – not all typologies are fully consistent and combine different types of defining variables. Such inconsistencies usually have a pragmatic, pre-scientific origin. For example, Dau (1823) followed von Eiselen (1802) and – next to the 'hitherto commonly recognised' peatland types "Hochmoore" ('high mires') with a convex surface and the "Wiesen- oder Sumpf-Moore" ('meadow or swamp mires') with a horizontal surface – he distinguished "Holzmoore" (wood mires) to describe small peatlands between hills and around lakes with woody peat, and following Abildgaard (1765), "Meermoore" ('sea mires') that are located along the sea and have a vegetation of saltmarsh plants. This typology of Dau (1823) thus uses a morphologic criterion to separate the first two, a physiognomic to typify the third, and a topographic to define the fourth type.

2.6.2 Topographic (geomorphic) classification

Topographic classification is derived from the location, topography, or land-setting in which the mire is situated (cf. Rubtsov 1974). Examples include 'valley mire' (in a valley), 'saddle mire' (draped like a saddle between mountains), 'mountain mire', 'bird cliff mire', 'slope mire', 'floodplain mire', 'basin mire', 'watershed mire', 'oxbow mire', 'river side mire', 'terrace mire', etc. (see e.g. Chapter Russian Federation)

Various geomorphic peatland types were already mentioned by Lesquereux (1844). He must have referred to something we now call 'blanket bog' when he wrote that 'next to peat deposits that occur where an accumulation of standing water took place, peat layers sometimes cover rounded-off mountain knolls and hang down over their sides like a coat' (see Chapter 2.6.3). His description of mires that occur 'In the Alps and Vosges mountains, as well as in Ireland, […] even on very inclined slopes below small lakes, or below icebergs, from which they receive their water…', we would nowadays attribute to 'sloping mires'.

A topographic typology of mires was systematically elaborated by Früh & Schröter (1904), who differentiated mire types according to the locality where they had been formed. They distinguished, for example, "Plateaumoore" ('plateau mires', not to be confused with the hydromorphic 'plateau bog', see Chapter 2.6.3), "Talmoore" ('valley mires'), "Talstufenmoore" ('valley step mires'), "Terrassenmoore" ('terrace mires'), "Kammmoore" ('crest mires'), etc. (cf. Schreiber 1927). In particular in mountainous areas a topographic approach can be elaborated in detail, as for example Gams (1932) has done for the Alps.

The location of a mire will often determine relevant ecological conditions (Galkina et al. 1974). A 'watershed mire' will, obviously, only receive atmospheric water and thus always be ombrotrophic. A topographic classification does thus not necessarily only provide topographic information.

For example, Tansley (1939) described 'valley bogs' as "developed where water, draining from relatively acidic rocks, stagnates in a flat bottomed valley or depression, so as to keep the soil constanly wet. In such situations species of *Sphagnum* and associated plants appear and produce a bog limited to the area of wet soil. … In a sufficiently moist climate the characteristic *raised bog* (German *Hochmoor*) may develop on top of a valley bog. The valley bog itself, however, being fed by drainage water, is never so poor in soluble mineral constituents as a raised bog, and it contains plants, such as species of *Juncus* and *Carex*, which have no part in a typical raised bog."

Some terms from topographic classification were later adopted for naming mire types in other classification approaches, e.g. valley mires (Kulczyński 1949), 'Kesselmoore' (kettlehole mires, Joosten & Succow 2001), or 'blanket bogs' (Taylor 1983).

2.6.3 (Hydro-)morphic classification

Hydromorphic mire classification (often also called hydromorphologic(al), or hydrographic-topographic, Sjörs 1946, or hydrotopographic, Moen 1973) is mainly based on the shape of the mire massif (mesotope), the distribution of the mire sites (microtopes), and the form and pattern of its features (nanotopes). The shape of the massif (the macrorelief or 'Grossform') is one of the oldest ways of classifying mire massifs (cf. Photo 1).

The differentiation between "hooge veenen" ('high peatlands') and "laage veenen" ('low peatlands') was widely used in 17th century Holland (e.g. "hooge veen" mentioned in 1617, Blink 1891). The raised bog ("dry or red bog") was mentioned for Ireland by Boate (1652) and King (1685), who described 'bogs' as "generally higher then the land about them, and highest in the middle". Raised bogs were further described for Sweden by Linneaus (1747, 1751a), for Germany by Bansen (1754), and for Denmark by Borgen (1762) and Abildgaard (1765).

De Luc (1779) described the form of these 'high peatlands' in Northwest-Germany in detail: 'For example, over the distance of 5 leagues between the Oste and the Schwinge [streams], the surface of the peat has a convexity, which makes its centre 37 feet higher than the two streams. But in this centre there is 30 feet of peat, whereas there is only 4–5 feet of peat at the margins. Thus, over these 5 leagues the peat is curving 34 feet, against the soil below only 12. This is because in the centre the peat remains wetter and grows more rapidly than toward the edges.' Ganong (1897/1898) was probably the first to use the term 'raised bog' in English.

Von Eiselen (1802) distinguished

1. "Hochmoore" ('high peatlands'): peatlands that are 'generally completely sterile, with an uneven hummocky surface, and seemingly only grown over by long moss and especially heather, somewhat elevated compared to the rest of the land; or also being from several sides in such a water pressure, that they seem to be quasi thrown up'. Furthermore they must show 'a high or deep contiguous peat stock';
2. "Grünlandsmoore" ('grassland peatlands'): peatlands 'that only have a shallow peat stock' and 'an elongated, mostly horizontal position';
3. "Feldvehnen" ('field peatlands'): 'generally found between mountains and hills, also around small lakes, largely approaching the shape of a kettle' with 'the peat being in the surrounding foreland only very shallow and in the direction of the centre deeper and deeper'.

Staring (1833) noted that "Secundum fundi positionem et fortasse plantarum constituentium discrima, turfinae distinguendae sunt in excelsioribus et humilioribus" ('According to the position of their basis, and perhaps according to their plant composition, peatlands have to be distinguished in higher ones and lower ones').

Staring (1856) described "laag veen" ('low peatland') as peatland 'of which the surface lies at the same height as the water table in the surroundings', whereas "hoog veen" (high peatland') is a peatland 'of which the subsoil is so highly elevated above the surrounding water, that no real water plants grow on it'.

Table 2.13: A classification of mire massif classifications.

Site/tope level	Chapter	Massif level	Chapter	Landscape/chore level
Water table in relation to peat formation		Water table in relation to peat formation	2.4.2	
Origin of the water		Origin of the water	2.4.3	
Acidity and base saturation of the soil		Acidity and base saturation of the soil	2.4.4	
Nutrient availability		Nutrient availability	2.4.5	
Physiognomy of the vegetation		Physiognomy of the vegetation	2.4.7	
Vegetation composition		Vegetation composition	2.4.6	
Vegetation as indicator of site conditions		Vegetation as indicator of site conditions	2.4.8	
Habitat type		Habitat type	2.4.9	
Surface peat		Surface peat	2.4.10	
Peat stratigraphy		Peat stratigraphy	2.4.10	
Peat accumulation and degradation		Active peat accumulation and degradation	2.4.11	
	2.6.2	Topographic (geomorphic)		Location
	2.6.3	Morphic/hydromorphic		Macrorelief, (arrangement of) microrelief elements, and ombro-/geotrophy
	2.6.4	Hydrogeomorphic		Macrorelief and water flow pattern
Water regime and peat formation strategy	2.6.5	Hydrogenetic		Water regime and peat formation strategy

At the beginning of the 20th century Weber (1903, 1907b, see Box 2.5) formalised the morphological distinction between:

- "Hochmoor, das eine aufwärts gewölbte Gestalt hat" ('high peatland, which has a upward domed shape'),
- "Flachmoor, ...dessen Oberfläche waagerecht oder etwas hohl ist" ('flat peatland, of which the surface is horizontal or somewhat concave') and
- „Mischmoor, …eine geographisch einheitliche Moorlandschaft, die sowohl Hoch- wie Flachmoor enthält" ('mixed peatland, …a geographically uniform peat-landscape that contains both high peatland and flat peatland').

Osvald (1925a) refined the morphological classification for European bogs by distinguishing "Waldhochmoor" ('forest raised bog'), "Eigentliches Hochmoor" ('typical raised bog'), "Flach-Hochmoor" ('flat raised bog'), and "Terrainbedeckendes Moor" ('terrain covering mire' = blanket bog). Sjörs (1948) introduced the terms 'concentric' and 'eccentric' referring to the arrangement of mire surface features. The recognition of such regular surface patterns was strongly enhanced by the development of aerial photography.

Gams & Ruoff (1929) were the first to use kite photography for identifying surface patterns. Impressive pictures of patterned mires were produced by the LZ 127 Graf Zeppelin airship on its 'Round-the-World' flight in August 1929 (Walter 1977). Major progress in peatland remote sensing was achieved by Galkina (1946) during the siege of Leningrad in the Second World War, when peatland pattern recognition was used to identify mire parts that were impassable (for enemy troops) or accessible (to supply the starving city).

A linkage between the shape of a 'raised bog' and water supply was first made by King (1685), who thought that raised bogs were fed by springs: "the chief springs that cause them being commonly about the middle, from whence they dilate themselves by degrees, as one would blow a bladder; but not always equally, because they sometimes meet with greater obstacles on one side, then on the other: whoever has seen Bogs, cannot doubt of this: and besides if you cut a deep trench thro' a Bog, you will find the original spring, & vast quantitys of water will run away, and the Bog subside".

Also Bansen (1754) linked the shape of the mire to the water it contained: 'with large and deep mires hanging full of water one finds … that in their centre they have a ridge or an elevation running along their length, and that they become lower everywhere along their margin or extreme parts. Without doubt this is because the water, as long as the peatland still lies "in heiler Haut" ('in pristine skin') as it is called, discharges at such outer parts, but in the centre remains standing as on an even plain and because the mire, which absorbs the moisture like a sponge, expands and strives for greater height.'

Dau (1823) was the first to link morphological peatland classification with the origin of the water. This understanding he revealed in a riddle on the first pages of his "Neues Handbuch über den Torf" ('New manual on peat'), in which he both described the macrorelief of what we would now call a 'raised bog' and the origin of its water (Fig. 2.8). This formed the start of hydromorphic mire classification.

Hydromorphic classification not only considers macrorelief and microrelief patterning of the peatland massif, but it also considers the origin of the water (the 'hydro-' part) as so important that it uses the degree of ombrotrophy as the prime variable of classification (cf. Du Rietz 1949, 1954, Chapter 2.4.3).

Whereas the degree of ombrotrophy is not always easy to observe (and even contested, see Chapter 2.4.3), hydromorphic mire classification has become very popular because the morphological patterns, which define most types and subtypes, can easily be recognised by surficial observation and remote sensing (e.g. Galkina 1946, Ruuhijärvi 1960, 1963, Aartolahti 1965, Moen et al. 2011a). Therefore, we follow this approach for defining mire regions in Chapter 4. Table 2.14 presents the hydromorphic mire types in a schematic way.

'Raised bogs' (also called 'domed bogs', Du Rietz 1950) are bog massifs with a distinct dome and a rotational or reflectional symmetry. The peat dome imposes itself over any underlying relief in the terrain. Raised bogs rise on all sides so that the domed part of the massif is out of reach of geogenous water influence. They show a typical series of microtopes going from the centre to the margin: a mire expanse (sometimes with larger open water bodies), areas with hummocks/strings and hollows, a steeper sloping rand (often forested), and a geotrophic lagg.

Already Grisebach (1846) recognised the origin of the cupola shape of raised bogs: 'if the mire is in its original, natural condition, water flow faces a twofold impediment: downward in the impenetrability of the peat, sideward in the vegetation cover, which is formed by compact, gregariously growing heath shrubs that only allow a slow run-off at the surface that is thus furthermore restricted by evaporation. These impediments work to a much lesser degree at the margin of the mire. Here shallow peat layers sit over barely sloping depressions in the sandy soil; here outflow is open laterally as well as downward, as long as the underlayer does not consist of clay but of sand. In this way the peripheral lowering of raised bogs appears as the simple effect of the facilitated run-off: it is the lower level of the water in which peat formation takes place.'

Raised bogs are subdivided into

- 'Typical raised bogs' (see Photo 62) with a more or less open expanse, a marginal forest, and a clear lagg; and
- 'Oceanic raised bogs' with a less well-developed margin and lagg.

Typical raised bogs and their distribution are described by e.g. Blytt (1883), Weber (1902), Holmsen (1922), Granlund (1932), Sjörs (1948), Kulczyński (1949), Ruuhijärvi (1960), Eurola (1962), Aartolahti (1965, incl. several profiles), Aletsee (1967), Overbeck (1975), Dierssen (1982), and Masing (1984).

Although the definitions of the types are clear, it is often difficult to ascribe a particular mire to a specific type or subtype. Large-scale aerial (stereo) photos can be very useful and have been much used over the past decades (e.g. by Galkina 1967, Galkina & Kiryushkin 1969, Kiryushkin 1980, Moen et al. 2011a, Lyngstad & Vold 2015). Next to well developed, typical examples, also mires that are transitional between types and subtypes are widespread. Local differences in geological, topographical, and hydrological conditions determine how a particular mire will develop and may to some extent obscure regional, climate-induced features. It is often impossible to ascribe drained mires to a distinct type without in-depth studies.

Box 2.5: C.A. Weber and mire classication definitions

Carl Albert Weber (1856–1931) was probably the most influential European mire scientist of the 20th century because of his pioneering, integrative scientific studies and the clarity of his concepts (Couwenberg 2002, Glaser 2002, Sirin & Minaeva 2002). His definitions of mire types have become standard in many countries of Europe. However, his definitions varied over time and in different contexts. And in fact his most cited work in this respect (Weber 1902) does not contain definitions of 'bog', 'fen' or 'transitional mire' at all…

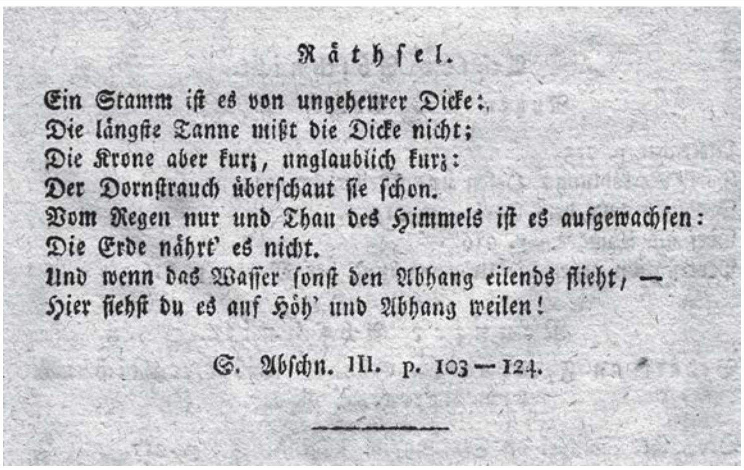
In his 1900 publication, Weber used a clearly morphological concept: '"Hochmoore" derive their name from their shape. They rise above their surroundings, arching roughly "like a watchglass". In contrast, "Niederungsmoore" ('depression or lowland mires') 'derive their name from their occurrence: they are bound to depressions, be it kettle-like basins of the heights, where water converges at least temporarily, or the shores of lakes, ponds, and river valleys.' 'The surface of "Niederungsmoore" is always flat (which is why they are also called "Flachmoore" ('flat mires')) and either horizontal, or inclined towards the centre of the depression.'

In contrast, in 1903 Weber used a geological/pedological concept when he defined a "Hochmoor" as 'a mire which directly underneath the cover of raw humus or litter shows a layer of *Sphagnum* peat of at least 20 cm thick (when drained), or in which the uppermost 20 cm consist of *Sphagnum* peat or its more or less 'moder'-like decomposition products'. A fen he described as 'a mire that – in drained state – is covered by a layer of at least 20 cm of alder peat (wood peat), sedge peat, reed peat, or gyttja'. A transitional mire he described 'a mire, that – in drained state – is covered by at least 20 cm of birch peat, pine peat, *Scheuchzeria-Hypnum* peat'.

His 1905 publication followed the 1903 definitions but added that '"Hochmoore" owe their name to their shape. In contrast to fens, their central parts are laying higher than their margins'. With respect to fens he noted that it would be linguistically more correct to call them "Niedermoore" ('low mires') instead of "Niederungsmoore". With respect to their peats he added that they must 'have been formed in contact with nutrient rich water', and 'in most North-German fens will be reed peat, sedge peat, or swamp forest peat'. With respect to transitional mires, he added that they should contain 'such peat types, which immediately precede *Sphagnum* peat formation. This can be […] cottongrass peat, or pine or birch forest peat'.

Later, Weber (1907a) grouped fens and transitional mires together into "Flachmoore" ('flat mires') because 'their usual surface shape' (at least before drainage) 'is gently inclined towards the centre of the basin' or (in case of transitional mires) could also be horizontal, whereas that of bogs was 'gently sloping upward'. "Hochmoore" were furthermore defined as having 'in a drained state a layer of oligotrophic peat of at least 20 cm thick', fens a similar layer of 'eutrophic peat', and transitional mires of 'mesotrophic peat'. Weber (1907b) further specified that 'our peat' consists 'mostly of *Sphagnum* peat, sometimes with cottongrass peat from *Eriophorum vaginatum* or with heath moder, e.g. from *Calluna vulgaris*' in case of bogs, of 'nutrient rich, ash poor gyttjas, swamp peat types, and swamp forest peat' in case of fens, and of 'birch peat, pine peat, *Scheuchzeria-Hypnum* peat, *Carex rostrata-Sphagnum* peat, or *Polytrichum* peat (from *P. commune*, *P. juniperinum* or *P. strictum*)' in case of transitional mires.

Finally in 1930, Weber remarked: 'The often used term "Niederungsmoore" ('lowland mires') is misleading. The mires of the Northwest-German lowlands are largely bogs. […] Similarly wrong is the term "Flachmoor"; flat and high are no opposites.'


Räthsel.

Ein Stamm ist es von ungeheurer Dicke:,
Die längste Tanne mißt die Dicke nicht;
Die Krone aber kurz, unglaublich kurz:
Der Dornstrauch überschaut sie schon.
Vom Regen nur und Thau des Himmels ist es aufgewachsen:
Die Erde nährt' es nicht.
Und wenn das Wasser sonst den Abhang eilends flieht, —
Hier siehst du es auf Höh' und Abhang weilen!

S. Abschn. III. p. 103—124.

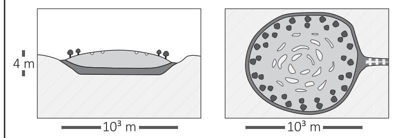
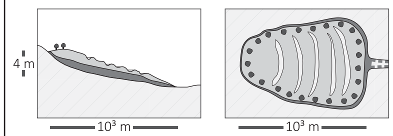
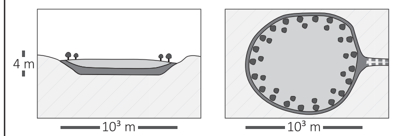
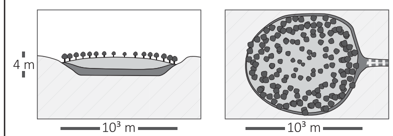
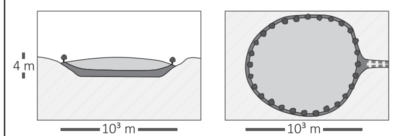
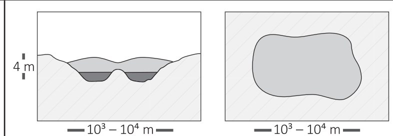
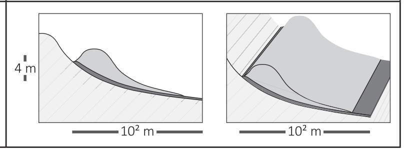
Riddle.

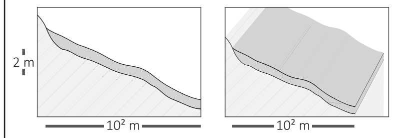
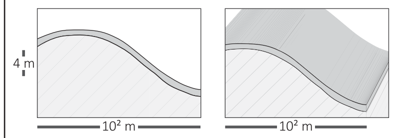
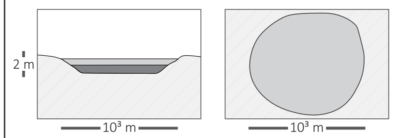
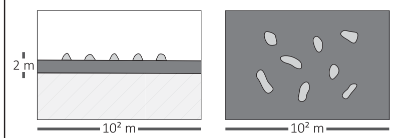
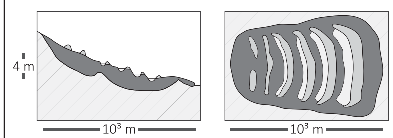
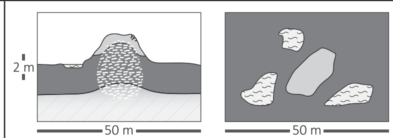
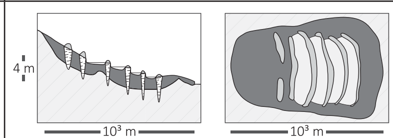
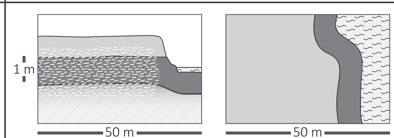
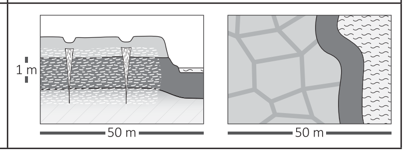
A trunk it is of awe-inspiring thickness:
The longest fir does not reach this width;
The crown however short beyond belief:
The thornbush can see over it.
Of merely rain and dew of heaven has it grown:
It is not fed from Earth.
And where the water usually hurries down, –
Here you see it linger both on top and slope!

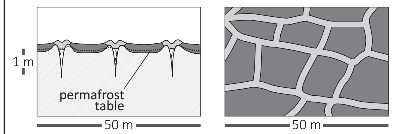
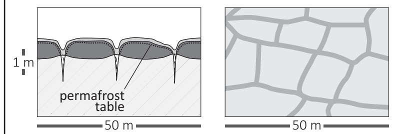
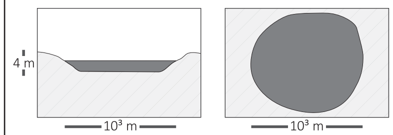
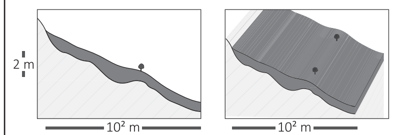
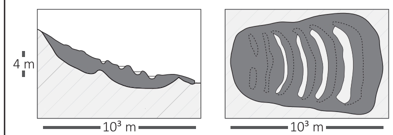
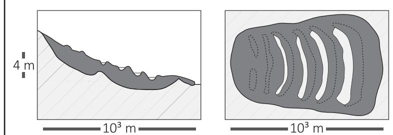
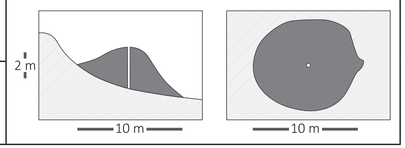
See par. III. p. 103–124.

Fig. 2.8: The riddle with which Dau (1823) opened his book and which marked the start to systematic hydromorphic mire classification.

Table 2.14: Characteristics of hydromorphic mire massif types (after Moen 1973, 1999, Rydin et al. 1999). Dark grey=fen, light grey=bog/hummock, white=hollows (incl. open water), horizontally striped=permafrost (but ice wedges vertically striped), dark circles=trees.

Degree of ombrotrophy of the massif	Group	Subgroup	Massif (mesotope)	Site (microtope)	Feature (nanotope)	Name of mire type	Scheme
Bog: >80% ombrotrophic	**Raised**: distinctly raised over surroundings	**Typical**: With marginal forest and lagg	Completely domed	Open expanse, mire margin, lagg	Expanse with concentric arrangement of features	**Concentric raised bog**	
			Flattened dome, reflectional symmetry		Expanse with eccentric arrangement of features sloping into one direction	**Eccentric raised bog**	
			Flat expanse		Expanse without regular arrangement of features	**Plateau raised bog**	
			Little raised	Indistinct separation between expanse, margin and lagg	Expanse covered by trees	**Wooded raised bog**	
		Oceanic: No marginal forest, lagg incomplete	Completely domed	Open expanse, ± shrubby margin	No surface patterning in expanse	**Percolation raised bog**	
			Fully open complex of amalgated domed massifs, without distinct borders in between	No clear differentiation in expanse, rand, and lagg	Expanse with hummock/hollows, partly regular features, may include pools/secondary lakes	**Atlantic raised bog**	
			Steeply domed	Relatively wide rand; narrow lagg along mineral ridge	Small expanse with irregular hummocks and hollows	**Rim raised bog**	

Degree of ombrotrophy of the massif	Group	Subgroup	Massif (mesotope)	Site (microtope)	Feature (nanotope)	Name of mire type	Scheme
Bog: >80% ombrotrophic	**Non-raised**: not distinctly raised over the surroundings	**Blanket**: covers undulating mineral subsoil like a blanket	With a distinct slope (>3°)		Erosion channels in direction of slope	**Sloping blanket bog**	
			With distinct mound		Erosion channels	**Mound blanket bog**	
		Plane	Weakly sloping or flat, mostly small with thin peat	No differentation in sites	Indistinct features, with local geotrophic influences	**Plane bog**	
Mixed mire: 20-80% ombrotrophic	**Islet**		Flat	No differentation in sites	Single ombrotrophic hummocks in geotrophic matrix	**Islet mixed mire**	
	High string-flark		Sloping	Partly ombrotrophic strings and mud-bottom/carpet flarks		**String-flark mixed mire**	
	Palsa: with local permafrost	With permafrost in mounds	Flat	Individual mounds in fen matrix		**Domed palsa mire**	
		With permafrost in strings	Sloping	Permafrost underlain strings alternating with unfrozen flarks		**Ribbed palsa mire**	
		With permafrost in plateaus	Flat	Without polygonal surface structure		**(Typical) flat palsa mire**	
			Flat	With irregular polygonal surface structure		**Polygonal flat palsa mire**	

Degree of ombrotrophy of the massif	Group	Subgroup	Massif (mesotope)	Site (microtope)	Feature (nanotope)	Name of mire type	Scheme
Mixed mire: 20-80% ombrotrophic	**Polygon**: with contiguous permafrost	With polygon centres lower than ice wedge ridges	Flat	Low centres surrounded by higher ice wedge ridges		**Low centre polygon mire**	
		With polygon centres higher than ice wedge troughs	Flat	High centres surrounded by lower ice wedge collapse troughs		**High centre polygon mire**	
Fen: <20% ombrotrophic	**Flat**: with <3° slope, no regular surface pattern		Flat or gently sloping	No regular microrelief differentiation		**Flat fen**	
	Sloping: with >3° slope, no regular surface pattern		Steeply (>6°) or very steeply (>12°) sloping	No regular microrelief differentation		**Sloping fen**	
	String-flark: with strings and flarks	With low strings	Gently sloping	Low strings and rather dry (high carpet or wet lawn) flarks		**Low string-flark fen**	
		With higher strings	Gently sloping		High lawn/low hummock strings and carpet flarks	**Medium string-flark fen**	
	Spring: with dome and artesian water discharge	With varying flux, temperature, and chemical composition of the water throughout the year				**Astatic spring fen**	
		with constant flux, temperature and chemical composition of the water throughout the year				**Eustatic spring fen**	

Typical raised bogs are subdivided into

- 'Concentric raised bogs' with the highest point near the centre of the massif and the pattern of mire micro- and elongated nanotopes (hummocks/ridges and hollows/pools) arranged concentrically around the highest point of the bog;
- 'Eccentric raised bogs' with the highest point and the 'midpoint' of the semi-circular pattern lying eccentrically, i.e. away from the centre of the massif or even outside of the bog. Massifs can also be divergent (fan-shaped), or ridge- or saddle-shaped. Eccentric raised bogs are often less raised and have a thinner peat layer than the other raised bog subtypes. In addition to the geotrophic lagg between the mineral soil and the bog massif, groups of eccentric raised bog massifs can occur that are separated by geotrophic soaks. Transitions to plateau bogs are common;
- 'Plateau bogs' with a raised flat expanse ('plateau'), a marginal forest, and a lagg. The features on the open mire expanse lack a regular pattern;
- 'Wooded bogs' with an only slightly raised mound and the expanse covered by trees. The separation between mire expanse and marginal forest is gradual, and also the lagg is most often indistinct. Wooded bogs occur in areas with smaller precipitation surplus than the former subtypes.

Oceanic raised bogs are subdivided in

- 'Percolation bogs' (Photo 39) with a domed, open, and featureless, monotonous expanse dominated by *Sphagnum*. Percolation bogs are only known from Kolkheti (western Georgia; Haberl et al. 2006, Kaffke 2008, Chapter 4.8.4, Chapter Georgia);
- 'Rim raised bogs' (Photo 73) with a narrowly elongated steep dome, which is on one side separated from a steeply sloping mineral hill by a marked narrow lagg and on the other side often transitions into a larger mire massif like a sloping fen. The steep slope is covered by bog margin vegetation, whereas the small open, elongated centre (where the peat is 3–5 m thick) is covered by an irregular mosaic of hummock and lawn communities. Downslope of the elongated centre the mire commonly shows mud-bottom areas and erosion. Transitions to eccentric bog, plane bog, and blanket bog occur. Rim raised bogs are described in Moen (1970, 1983), Hildebrandt (2008), Moen et al. 2011b, and Chapter Norway. Sjörs (1946) describes small, upper boreal raised bogs from Jämtland with a strong affinity to the rim raised bog.

  This type was earlier described under the name 'ridge raised bog' (Moen 1970, 1983; Hildebrandt 2008), but we rename it to avoid confusion. Kulczyński (1949) already described a continental "ridge raised bog" for Polesia of which the steep convexity is "connected with the relief of the bog's substratum, and not with the convexity of the bog's cupola itself" and whose laggs "are developed to an enormous degree", but "not developed everywhere". Because of its "mantle-like spreading on the water-parting ridge" his ridge raised bog "resembles to a certain degree H. Osvald's 'terrainbedeckenden Hochmooren' ['blanket bogs']", but differs "fundamentally in all other respect, approaching closest, on account of its floristic and biological features, continental raised bogs", because of the "uniform pine growth on the wide expanses […] and the dense covering of the bog with hummocks". Moore & Bellamy (1974) – referring to Kulczyński (1949) – described oceanic 'ridge raised mires' as intermediate between domed bogs and blanket mires and show a profile (their Fig. 3.3) resembling that of the 'rim raised bog' described above. In their description of 'ridge raised complexes' in central Ireland, however, they show a profile (their Fig. 2.11) that rather reflects an 'atlantic raised bog' (see below). Goodwillie (1980) then equaled 'ridge raised mire' to 'oceanic raised mire'; and Lindsay (1995) described his 'ridge raised bog' (or 'intermediate bog' or 'semi-confined raised bog') as 'part of the continuum from lowland raised bog to blanket bog, but […] not sufficiently distinct in its own right to merit a separate category of bog'.

- 'Atlantic raised bogs' (Photo 17) lack a marginal forest and often also a typical lagg. Their (rather flat) domes often coalesce with other domes to form a bog complex in which the boundaries of the separate domes are difficult to determine (Osvald 1925b, 1949, Casparie 1972). Such unconfined, often huge bog complexes are common for this type. Consequently, they are sometimes difficult to distinguish from blanket bogs, with which they can co-occur. Transitional forms to other types of raised bogs (e.g. plateau bogs) are locally common.

  Atlantic raised bogs have been described by Osvald (1949) who suggested the names 'bare raised moss', 'naked raised moss', or 'treeless raised bog', Aletsee (1967, naming them 'Plan-Hochmoore'), Overbeck (1975), Aaby (1987), and Succow & Joosten (2001, naming them 'Planregenmoore').
  The Bourtangermoor (c. 3,000 km^2) on the border of the Netherlands and Germany must have been the largest contiguous raised bog complex of mainland Europe (Grootjans et al. 2015) and was described by Grisebach (1846) as follows: 'On the border between Hannover and Holland, between Hesepertwist and Ruetenbrock, I have, while traversing the pathless peatland of Boertange, visited a point where, like on open sea, the flat ground is at the horizon enclosed by a perfect circle and no tree, no shrub, no hut, no object as large as a child could be distinguished on the seemingly infinite solitude. The highest objects, the trees of Hesepertwist, would indeed have remained visible on a completely horizontal plain: this is, however, not the case, because, as I will explicate below, the Bourtangermoor has to be considered as a convex body with a stronger curvature than the surface of the sea.'

'Non-raised bogs' are either weakly sloping (also in different directions, like saddle-shaped bogs) or flat. They are subdivided into 'blanket bogs' and 'plane bogs'.

- 'Blanket bogs' (Photo 94) cover the underlying often undulating mineral subsoil like a blanket. When blanket bogs include areas with a distinct mound in the topography or areas with a distinct slope (>3°), these areas are often separately distinguished as 'mound blanket bogs' and 'sloping blanket bogs', respectively. If the blanket bog massifs are close to flat, they are difficult to separate from plateau bogs and plane bogs. Blanket bogs have often established as a result of human activities like land clearing, burning, and livestock grazing (Moore 1975, 1993, Kaland 1986, Solem 1989). Blanket bogs often occur in mosaic with heathlands (like the British 'moors') and other mire massif types. Smaller minerotrophic fen areas may occur inside blanket bog complexes, for example in soaks and erosion channels.

The first known explicit reference to a blanket bog is by Young (1780) who was travelling from Boyle to Ballymote (Co. Sligo, Ireland) and "Crossed an immense mountainy bog, where I stopped and made enquiries. Found that it was ten miles long and three and a half over, containing thirty-five square miles; … What an immense field of improvement! nothing would be easier than to drain it, vast tracts of land have such a fall, that not a drop of water could remain. These hilly bogs are extremely different from any I have seen in England. In the moors in the north, the hills and mountains are all covered with heath, like the Irish bogs, but they are of various soils, gravel, shingle, moor, etc. and boggy only in spots, but the Irish bog hills are all pure bog to a great depth, without the least variation of soil, and a bog being of a hilly form is a proof that it is a growing vegetable mass and not owing merely to stagnant water." Shortly after, Anderson (1794) described that "Most of the hills on the west coast of Scotland, and the islands of the Hebrides, have their surface entirely covered with moss".

The concept blanket bog is used differently in literature (Joosten et al. 2016b). In Britain and Ireland the term is often used for mire complexes or even for a landscape type, which also may include sloping fens, flat fens, and other types of minerotrophic mires. Whereas the definition refers to ombrotrophic mire, the practical delineation is often wider. Another problem is that the division between ombrotrophic and geotrophic (Sjörs 1948, Du Rietz 1954) is not accepted among all mire scientists as the main ecological criterion for classification (see for example Wheeler & Proctor 2000 and the rebuttal by Økland et al. 2001). As a result, many scientists use the term 'blanket mire' and include geotrophic mires (e.g. sloping fen) in their 'blanket' concept. Here we use 'blanket bog' solely for mire massifs that are dominated by ombrotrophic vegetation (see Joosten et al. 2016b).

Bohn et al. (2000–2004) distinguished three types of blanket bogs (types S5–S7), mainly based on differences in plant cover: two lowland types in Ireland and Britain, and one upland/montane type with a wider distribution.

Blanket bogs may be divided into many subtypes related to form, hydrology, surface features, slope, etc. For example, Lindsay (1995) differentiates for Britain between watershed mire, valleyside mire, spur mire, and saddle mire. In Norway Moen et al. (2011a) separate between two topography based subtypes: mound blanket bog (which covers a mineral hill) and sloping blanket bog (on slopes >3°).

- 'Plane bogs' (Photo 70) are bogs that are not distinctly domed: they are only weakly sloping or flat. They often include small geotrophic areas. Plane bogs are young ombrotrophic mire massifs (meaning all bogs have gone through a stage of plane bog) or occur in areas where peat accumulation is very slow, like in upland (including alpine) areas. The plane bog is thus a heterogeneous mire type.

'Mixed mires' show both ombrotrophic and geotrophic features (nanotopes) in one massif (mesotope). In an advanced phase of development also polygon and palsa mires often contain ombrotrophic elements, and so we include them in the mixed mire group, which then encompasses:

- 'Islet mixed mires' with roundish ombrotrophic nanotopes situated as islands in a geotrophic matrix; transitional to palsa if an ice core is present;
- 'String-flark mixed mires' with partly ombrotrophic, *Sphagnum fuscum*-dominated strings arranged perpendicularly to the water flow. The strings have an ice core during most of the year and are transitional to palsas. The flarks have a mud-bottom or carpet vegetation, often including areas with open water;
- 'Palsa mires' (Box 2.6) with mounds or ridges of peat with ice lenses, which remain frozen throughout the year, subdivided into
  - 'Domed palsa mires': cupola-shaped elevations with a perennial ice (permafrost) core in a mosaic with wet fen areas (Photo 76);
  - 'Ribbed palsa mires', which have developed by permafrost formation in the strings of string-flark mires, with string-flark mixed mires mentioned above as a transitional stage (Vorren 1979a);
  - 'Flat palsas' (also called 'low palsas', 'permafrost plateaus', or 'peat plateau mires') in which the permafrost is not localised but extends over a larger area. Flat palsas are subdivided into
    - 'Typical flat palsas' without polygonal surface patterning;
    - 'Polygonal flat palsas' with polygonal surface patterning as a result of secondary ice wedge formation after the establishment of permafrost. The permafrost itself is induced by peat and vegetation lowering the heat conductivity of the soil (Shur & Jorgenson 2007). The polygonal structure is usually more irregular than that of 'polygon mires', see below).
- 'Polygon mires' (or 'frost crack mires'), which are characterised by a polygonal arrangement of their vegetation and peat deposits.

The distinct polygonal pattern originates under permafrost conditions when rapidly falling temperatures in winter lead to the formation of cracks in the shrinking, permanently frozen soil. Similar to drying clay, these cracks form a polygonal pattern. In spring, water from melting snow trickles into the open cracks, refreezes, and forms ice-veins. Because they are the weakest spots in the permafrost body, these veins of pure ice are the preferential zones for subsequent cracking in following winters. In the course of time the veins thus become wider. In summer the ice veins obstruct the warming and expanding soil, which is then pushed up against the ice wedges, creating 'rims' (or 'shoulders') that enclose depressions, together forming low-centred ice-wedge polygons. Peat formation is favoured by surface water that is trapped during the short arctic summer when the shallow permafrost prevents subterranean drainage, and by the slow decay of organic material in the cold climate (P'yavchenko 1955, Zoltai & Tarnocai 1975, Washburn 1979, Billings & Peterson 1980, Botch & Masing 1983, Chernov & Matveyeva 1997, Mackay 2000, Minke et al. 2007, de Klerk et al. 2011, Gao & Couwenberg 2015). Depending on the inclination of the land the polygon shape may vary from strictly rectangular (in case of a gentle slope), via pentagonal or hexangular to almost circular (in case of a completely horizontal surface), whereas the size of the polygons (10–30 m) is further determined by the nature of the substrate and the intensity of the abrupt cooling (Lachenbruch 1962).

Polygon mires are subdivided into
– 'Low centre polygon mires', characterised by elevated and elongated ombrotrophic nanotopes ordered in a polygonal pattern that enclose geotrophic depressions (Photo 96);
– 'High centre polygon mires', which show the opposite pattern (drier, more ombrotrophic centres surrounded by elongated geotrophic depressions in a polygonal pattern).

'Low centre polygon mires' are the classical and most common polygon peatlands. They constitute an early development stage. The ridges of the polygon may expand inwards through segregation ice development and eventually fill the entire central depression. Under not entirely understood conditions, the ice wedges may (partly) melt causing the ridges to collapse, forming trenches surrounding the polygon centre: the relief inverts and 'high centre polygons' originate (Billings & Peterson 1980). High centre polygon peatlands are an advanced stage of polygon mire development and are actually erosional phenomena: drainage improves through the interconnected trenches, the surface dries out, shrubs expand, peat accumulation stops, and the peat is decomposed or eroded by wind (Zoltai & Pollett 1983).

The group of mixed mires thus encompasses mire massifs of various origins including:
- Transient mires where a fen changes into a bog;
- Mires in a subcontinental setting where *Sphagnum* hummocks establish on a small scale because of the development of rainwater lenses in the fen peat. After their establishment the hummocks enlarge the rainwater lense, which facilitates their long-term persistence;
- Fens in which strings and flarks develop and where the higher strings develop an oligotrophic acid (ombrotrophic?) character (like in string-flark mixed mires);
- Horizontal and sloping mires where – as a result of irregular snow cover or differences in vegetation – permafrost starts to develop that locally raises the surface initiating a positive feedback in which ice core growth stimulates height growth and the establishment/expansion of drier, more oligotrophic vegetation (*Sphagnum*, lichens) that provide better summer insulation, resulting in colder temperatures and subsequent ice core growth, etc. (e.g. palsa mires);
- Polygon mires, which originate in continuous permafrost when ice wedge formation and thermal permafrost expansion create a polygonal pattern of elevated ombrotrophic 'shoulders' that enclose geotrophic depressions.

Fens include a heterogeneous group of morphic and hydrological mire types with the common property that >80% of the area is geotrophic. Polygon and palsa mires are described as 'mixed mires' above, although the geotrophic part of these mires is often >80%.

'Fens' are subdivided into:
- 'Flat fens' (with a slope <3°);
- 'Sloping fens' (with a slope >3°);
- 'String-flark fens'; and
- 'Spring fens'.

Hydromorphic classification does not further subdivide 'flat fens' but further separation may follow the hydrogenetic differentiation in terrestrialisation mires, water rise mires, floodwater mires, and percolation mires (Chapter 2.6.5). Kettlehole fens and wooded fens may also be included in the wide concept of 'flat fens'.

Sloping fens (Photo 74) strongly depend on climate (Havas 1961). In a climate with a humid summer and a long-lasting snow cover there is only a short period of drying out during the growing season. Melting snow provides flowing water and a high groundwater table in spring/early summer, which leads to a dominance of graminoids.

The typical sloping fen consists of graminoid lawn communities with a dense moss layer and some herbs. The dominant and typical species are largely the same all over Europe and include *Carex echinata*, *C. nigra*, *C. rostrata*, *Eriophorum angustifolium*, *Molinia caerulea*, and *Scirpus cespitosus* ssp. *cespitosus*. Also rich sloping fens in southern Europe share a large majority of species with fens in the North (Jiménez-Alfaro et al. 2014; Chapter 4.3). In the bottom layer these rich fens are dominated by brownmosses (e.g. *Campylium stellatum*, *Drepanocladus aduncus,* and *Scorpidium* spp.). Sloping fens with species poor vegetation are dominated by peatmosses (*Sphagnum* spp.).

Sloping fens typically form strips on slopes and – in many boreal and alpine areas – join string-flark and flat fens in the valleys. Sloping fens are described e.g. by Booberg (1930), Sjörs (1948), Persson (1961, 1962), Nordhagen (1928, 1943), Dierssen (1982), Moen (1990), and Moen et al. (2012).

Auer (1922) gives a detailed description of the hydrology, hydromorphology, peat type, and vegetation of sloping fens in Finland. Von Post & Granlund (1926) and Granlund (1932) include sloping fens in their 'soligenous' mires. Sjörs (1946) found sloping fens (backmyr) to be the dominant mire type in Jämtland, where fens occur with an inclination of more than 20°. Havas (1961) presents a detailed overview of the literature concerning sloping fens ("Hangmoore") in Finland and Europe. He and Persson (1961, 1962) provide detailed descriptions of the vegetation and ecology of sloping fens in eastern Finland and northernmost Sweden, respectively.

The definition of sloping fen varies per country. In Sweden a minimum slope of 2° is used. If the slopes is steeper than 5° the fens are called 'strongly sloping' (Gunnarsson & Löfroth 2014). The mire protection plan of Norway uses 3° and 8°, respectively (with a minimum area of 0.1 ha) and calls fens with slopes steeper than 15° 'very strongly sloping' (Moen 1983). In Finland, sloping fens do not exceed 8° of inclination (Havas 1961) and are called 'aapa fens' (Eurola et al. 1984).

'Dwarf shrub sloping fens' (also called 'smooth grass-fens') are found in areas where water supply from snow melt and run-off is only small. Consequently, the fen slopes carry plant communities with *Calluna vulgaris* and other (dwarf) shrubs next to minerotrophic species. In highly oceanic areas, like Ireland, Great Britain, and West-Norway, sloping fens of this type (called 'Feuchtheiden' by Dierssen 1982) are common and can be transitional to blanket bog, with which they share more or less the same geographic distribution. In Ireland and Great Britain, dwarf shrub sloping fens are generally included in the blanket bog concept and literature generally does not recognise sloping fen as an own mire type. In Finland, dwarf shrub sloping fens are excluded from the aapa mire concept.

'String-flark fens' (Photo 100) are fens with a regular alternation of elongated, dry ridges (strings) and linear, wet, geotrophic depressions (flarks). The features are oriented perpendicular to the slope of the fen. The string-flark fens are subdivided into:

Box 2.6: Palsas

Palsa mires were first described by Kihlman (1889, 1890) from Kola Peninsula: 'Across a large part of the peninsula (Kola) one finds enormous peat mounds of a rounded, oblong or irregularly lobed shape. Their height varies considerably. It may reach 3–3.5 sometimes 4 m, but shows all gradations down to still growing bog hummocks. In horizontal direction their dimensions are just as varied and increase from a few meters wide, rounded surfaces, or spine-shaped ridges to long, 20–30 paces wide plateaux. Often two or more mounds are connected by narrow, bridge-shaped constructions. The interspaces are partly occupied by deep, usually wet but sometimes very dry gullies, and partly by smaller or larger pools. These pools differ much in water level and are mostly filled with black mud earth to within a few inches from the water surface. A loose carpet of water-loving Sphagna (*S. lindbergii* […]) interspersed with sedges stretches along the pond edge and often covers the entire water surface. The surface of the mounds is flattened and without exception adjacent hills all are approximately in the same horizontal plane. The surface is almost always furrowed and wrinkled by irregular 1–2 dm deep irregularities. There are large spots of bare *Sphagnum* peat, whereas the surface is otherwise covered by a cracked, brittle crust of lichens, punctured by sparse brushwood only. The steeply sloping or inclined sides, however, are covered by sturdy dwarf shrubs (at the top *Ledum* and *Empetrum*, at the bottom primarily *Betula nana*), between which cloudberry reaches an elsewhere rarely observed size; also the fruticose lichen (*Cladonia*, *Platismatia*, and *Alectoria* species) often achieve a lush growth. The ensemble forms a miniature hilly landscape, where a pedestrian may move through winding valleys without being seen from the sides' (Kihlman 1890).

Other important descriptions of palsa mires are presented by Regel (1941), Ruuhijärvi (1960), Lundqvist (1962), Sonesson (1970a,b), Vorren (1979b), Dierssen (1982), and Yurkovskaya (1992). P'yavchenko (1955) devoted an entire monograph to them, and recently Seppälä (2011) reviewed the state-of-the-art knowledge.

Palsas are mounds of peat with a permafrost core, occurring within a non-permafrost wetland. Under the right climatic conditions such a permafrost core establishes in a wet mire when the winter freezing front penetrates faster in a specific spot than in the surrounding area. If the cover of snow is unusually thin, for example, the related lack of thermal insulation that thick snow would provide permits much deeper freezing in winter. Alternatively, a patch of vegetation (e.g. *Sphagnum*) may establish that has better insulating properties when dry in summer than when wet/frozen in winter. Consequently, more cold penetrates the soil in winter than can escape in summer. As ice occupies more space than water and attracts additional water (forming 'segregation ice'), the ice core expands and pushes up the surface. In summer, the elevated vegetation and peat dries out more and like a blanket provides better thermal insulation to the ice core below. In winter, insulating snow is blown off the exposed top so that even more cold penetrates and the permafrost core expands in a positive feedback loop that results in further uplift of the peat and also of the mineral soil when the ice frond expands downwards. The permafrost core commonly contains lenses of pure ice of 2–3 cm thick, although lenses of almost 40 cm thick have been described as well.

The lower, wet mire parts between the ice core mounds do not develop permafrost. Compared with the higher and drier hummocks they accumulate more heat in summer that is stored better, because of the large specific heat capacity of water compared with ice, wood, or air. Palsa mires can exist as single mounds or as groups of mounds within a landscape depression. Palsa mounds deteriorate when their insulating 'skin' cracks by dome expansion (dilation cracking), frost cracking, or desiccation, causing the ice core to become exposed to the warm summer air. Palsas may also collapse when the surrounding wetland becomes more deeply flooded as a result of their own weight depressing the adjacent peatland surface; the open water warms up more strongly attacking the ice core 'from below'. After a palsa has collapsed, all that is left is usually a depression surrounded by a rim. Palsas in various stages of growth and decay occur together and their collapse is not necessarily an indication for climatic change.

Depending on the water regime, palsas may develop various shapes and forms of which a wide range has been described (e.g. Åhman 1977, Åkerman 1982). Heights range from less than 1 m to 10 m above the surrounding area (Kats 1971). Large forms tend to be considerably less conical than small ones.

Elongated 'ribbed palsas' may develop from the elevated (ombrotrophic, *Sphagnum* covered) strings of string-flark mires. When the initial ice core expands not only vertically but also horizontally, 'flat palsas' develop in which the permafrost covers a larger area. Extensive flat palsas with their elevated expanse of ombrotrophic vegetation resemble raised bogs (and may include scattered hollows, hummock-hollow, and ridge-hollow complexes on the slopes, with their geotrophic margins looking like laggs, cf. P'yavchenko 1955, Kiryushkin 1966, Yurkovskaya 1977), but differ from raised bogs by the underlying permafrost.

Flat palsas may also become subject to ice-cracking and the formation of ice wedges (see polygon mires above) if temperatures drop sufficiently rapidly in winter. In this way 'polygonal flat palsas' originate. The polygonal structure of polygonal flat palsas develops only secondarily after permafrost has established in a sufficiently thick insulating peat layer. These polygons thus only occur in the zone of discontinuous permafrost where peatlands with their insulating peat and vegetation facilitate permafrost formation. In contrast, the polygonal structure of 'real' polygon mires has its origin in ice wedge formation in the mineral subsoil in the zone of continuous permafrost (although also here a shallow peat layer may have facilitated initial permafrost and ice wedge formation in an emerging talik, cf. de Klerk et al. 2011, Gao & Couwenberg 2015). The different origin of the two polygonal mire types is not sufficiently recognised (Minke et al. 2007) and in practice both types are often lumped. The structure of polygonal flat palsas is often more irregular; its sides are less straight than in polygon mires sensu stricto, because the ice wedges developed in peat, which is structurally and thermically different and more diverse than clastic sediments. We think that at least part of the 'polygon mires' described for the northeasternmost part of mainland Europe (Chapter 4.7) are polygonal flat palsas.

The vegetation of palsas is most closely related to high hummock vegetation of the alliance Oxycocco-Empetrion hermaphroditi (Vorren 1979b, Dierssen 1982). Palsas are characterised by microaltitudinal vegetation belts: the top of a mound is either composed of crumbly bare peat or covered by lichens, some mosses, and very few, low-flowering plants (e.g. *Vaccinium vitis-idaea*, *Empetrum nigrum*, *Andromeda polifolia*, *Rubus chamaemorus*). The upper slopes are covered by lichens, green mosses, and short *Ledum palustre* and *Rubus chamaemorus*; the lower slopes by *Sphagnum* mosses and dense *Betula nana*. The hollows are occupied by *Carex*-*Eriophorum* communities with *Sphagnum* or brownmosses.

According to radiocarbon datings from Finland, most palsas are less than 1,000 years old (Seppälä 2006), and the oldest reported is c. 2,500 years. The age of palsas in Russia is estimated at 2,500–3,000 years, and bottom layers may date back some 8,000 years (Chapter Russian Federation). Some small palsas in northern Finland are only a few years old and established after cold winters. Low temperatures together with low precipitation and thin snow cover are the most important factors for such palsa formation.

- 'Low string-flark fens' with low lawn strings and mostly rather dry flarks (high carpet or wet lawn). The low string-flark fens can be transitional to sloping fens. Sjörs (1946) uses the term "sloping fen with flarks" for this less marked type, which is also called 'flark fen';
- 'Medium string-flark fens' with high lawn/low hummock strings, which are mainly geotrophic, and carpet flarks.

String-flark fens (and mixed mires) are often named 'aapa mire' in literature (e.g. Cajander 1913, Auer 1920, Ruuhijärvi 1960, Eurola 1962, Overbeck 1975, Bohn et al. 2000–2004, Ellenberg & Leuschner 2010). However, the Finnish (original Saami, see Chapter 3) term 'aapa' is used in Finland and by Finnish authors to include also other mire massif types besides string-flark mires (see Lindholm 2015). String-flark mires develop in various types of depressions (from small narrow valleys in tectonic faults to wide basins on moraines) after terrestrialisation of shallow post-glacial lakes or paludification of damp depressions. On lateral cross section they have a concave surface, which makes water collect in their central parts. Moreover, they have a considerable longitudinal slope and the resulting water flow causes the conspicuous ridge and hollow features to develop perpendicular to this slope (Couwenberg 2005, see Chapter 2.5.3).

'Spring mires' are classified as either eustatic or astatic, depending on whether the flow, temperature, and chemical composition of the water remain constant or vary throughout the year (Dahl 1957). Springs and spring fens are included with six alliances in the phytosociological review (Table 2.4).

A mire type newly identified at the mire classification workshop of the International Mire Conservation Group in Tamsweg (Austria, 2001) was the 'bird top' ("Skua Hummock", Summerhayes & Elton 1923, see Chapter Svalbard, Photo 98). These 'bird tops' are the only European mire type in which peat accumulates because of increased production and not because of reduced decay. Increased production is brought about by fertilisation with the excrements of the Skuas that use the mounds to survey their territory. Whereas higher plant productivity by NPK-fertilisation is usually associated with increased decay rates, the low temperatures in the Arctic limit decay and fertilisation may thus result in peat accumulation. Some of these tops have accumulated peat for over 4,500 years (van der Knaap 1988).

2.6.4 Hydrogeomorphic classification

Hydrogeomorphic classification of wetlands (e.g. Brinson 1993) emphasises the importance of local relief and topography for water movement and water quality and therewith for peatland development. Unlike other classification systems the hydrogeomorphic system requires that factors external to the peatland are recognised and integrated. Special attention is paid to (Brinson 1993):

- Geomorphic setting (i.e. the topographic location of the peatland within the surrounding landscape);
- The associated source of water (precipitation, surface or near-surface flow, or groundwater) and its transport; and
- Hydrodynamics (flow and strength of water movement).

In Russia, the principles of 'morphogenetic' mire classification were systematically worked out by Galkina (1959, 1967) and Ivanov (1975, 1981, Fig. 2.9), who stressed the importance of relief (watersheds, slopes and terraces, river and lake valleys) in determining water flow and mire development. Ivanov divided mires into two main groups: watershed mires and river valley mires. Watershed mires are, by virtue of their position on the highest point in the landscape, almost completely deprived of geogenic nutrient supply, and precipitation is the sole or principal source of nutrients. In contrast, valley mires may receive water from various types of sources. For example, shallow depressions without connection to an aquifer are next to precipitation also fed by surface water, whereas deep basins and valleys with aquifers discharging at their slope may receive substantial amounts of groundwater. The hydrogeomorphic approach is intermediate between a strict topographic classification and hydromorphic and hydrogenetic approaches.

2.6.5 Hydrogenetic mire classification

Hydrogenetic mire classification focusses on the processes that drive peat formation and peatland development. Special attention is paid to the interrelations and feedback mechanisms between 1) water flow and fluctuations, 2) vegetation, and 3) peat formation, and to the role peatland development plays in landscape hydrology

The first hydrogenetic concept, which has dominated thinking on mire development ever since, is that of terrestrialisation. The first systematic description of the colonisation and succession in open water bodies was provided by Zeylmans (1770): 'The downward pressure of the upper crust results from annual increment of the rotting substances that fall upon it and lasts until it touches upon the lower soil, or better until it meets the new peat that increases from below. As soon as the lower soil does not allow compression anymore, the new land starts rising up and lifts its head after some time far enough above the water. This upgrowth continues until the land has acquired its complete height and consistency, upgrowth stops, and the mire is full-grown.'

Gough (1793) summarised his thoughts on terrestrialisation as follows: "those extensive hollows in the surface of the earth, which were originally reservoirs of water, and which we call lakes, have been gradually filled up, and at length wholly obliterated, by the alternate production and death of aquatic and other vegetables, whose component parts […] undergo no decomposition, because of their constant submersion", which he considers as "a means of preventing that action of the air, which would otherwise effect a dissolution of their particles. By this accumulation of vegetable matter, the adventitious mixture of other substances that descend from the surface of the lake, and, above all, by the interweaving of the radical portions of plants, the production of peat is accounted for."

Aiton (1811) described the succession in detail: "The first vegetable settlers in the loch, and those which advance farthest into the deep waters, are the following, viz : Pondweed – *Potamogeton natans*, Water Lilies – *Nymphea Lutea et Alba*, Bull rush – *Scirpus Lacustris*, Reed Grass – *Arundo phragmytis*. When these have grown some time, and raised up the bottom of the lake, the water Plantago (*alisma plantago*), the marsh parsnip (*sium angustifolium*), *comarum palustre*, *pediculus palustris*, *equisetum fluviale*, some of the sedges (*carices*) and others introduce themselves; and when these have raised the mossy turf to the level of the water, the Cotton heads (*eriophera*), marsh fogs, and whole tribes of plants, which grow on wet flow-mosses, start up, add to the depth of the mossy stratum, and raise it to a great height above what once formed the surface of the lake. In this way have many lochs, lakes, and pools of water, of moderate depth, and where the bottom was of earth or mud, gradually grown up, with lake turf, till it rose to the surface of the water; and the flow-moss has afterwards risen over that turf to a great height, and is still increasing in depth, in proportion to the humidity of the surface".

Terrestrialisation has developed to become the paradigm of peatland formation. Picardt (1660) already stated: 'Also it is certain and unquestionable, that all peatlands formerly have been lakes or pools', and Gough (1793) expressed: "it is upon this Principle alone, that we can account for the production of those flat marshes that supply many countries in the north of Europe with fuel." In fact, however, terrestrialisation is not as common as assumed, and the other initial peatland formation process, paludification, is equally important (Walker 1970, Tallis 1983, Succow & Joosten 2001).

Since the end of the 19th century, a distinction has been made between terrestrialisation mires, which develop from open water, and paludification mires, where peat accumulation starts directly over a paludifying, originally dry mineral soil, often covered by forest (Weber 1900, Cajander 1913, Gams & Ruoff 1929). Next to these two mire formation strategies, von Post (1926) also identified "Überrieselung" (irrigation by trickling water) as a mode of peatland initiation, but abandoned this approach arguing that trickling water also causes paludification. Moreover, he observed a fundamental difference in peat formation caused by upwelling groundwater (springs) and by (near) surface run-off into depressions. Consequently, he proposed his division into ombrogenous, soligenous, and topogenous (Chapter 2.4.3). To complement the terrestrialisation and paludification strategies, Sjörs (1965) introduced the concept of 'primary' peat formation on 'new land' emerging from the sea (cf. Brandt 1948, Ingmar 1963) or exposed by retreating glaciers. Kulczyński (1949) contributed to the development of a hydrological mire typology by pointing out the importance of water movement (cf. Bellamy 1972, Moore & Bellamy 1974).

Whereas the genetic approaches of Weber and von Post were focussing more on the start of peat formation or on the origin (genesis) of the mire, later hydrogenetic approaches paid more attention to the processes that drive and maintain peat formation. Moore & Bellamy (1974) considered the "hydrological balance of the basin and the amount of the minerals in solution" as the most important factors determining peat(land) formation and presented three main types:

- 'Primary' mire systems (and 'primary' peats) develop in basins and depressions where the growing peat displaces the basin's water and peat stops growing when it has filled up the water completely (note that 'primary peat formation' sensu Moore & Bellamy is thus complety different from 'primary peat formation' sensu Sjörs 1965);
- 'Secondary' mire systems (and 'secondary' peats) develop beyond the physical confines of the basin or depression and the peat itself is acting as a reservoir and increasing the retention of water in the landscape;
- 'Tertiary' mire systems (and 'tertiary' peats) form above the physical limits of the groundwater table with the peat itself acting as a reservoir with its 'perched water table' directly fed by precipitation.

Whereas primary and tertiary peat formation echoed the classical terrestrialisation and raised bog concepts, secondary peat formation constituted a hitherto largely neglected concept. The idea of Moore & Bellamy (1974) that peat formation triggers higher water tables in the catchment and is a driver for peatland expansion, was clearly inspired by Kulczyński, under whose guidance D.J. Bellamy had absolved a postgraduate project (Bellamy 2003). However, the proposal of Moore & Bellamy (1974) was not widely applied, but absorbed in the further development of the hydrogenetic classification concepts of M. Succow.

The idea to use landscape hydrologic setting and resulting mire hydrologic conditions to discriminate peat-forming

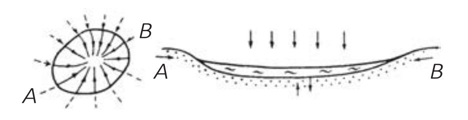
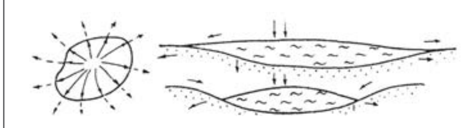
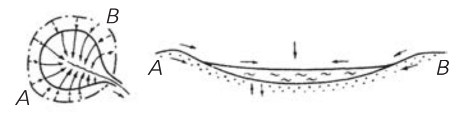
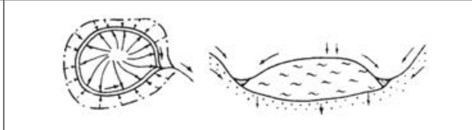
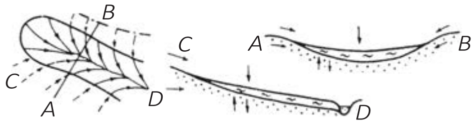
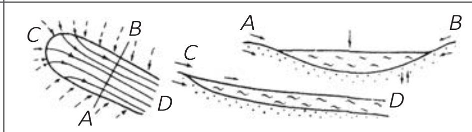
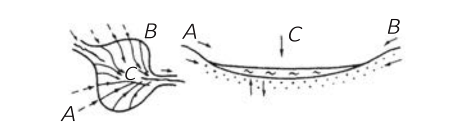
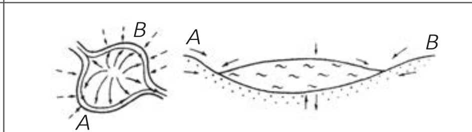
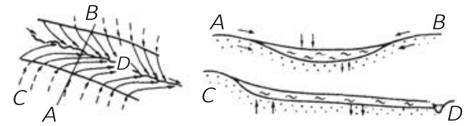
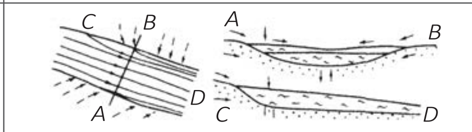
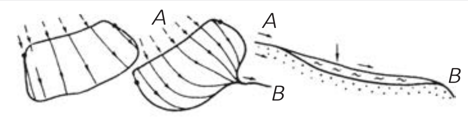
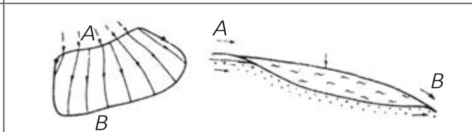
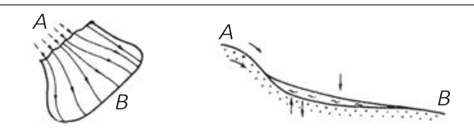
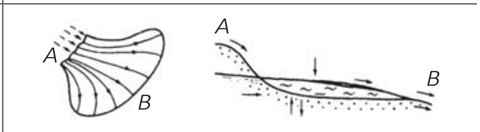
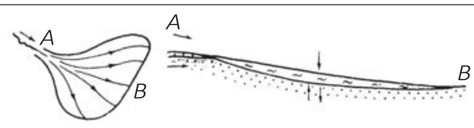
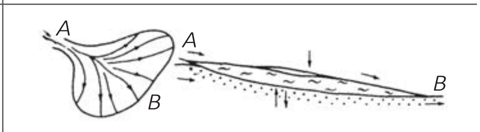
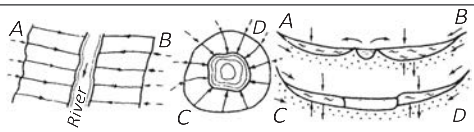
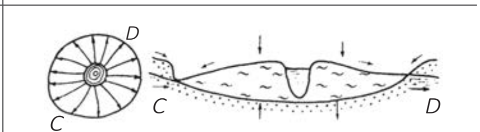
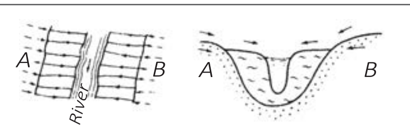
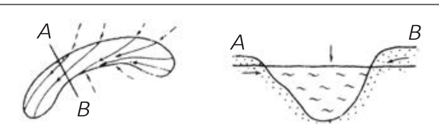
Type of mire massif	Development process	Phase I (concave landform)	Phase III (convex landform)
Closed basin (I)	Central-oligotrophic		
Draining basin (III)	Central-oligotrophic		
Draining valley (IIb)	Peripheral-oligotrophic		
Throughflow basin (IV)	Mixed		
Throughflow valley (IIa)	Peripheral-oligotrophic		
Gentle slope (Vb)	Mixed		
Foot of the slope (Va)	Mixed		
Delta (VIII)	Mixed		
Lakeshore and river floodplain (VII)	Peripheral-oligotrophic, central-oligotrophic		
Stretch of a river (VI)	Peripheral-oligotrophic		No transition to phase III
Oxbow (IX)			No transition to phase III

Fig. 2.9: Hydrogeomorphic classification scheme of mire massif developmental under different relief conditions (modified after Ivanov 1975). I–IX=mire massif classes according to Galkina & Kiryushkin 1969). 1=peat, 2=subsoil, 3=water flow within the massif, 4=direction of external water supply, 5=groundwater table in the mineral soil, 6=lakes and rivers, 7=draining streams.

processes for the classification of peatlands was further developed by Succow (1971, 1981, 1983, 1988, Succow & Lange 1984) and Succow & Joosten (2001) who differentiated eight 'hydrologic-biogenetical' (shortly 'hydrogenetic') mire types. Steiner (1992) added the 'condensation mire' to this typology.

In contrast to hydromorphic mire classification, the 'hydro-' of 'hydrogenetic' does not refer to the origin of the water, its consequent quality, and its effect on the composition of the mire vegetation (cf. Sjörs 1948, Chapter 2.4.3), but rather to water table and water flow and their dynamics and how they affect peat formation, and how peat formation in return affects catchment hydrology (cf. Moore & Bellamy 1974). Whereas hydrogenetic classification is "pleasing from a holistic, ecological point of view" (Moore 1984b) and most promising for understanding mire functioning and the associated provision of ecosystem services (Joosten 2016b), the correct identification of hydrogenetic mire types requires substantial field research (incl. peat borings and hydrologic observations). Therefore the approach is less appropriate for rapid field assessments.

Whereas Succow (1988) still made a first order division between ombrotrophic and geotrophic mires, Succow & Joosten (2001) and Joosten & Clarke (2002) look at peat formation strategies and associated hydrological conditions (water flow and water table fluctuations) as the prime criteria for distinguishing mire types; they use the origin of the water as an independent secondary criterion. Similar to Weber (1897) and Sjörs (1946), hydrogenetic mire classification distinguishes between mires with a horizontal surface without substantial lateral water flow and mires with a sloping surface in which lateral water flow initiates distinct self-organising and self-regulating processes.

Water table fluctuations and water flow play an important role in peat and mire formation. Water table fluctuations influence redox processes that affect the turn-over rate and solubility of chemical substances (nutrients, but also poisonous substances like reduced Sulphur S^{2-}), that in turn affect the vegetation and eventually the composition of the deposited peat. Moreover, water table fluctuations determine the rate of decomposition, leading to a change from coarse to fine peat material and hence to a decrease in pore size. Smaller pore size means a lower storage coefficient, which means that water table fluctuations become larger and more frequent. The fluctuating water and O_2 availability result in even higher decomposition. The small storage coefficient not only leaves less room for water to be stored in the peat during periods of drought, but furthermore obstructs infiltration, enhancing the effect. Moreover, reduced elasticity decreases the ability of the peat to expand and shrink (so-called 'Mooratmung' or 'bog-breathing'), resulting in an even lower storage capacity. Thus, periodically low water tables may set off a self amplifying positive feedback that leads to increasingly smaller pore space. In a peat accumulating mire this destructive positive feedback is counteracted by the addition of fresh plant material with large pores.

In peatlands with lateral water flow, additional feedbacks occur. Most importantly, the very presence of peat slows down water flow – a positive feedback in which the presence of peat secures the presence of the water necessary for the formation of peat. This positive feedback runs opposite to the one dealing with water table fluctuations and pore space described above. When there is lateral water flow, smaller pores also mean smaller hydraulic conductivity, which reduces subsurface run-off, constituting an additional negative feedback not found in mires without lateral flow (Fig. 2.10). Their additional feedback mechanisms make sloping (inclining) mires with lateral waterflow fundamentally different from horizontal mires with predominantly standing water.

Hydrogenetic mire types consist of two major groups: the 'horizontal mires' and the 'inclining (sloping) mires' (Table 2.15).

Horizontal mires occur in closed basins, where water movement is largely prevented by a flat relief and impervious substrates, and the water surface is therefore horizontal (Sjörs 1948). Vertical (seasonal or inter-annual) water table fluctuations can be small to very large. Peat formation only occurs if the periods of waterlogging are much longer than the dry periods. Horizontal mires have almost no influence on water flow in the landscape or on the water table of their surroundings. Their effect on landscape hydrology is merely that they diminish basin water storage as they fill the basins up with peat, which may lead to a larger (near-)surface peak flow elsewhere in the landscape.

Horizontal mires are subdivided into

- 'Terrestrialisation mires' (German: "Verlandungsmoore"), where peat formation takes place in or over 'open' water. Terrestrialisation mires are subdivided into
  - 'Schwingmoor mires' in which peat accumulates in a floating mat; and
  - 'Immersion mires' in which peat accumulates on the bottom of the water body.

  The peat deposited at the start of terrestrialisation is mostly weakly decomposed. As the basin fills up with continued terrestrialisation, the more recently deposited upper peat layers are subject to stronger decomposition because of increasing water table fluctuations. At the end of the terrestrialisation process, when the basin is completely filled, peat accumulation stops unless another peat formation strategy takes over.
- 'Water rise mires', where peat formation takes place following a rising water table (that is insufficient to create open water, see above). As water table fluctuations are usually large, strongly decomposed peats are deposited that have a low hydraulic conductivity and only a small storage coefficient, but high capillarity. Water rise mires are subdivided into
  - 'Groundwater rise mires' ("Grundwasseranstiegsmoore") in contact with groundwater;
  - 'Backwater rise mires' ("Stauwasserversumpfungsmoore") without groundwater contact and with allogenic sealing; and
  - 'Self-sealing mires' ("Kesselmoore") without groundwater contact and with autogenic sealing ("selfsealing").

  A rise in the groundwater level may occur regionally (e.g. because of sea level rise, a change in climate or in land use, or because of peat formation in lower lying valleys, cf. Kulczyński 1949, Driescher 1974). A relative rise in groundwater level may also result from tectonic or glacialisostatic landfall (cf. German Baltic coast, Kliewe & Sterr 1995) or karst breaches (cf. Früh & Schröter 1904: Dolinenmoore; Paulson 2001). In depressions without connection to the groundwater, the water table may rise locally because less water infiltrates due to sealing of the subsoil (German: "Kolmation") by mineral or organic particles (hardpan, B horizons of podsol soils, cf. Tüxen et al. 1977, Koopman 1988), or because less water is lost laterally (for example due to beaver dams or mill weirs, cf. Sjörs 1983, Schwaar & Brandt 1984, Brande 1986), or

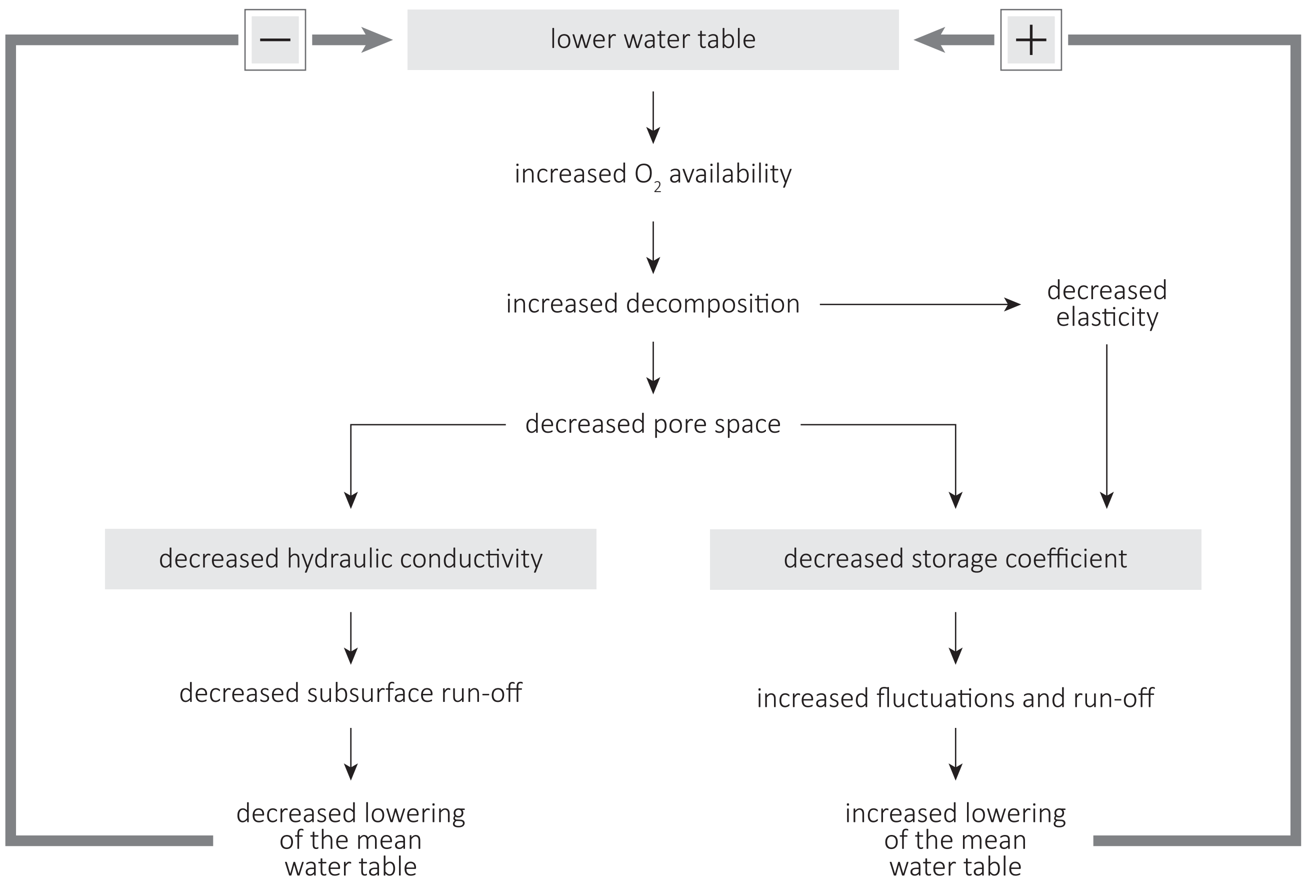


Fig. 2.10: Positive and negative feedback mechanisms between water table and hydraulic characteristics in a mire with lateral water flow (changed after Couwenberg & Joosten 1999a).

because more water flows into the depression (for example due to reclamation or soil compression in the catchment).
A particular subtype of water rise mires is the 'self-sealing mire' (='kettlehole mire' sensu Succow & Joosten 2001). Self-sealing mires form themselves a stagnating layer in the previously more permeable mineral subsoil, usually in a kettle shaped basin. As water outflow is impeded to a higher and higher level, the mire internal water table rises (Gaudig et al. 2006). Although the sealing occurs under the influence of flowing water that transports the humus colloids responsible for the sealing from the mire to the mineral subsoil, the peat accumulation strategy is that of a mire without substantial lateral water flow.

- 'Floodwater mires', which are bound to periodically flooded areas. The water surplus usually runs off fast. Floodwater mires are subdivided into
  - 'River floodwater mires', where regular flooding is caused by (annual/subannual) water pulses from the catchment area;
  - 'Marine floodwater mires', where regular flooding is caused by lunar tides (e.g. peat accumulating mangroves and saltmarshes); and
  - 'Lake floodwater mires', where regular flooding is caused by wind tides (e.g. large lakes, Baltic Sea).

Usually floodwater mires have strongly decomposed peats because of strong water table fluctuations. Floodwater mires with a substantial peat thickness can only occur if (relative) water tables are rising (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 (sand, clay). As a rule, changing water supply is not buffered by mire oscillation ('Mooratmung'), because of the high bulk density of the peat (Kulczyński 1949). As the hydraulic conductivity of the peat is low, surface run-off is high, although it is somewhat retarded by the vegetation. With this influence on lateral water flow this type forms the transition to the group of inclining mire types.

Horizontal mires are 'passive': they lie horizontally in the landscape, water movement is largely vertical, and they have no (or only a very limited) hydrologic influence on the catchment area. Over time, as their basins gradually fill with peat, they reduce the water storage capacity of the landscape.

'Inclining mires' are more 'active': the mire surface shows a slope and a significant amount of water is lost through lateral flow. The vegetation and the peat retard this flow and so vegetation growth and peat accumulation

Table 2.15: Hydrogenetic mire types (columns) combined with their hydrological properties and the origin of the water (rows), with examples in italics (the table excludes condensation mires; modified after Joosten & Clarke 2002). Grey fields denote combinations that are probably not existing.

			Horizontal mires				**Inclining mires**		
	Water regime		**Terrestrialisation**		**Water rise**	**Floodwater**	**Surface flow**	**Acrotelm**	**Percolation**
			Schwingmoor	**Immersion**					
Water supply			Continuous	Mostly continuous	Small	Periodic	Frequent	Frequent	Continuous
Mire surface 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 decreasing	Storage decreasing	Storage decreasing	Storage decreasing (maybe increasing?)	Storage increasing	Storage increasing	Storage increasing
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 floodwater mire *floodwater mire along large bog lake*	Ombrogenous surface flow mire *blanket bog*	Ombrogenous acrotelm mire *typical raised bog*	Ombrogenous percolation mire *percolation bog*
	Geogenous *fen*	**Soligenous**	Soligenous schwingmoor mire *floating mat in moorpool*	Soligenous immersion mire *terrestrialisation in moorpool*	Soligenous water rise mire *Self-sealing mire (Kesselmoor)*	Soligenous floodwater mire *Self-sealing mire (Kessel-standmoor)*	Soligenous surface flow mires *sloping fen, Hangmoor*	Soligenous acrotelm mire	Soligenous percolation mire *some sloping fens*
		Lithogenous	Lithogenous schwingmoor mire *floating mat on lake*	Lithogenous immersion mire *lake terrestrialisation mire*	Lithogenous water rise mire *groundwater rise mire*	Lithogenous floodwater mire *river floodplain mire*	Lithogenous surface flow mire *most spring mires*	Lithogenous acrotelm mire	Lithogenous percolation mire *typical percolation mire*
		Thalassogenous	Thalassogenous schwingmoor mire	Thalassogenous immersion mire *coastal terrestrialisation mire*	Thalassogenous water rise mire *coastal floodwater mire, mangrove*	Thalassogenous floodwater mire	Thalassogenous surface flow mire	Thalassogenous acrotelm mire	Thalassogenous percolation mires

lead to an absolute rise in water table, in the mire and often also in the catchment (Kulczyński 1949, Bellamy 1972, Moore & Bellamy 1974), with continued accumulation of peat as a result. In contrast to horizontal mires, inclining mires enlarge the water retention of the landscape.

Inclining mires can regulate the water available to them to some extent. Most importantly, they retard its run off, but they can also discharge surplus water effectively over the surface because of their slope. In regulating water in- and outflow, the dynamic triangular relationship between water, vegetation, and peat plays an important role (cf. Ivanov 1981, Couwenberg & Joosten 1999a). Inclining mires are subdivided into:

- 'Percolation mires' ("Durchströmungsmoore"), which are bound to landscapes where water supply is large and evenly distributed over the year. As a result, the water table in the mire is almost constant relative to the surface. Dead plant material reaches the permanently waterlogged zone quickly and is subject to fast aerobic decay only for a short time. Consequently, the peat remains weakly decomposed and elastic (Succow 1982). Because of the large pores and the related high hydraulic conductivity, substantial water flow occurs over a substantial depth of the peat body (Wassen & Joosten 1996, Sirin et al. 1997, 1998, Schipper et al. 2007). Whereas young percolation mires are susceptible to water table fluctuations, with growing peat thickness fluctuations in water supply and loss are increasingly compensated by mire surface oscillation ('Mooratmung'). The peat's ability to oscillate makes conditions for peat formation at the surface increasingly stable (Michaelis & Joosten 2007). Percolation mires are subdivided into
  - 'Percolation fens', fed by groundwater (geogenous); and
  - 'Percolation bogs', only fed by precipitation (ombrogenous).

  Only large catchment areas can guarantee a large and continuous water supply in most climates. Therefore percolation mires are normally only found as groundwater-fed mires. In the Colchis area (Georgia), however, *Sphagnum*-dominated ombrogenous percolation mires exist under conditions of 'constant' heavy rainfall (Kaffke 2008, Chapter 4, Chapter Georgia).

- 'Surface flow mires' ("Überrieselungsmoore"), where strong peat decomposition forces the water to overflow the peat. Surface flow mires can only endure if oxidative losses are limited, i.e. if the water table drops only rarely. They are therefore limited to areas with almost constant water supply over the year and/or with only little water losses (especially due to evapotranspiration). Because of the small storage coefficient of the peat, any water shortages may still lead to rather large drops in the water table. Because of their low hydraulic conductivity and large water supply, surface flow mires may occur on and with steep slopes. Surface flow mires are subdivided into
  - 'Blanket bogs' ("Deckenregenmoore"), only fed by rainwater;
  - 'Hill slope mires' ("Hangmoore"), also fed by surface run-off; and
  - 'Spring mires' ("Quellmoore"), also fed by groundwater.
- 'Acrotelm mires' (sensu Couwenberg & Joosten 1999) that show a distinct vertical gradient in hydraulic conductivity in their vegetation layer and near surface peat that allows them to regulate water flow and limit water losses. Acrotelm mires are characterised by a continuous accumulation of fresh organic material that combines a high storage coefficient (many and large pores) with a small decayability of the material. This limited decayability keeps the effect of water table fluctuations on pore space relatively small. Water losses by run-off and evapotranspiration cause only limited water table drop-downs because of the large pores and the large storage coefficient of the peat. The deeper, older peat material has longer been prone to oxidation (and to pressure) and a distinct vertical gradient in pore space and hydraulic conductivity results (Ivanov 1981). If the water table does drop in times of water shortage, only little water can flow off through the less permeable part of the 'acrotelm'. In this way, the deeper peat layers (the 'catotelm') remain continuously waterlogged, even if water supply varies. In acrotelm mires the negative feedback shown in Fig. 2.10 is effective, but contrary to surface flow mires, acrotelm mires do not fall into the trap of the positive feedback.

  To build an acrotelm, plants and their peat must combine a number of opposing features:
  - On the one hand a large storage coefficient (large and many pores) to prevent large water table drops by evapotranspiration losses, and on the other hand a small hydraulic conductivity (small and few pores) to prevent large run-off losses. Because these requirements are hard to reconcile, acrotelm mires are not found on steep slopes but only in rather level areas.
  - On the one hand a large decayability to acquire the necessary permeability gradient within a limited depth range that is effective in regulation of the water table, and on the other hand a small decayability to allow peat accumulation at all.

  In case of the *typus classicus* of acrotelm mires, the *Sphagnum* dominated raised bog, these requirements are only fulfilled by a handful of *Sphagnum* species (Joosten 1993), first and foremost *Sphagnum austinii*, *S. fuscum*, *S. magellanicum*, *S. papillosum*, and *S. rubellum*/*capillifolium*. These species combine a limited decayability (Clymo 1983, Johnson & Damman 1991) with favourable nutrient poor and acid conditions, inherent to ombrotrophic conditions. The surprisingly wide distribution of the *Sphagnum* acrotelm mire type (cf. Fig. 4.27 and 4.28) shows the effectiveness of this strategy.

Condensation mires ("Kondenswassermoore") were first described by Schaeftlein (1962). They are restricted to land slide regions with an inclination >25°. The air temperature inside the cavities between the land slide blocks is about the average temperature of the region. In summer the surface of the land slide heats up and the warm air rises, causing cold air to emerge from the cavities, creating circulation of air. The warmer it gets outside the colder it gets inside the cavities, because the 'circulation wind' loses heat energy by taking up humidity. On warm days the outcoming air can reach 0° C. At the surface this cold air causes enough condensation of humidity in the warm air outside to support the development of *Sphagnum capillifolium* hummocks. These hummocks can grow together and finally form a steep sloping bog.

2.7 The classification of mire complexes (macrotope)

Especially in areas where good conditions for mire development are widespread, separate mire massifs may coalesce and start influencing each other's development. In this way mire complexes (macrotopes) form, in which the individual mire massifs grow in, up against, and over each other. A mire complex thus encompasses a (large) mire area bounded by mineral soil, and formed by fusion of several single mire massifs.

Following Cajander (1913), Sjörs (1948) and his followers use the term 'complex' to indicate every mire within its mineral soil boundaries, independent of whether the mire is a single massif or a conglomerate of massifs (see Chapter 2.5.1). In the following we use the term 'complex' for conglomerates only.

The fusion of mire massifs may be so intense, that previously independent massifs can only be distinguished by looking from a distance (using remote sensing) or by looking back in time (using palaeoecological studies). Air photographs of the Nigula mire system (Southwest-Estonia), for example, reveal that in the northwesten part of the system one concentric bog massif is creeping over another massif (cf. Lode & Leivits 2011). Casparie (1972) showed by detailed stratigraphic research that the extensive Bourtangermoor on the border of Germany and the Netherlands was a conglomerate of several bog massifs, each with a diameter of ca. 6 km (Fig. 2.11).

The individual massifs closely interact with eachother, producing habitats, vegetation types, and mire sites that are restricted to mire complexes and that do not occur in the simple mire massifs (Fig. 2.12; Yurkovskaya 1995). The only place where *Saxifraga hirculus* was ever found in the Netherlands, for example, was on a place where several bog massifs of the Bourtangermoor had merged to form the intercupola mire lake Zwarte Meer (Fig. 2.11; Beijerinck 1929, Barkman & Westhoff 1969).

Galkina et al. (1974) proposed three, theoretical, ways of classifying mire complexes:

1. The landscape features that facilitate the formation of the complex;
2. The types of mire massifs that constitute the complex;
3. The degree of fusion of the single massifs, i.e. the clarity of the boundaries between the various massifs.

Following the second approach, Yurkovskaya (1995) and Masing (1998) distinguished three groups of mire complexes:

- 'Homonomous isochronal' mire complexes formed by mire massifs of the same basic type and the same age, whose structural and compositional diversity is similar. Their communities have the same spectrum of characteristic and dominant species (Fig. 2.12);
- 'Homonomous diachronal' mire complexes formed by mire massifs of the same developmental pathway but with structural differences that are related to their age. Their communities have a similar spectrum of essential species;
- 'Heteronomous' mire complexes formed by mire massifs of different types that belong to different classes, have thus followed a different course of development, and display different structural elements and greatly differing plant community composition (Masing 1972).

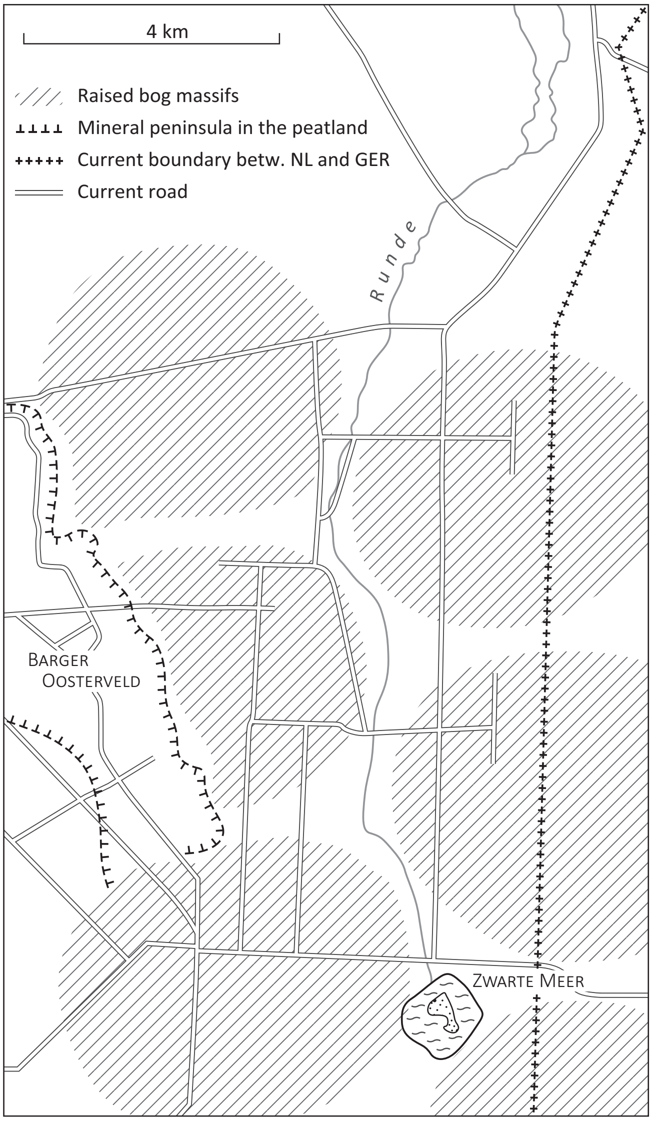


Fig. 2.11: Location of raised bog massifs (hatched) spread out within the Bourtangermoor peatland complex near Barger-Oosterveld with the Zwarte Meer mire lake and the Runde mire river (after Casparie 1972, Casparie et al. 1980).

Photo 1: ‘Der Weiher’ (1495) of Albrecht Dürer (1471–1528), the first known painting of a natural mire in Europe. ©The Trustees of the British Museum. All rights reserved.

Photo 2: One of Albania’s larger peatlands is located in the inter-montane basin north of Korçë at >800 m a.s.l. (Albania, H. Müller, March 2015).

Photo 3: A small mountain peatland near Doberdol, which has been recently discovered (northeastern Albania, L. Shuka, October 2015).

Photo 4: The ‘group 2’ wetland Basses de Setut V in Madriu valley (Andorra, S. Riba Mazas, August 2004).

Photo 5: A small peat extraction site in the drained area of Gilli (Armenia, K. Jenderedjian, August 2008).

Photo 6: The remnant wetland part of Lake Gilli (Armenia, K. Jenderedjian, August 2008).

Photo 7: Raised bog at 1,300 m a.s.l. at Zlaimalm-Zlaimmöser (Austria, M. Succow, June 1995).

Photo 8: Alpine fen with dominant *Eriophorum scheuchzeri*, a species in central Europe restricted to mires in high altitudes, in the Central Alps of Carinthia at Kreuzeckgruppe near Hugo Gerbershütte (Austria, F. Essl, July 2010).

Photo 9: The ‚bugry' mire at the foot of Mount Gyzylgaya on 2,600 m a.s.l. with peat hummocks formed by frost action (Azerbaijan, A. Thiele, July 2007).

Photo 10: Peatland with lowland *Alnus* forests near the village of Tengerud in Talysh region, which in 2008 was destroyed and has disappeared by now (Azerbaijan, J. Etzold, November 2006).

Photo 11: *Sphagnum* bog on Terceira island with geothermal energy plant in the background (Azores, C. Mendes, December 2013).

Photo 12: Thermal *Sphagnum* mires at Furnas do Enxofre, Planalto Central da Terceira (Azores, C. Mendes, May 2014).

Photo 13: Yelnia is one of Belarus' most beautiful and least disturbed bogs in the northern peatland region (Belarus, A. Thiele, September 2009).

Photo 14: Industrial milled peat extraction in Tsna, Minsk oblast (Belarus, H. Joosten, June 2014).

Photo 15: The Aquatic Warbler *Acrocephalus paludicola* is a flagship species for fen mires and the only globally threatened passerine species of continental Europe (Belarus, A. Kozulin, May 2005).

Photo 16: A train with extracted peat crossing the rewetted part of the peatland Grichino-Starobinskoye (Belarus, S. Koltovich, August 2010).

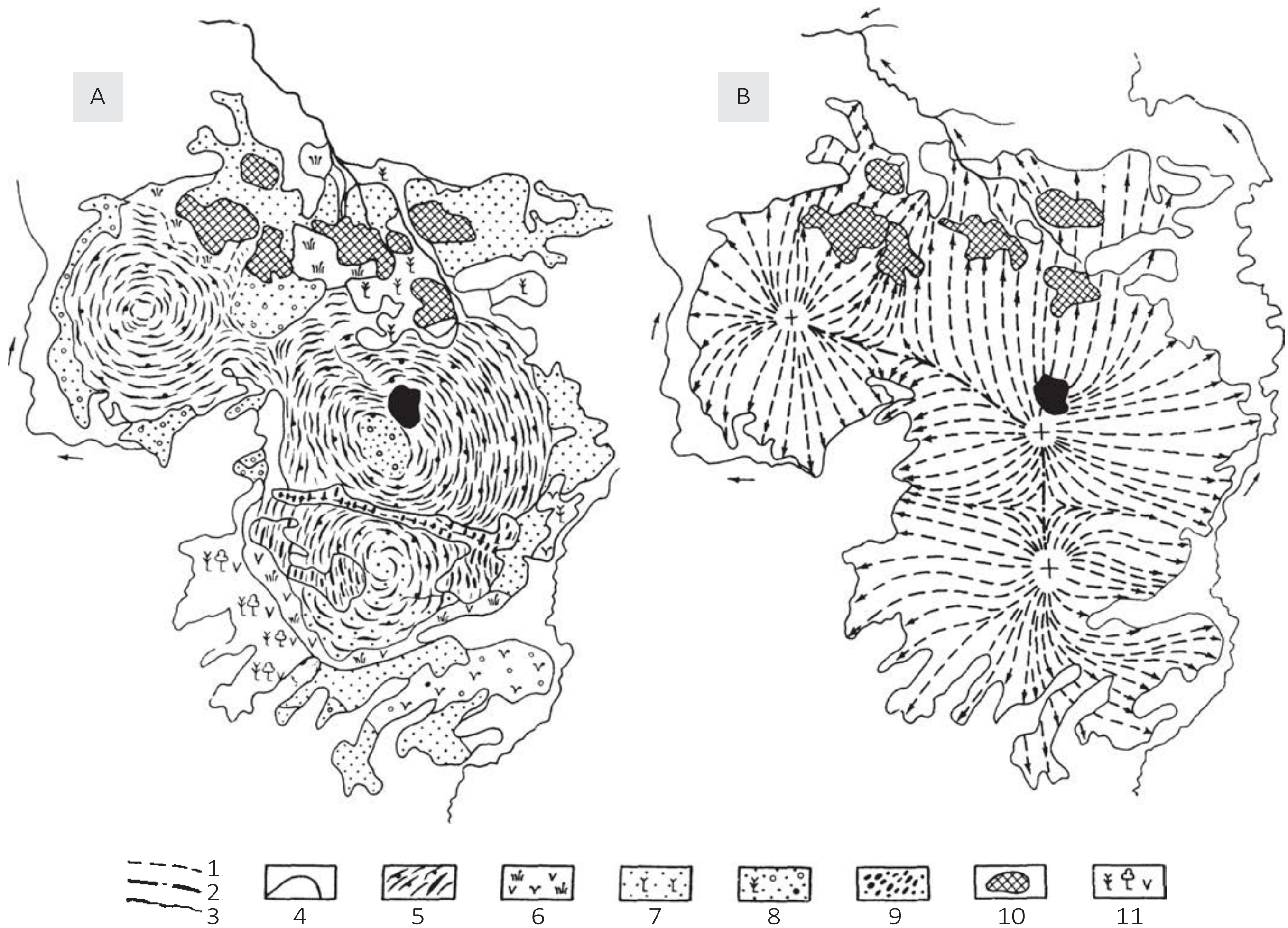


Fig. 2.12: Example of a watershed mire complex with different development stages of the constituting mire massifs (after Ivanov 1975). 1=run-off lines, 2=mire internal watershed, 3=brooks and rivers (all depicted in part B), 4=border of mire sites, 5=hummock-hollow mire sites with lense-shaped hummocks, 6=mire site of the *Sphagnum-Eriophorum*-shrub and *Sphagnum-Eriophorum-Carex* group, 7=*Sphagnum-Pinus*-shrub mire sites; 8=*Pinus*-shrub mire sites, 9=hummock-pool mire sites, 10=mineral islands between mire systems with mineral soil, 11=*Pinus-Betula-Carex* mire sites (all depicted in part A).

A mire complex can thus be characterised and named after the dominant type of mire massif (e.g. sloping fen complex when sloping fens dominate), or a single typical mire massif (e.g. a concentric raised bog complex, even if the raised bog covers less area than the flat fens surrounding it).

A simple classification into ombrotrophic, geotrophic, ombro-geotrophic, and geo-ombrotrophic systems, according to the local dominance, has frequently been used in Norway (e.g. Moen & Singsaas 1994). An ombrotrophic complex is at least 80% ombrotrophic, a geotrophic complex at least 80% geotrophic, and ombro-geotrophic and geo-ombrotrophic complexes are in between.

2.8 Towards integration?

As already noted in Chapter 2.2.2, the number of variables, each dividable into unlimited interval classes, would make the total number of possible peatland types infinitely large, unless variables are systematically associated with each other.

From a mire functional point of view, the first limitation to 'unlimited peatland types' is in the plant species. Whereas peat may contain the remains of a very large diversity of plant species, many of these remains (pollen, seeds, leaves, and other air and water transported macrofossils) only constitute a sedimentary component of the peat. The number of plant species that leave a substantial amount of recognisable macrofossils 'on the spot' (i.e. 'sedentarily', see Box 2.2) and can therefore rightfully be called 'peat forming' is in Europe considerably less than 200 (D. Michaelis pers. comm.). Peat forming species must produce rather decay resistant tissues, must be capable of living under virtually permanent anoxic soil conditions, and must be able to reach 'mass' occurrence.

This combination of special characteristics is within Europe limited to only few plant families and genera. Among the vascular plants these are mainly various Cyperaceae taxa (e.g. *Carex*, *Eriophorum*, *Cladium*), some Poaceae species (notably *Phragmites australis*, but also *Molinia caerulea* and *Glyceria maxima*), the tree species *Alnus glutinosa*, *Betula pubescens*, *Picea abies*, and *Pinus sylvestris*, the (dwarf) shrubs *Calluna vulgaris*, *Myrica gale*, *Salix aurita/cinerea*, and the herbs *Menyanthes trifoliata*, *Narthecium ossifragum*, *Scheuchzeria palustris*, *Thelypteris palustris*, and *Equisetum fluviatile*. Also among the wide variety of mosses, only a few genera and species contribute substantially to peat formation, including *Aulacomnium palustre*, *Calliergon* (*giganteum*, *stramineum*, *trifarium*), *Calliergonella cuspidata*, *Drepanocladus/ Warnstorfia* spp., *Meesia triquetra*, *Paludella squarrosa*, *Polytrichum commune*, *Scorpium scorpioides*, *Tomentypnum nitens*, and – of course – the peatmosses (*Sphagnum* spp.). These species provide the close-knit matrix of vegetation and surficial peat in which many niches for other peatland species are generated, specifically with respect to water micro-regime (fluctuations, redox-potential), nutrient conditions, soil reaction, and light availability.

Which of the potentially peat forming plant species will constitute the mire depends largely on the quantitative and qualitative characteristics of the input water, which is in its turn determined by the climate and the hydrological catchment area. Under equal climatic, geologic, and relief conditions, the amount, duration, and frequency of water supply increase in the order ombrogenous – soligenous – lithogenous supply, but simultaneously the water quality changes, especially the base richness. However, a tight correlation between the quantity and quality of water and its source is not possible over large areas. A continuous water supply is, for example, in Europe largely bound to geogenous conditions (groundwater), but not necessarily: it can also be found in areas with very frequent rainfall (see Chapter 4.8.11 and Chapter Georgia). Also, ombrogenous water may show rather large differences in chemical composition (Wołejko & Ito 1986, Damman 1995). When the substrate is inert, deep groundwater may have a similar quality as rain water. Thallasogenous (sea) water is known to show large differences in salt content (e.g. Baltic vs. North Sea).

At a regional level, a correlation between quantity, quality, and source of water can more easily be made. Within a region, plant species are bound to certain conditions of water quality and regime, whereas the species themselves then to a large extent determine the peat formation strategy, based on their material composition and hydraulic characteristics. Joosten (1993) argues, for example, that the difficulty to produce a combination of both a limited permeability and a large storage coefficient limits the number of species that are able to build an (ombrotrophic!) raised bog in the non-tropical northern hemisphere to only a handful *Sphagnum* species. Similarly it are mainly Cyperaceae that appear to be able to shape the rootlet matrix that can support the existence of percolation fens. Regionally therefore, strong correlations between abiotics, vegetation, and hydrogenetic mire types can be found.

As a result of complex interactions between vegetation, water, and peat ('self-organisation'), mires may develop various morphological types, consisting of a characteristic landform (cross-sectional profile) combined with characteristic configurations of microtopographic surface-elements (see Fig. 2.2, Couwenberg & Joosten 2005).

Next to such mire internal developmental processes, also external mechanisms may be important in the configuration of peatland macro- and micro-structures. Frost may lead to features that also exist in mineral soils (e.g. ice wedges and frost bowls), but which, in case of peat-covered areas, produce specific morphic peatland types (polygon mires, palsa mires). In mire types with water flow, a colder climate leads to longer ice persistence in the higher compared to the lower relief elements. The resulting difference in hydraulic conductivity may then lead to a stronger differentiation between, and a more explicit arrangement of positive and negative microrelief elements (hummock and hollows, strings and flarks etc.), causing the formation of string-flark mires and concentric and eccentric bogs.

These interlinkages between peatland classification concepts on various spatial scales indicate that functional approaches may contribute to the development of more integrated mire classification concepts. These should include increasing attention to the interactions and feedback mechanisms between plants, animals, and the microbial community, the stabilising, buffering effects of the ecosystem on the topical level, and the role of topical elements in the functioning of the mire on the mesotope (massif) scale.

3 Mire and peatland terms and definitions in Europe

Hans Joosten, John Couwenberg, Asbjørn Moen & Franziska Tanneberger

'*...language is a dynamic system able to adapt to changing circumstances...'* (Thier 2007)

3.1 Introduction

It will have become clear from the plethora of terms in the previous chapter that communication about peatlands is not as straightforward as one might assume. This chapter deals specifically with terms. All communication requires terms (names, symbols, codes, labels) for the concepts (contents, objects, ideas, notions) it wants to exchange. Communication problems arise when terms are linked to concepts in different ways, which is more common than most people think. The meaning of a term may differ among disciplines and people depending on historical, cultural, and often purely personal backgrounds. It makes, however, no sense to argue about the 'right' definition of a term: As long as the connections are clear, unambiguous, and consistently used, one specific linkage of terms and concepts is not better than any other (Popper 1976).

In mire science unrecognised differences in concepts behind similar terms and inconsistencies in the definition of terms have led to much confusion (Potonié 1906, Overbeck 1975, Fuchsman 1980, Andrejko et al. 1983, Zoltai & Martikainen 1996, Joosten 2002, Joosten & Clarke 2002). The terms 'eutrophic', 'mesotrophic', and 'oligotrophic', for example, are used to denote nutrient availability, but also to describe the pH/base saturation gradient or a combination of the two (see Chapter 2.4.5). Confusion also arises because pre-scientific, vernacular terms have been adopted by various scientific disciplines and adapted to their own specific demands. And even within one country, one language, and one discipline the meaning of a word may change in time with changing insight, emphasis, or preference (cf. Wheeler & Proctor 2000, Økland et al. 2001, Table 3.1).

Even more complications arise when terms are translated into another language. 'Mire', 'myr', 'Moor', 'болото', 'turfeira', and 'suo' are not simply different names for the same concept in different languages. In fact, the concepts behind all these terms are different. It is generally impossible to find fully identical concepts in different languages, because the landscapes, the people, the traditions, and the perspectives in different countries and regions are so different. This problem is largely neglected in multilingual lexicons, which generally present simplistic one-to-one translations (Früh & Schröter 1904, Mali 1956, Masing 1972, Bick et al. 1973, Overbeck 1975, Gore 1983c, International Peat Society 1984). Many concepts have furthermore been mixed-up by uncritical translation of terms, even in important handbooks (Joosten 1995a, 2016c). In recent time, new conservation driven classifications (see Chapter 2.4.9) have added further confusion. Several mire associated habitat types of the European Union Habitats Directive, for example, are very differently defined in different countries and even within different federal states of the same country (Joosten & Greiser 2015).

This confusion in describing and understanding peatlands has been apparent from the early start of peatland science. The thoughts of Weber (1903) expressed in Box 3.1 on what a 'peatland' is, are surprisingly topical. The box also illustrates the difficulties of translation (cf. Couwenberg 2002, Chapter 3.3): In most texts the German 'Moor' can best be translated with the English 'peatland' (usually not with 'mire'!, cf. Joosten 1995a), but in this case no real equivalent exists, so the box is about 'Moor' and its plural 'Moore'.

In this chapter we justify our definitions of important terms used in this book (Chapter 3.2), explain the origin, development, and interrelation of frequently used peatland associated terms in various languages (Chapter 3.3), and present a glossary of the most important words used in peatland science (Chapter 3.4).

3.2 The justification of chosen definitions

A **wetland** is an area that is inundated or saturated by water to the extent that its vegetation is dominated by plants that are adapted to life in anoxic soil conditions (see also Fig. 2.3).

To differentiate 'wetland' from 'dryland' we use the criterion that the plants growing in a 'wetland' must show adaptations to water saturation (cf. Tiner 1999). The scarcity of oxygen in water saturated conditions requires plants growing in wetlands to be adapted in physiology, anatomy or growth form (Hook & Crawford 1978, Cronk & Fennessy 2001). Also wet lands where adapted plants *may* occur, but are actually absent because they had no opportunity to establish (such as with recently drained lakes, devegetated wet areas, and wet grounds newly exposed by glaciers) are ascribed to this concept. The border between 'land' and 'water' may be defined on the basis of vegetation coverage and water depth. As this border is outside the realm of proper peatlands, we refrain from defining it.

The wetland concept originally excluded those parts of the Earth's surface that are not 'land' and many publications still follow this approach. The Convention on Wetlands (=Ramsar Convention,

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Table 3.1: Different meanings assigned to the term 'bog' (or its equivalent) with selected references (see also Gorham 1953, Overbeck 1975).

Background	Focal meaning of the term 'bog'	References
Pre-scientific	Flexible (basic meaning of all related words, as the germ. 'biegen', engl. 'bow')	Indo-european root '*bheug' (Pokorny 1959)
	Soft (meaning of the Gaelic word from which it is borrowed)	From Proto-Celtic '*buggo-' (Pokorny 1959 s.v. bheug)
	Any wet soil in which the foot sinks	Colloquial (cf. Tansley 1939)
	Toilet	Rabelais/Urquhart 1653
Proto-scientific	A peatland	Boate 1652
	A peatland, raised above the surrounding land and highest in the centre	King 1685
	A peatland with more than 10 feet of peat	Von Eiselen 1802
Hydrological: origin of the water feeding the peatland	A peatland only fed by precipitation	Dau 1823
Ecological	A mire	Kulczyński 1949
	A mire of which the vegetation for its mineral nutrients entirely depends on precipitation	Sjörs 1948, Du Rietz 1954
	Wet acid peat vegetation	Tansley 1939
Nutrient conditions and base saturation	A peatland with extremely acid peat	Tansley 1939, p. 634
	A peatland with oligotrophic acid soil conditions	Ramann 1895 Ecological mire type sensu Succow 1988, Rose 1953
	A "soil-vegetation-type" that forms extremely acid peat	Tansley 1939
	A peatland with oligotrophic acid or mesotrophic acid soil conditions	Wheeler & Proctor 2000
Floristic	An area dominated by mosses of the genus *Sphagnum*	Tüxen 1983
Vegetational, phytosociological	An area with plant communities of the Oxycocco-Sphagnetea	Cf. Tüxen 1974
	A peatland with plant communities of the Oxycocco-Sphagnetea	Tüxen 1983
	An area with a vegetation belonging to the classes Oxycocco-Sphagnetea or Scheuchzerietea (Scheuchzerio-Caricetea fuscae)	Nordhagen 1936, Tüxen 1937
Geological, peat extraction	A peatland with bog peat (= peat of remnants of 'bog' plants) as the prevailing peat type in the total deposit	This book (Chapter Ukraine)
	A peatland with the peat below 0.5 m depth predominantly consisting of bog peat	This book (Chapter Belarus)
Soil science	An organic soil with an ash content of <6% and a pH of <4	This book (Chapter Ukraine)

1971), however, also includes all open fresh waters (of unlimited depth) and marine waters ("up to a depth of six metres at low tide") in its wetland definition (Ramsar Convention 2016).

A **peatland** is an area with a naturally accumulated layer of peat at the surface.

The criterion 'naturally accumulated' is necessary to exclude areas where peat has been artificially piled up, such as in the storage room of a peat processing factory. In this general definition we refrain from proposing a minimum thickness of the peat layer. For concrete mapping purposes, however, a concrete peat thickness has to be chosen. Varying with country and scientific discipline, peatlands have been defined as having a minimum thickness of 20, 25, 30, 40, 45, 50, 60 or 70 cm of peat (cf. Agriculture Canada 1987), although many peatland statistics do not mention a minimum thickness at all. In 1936, the Sub-commission for Peat Soils of the International Society of Soil Science adopted the following definition: "For land to be designated as peatland, the depth of the peat layer, excluding the thickness of the plant layer, must be at least 20 cm on drained and 30 cm on undrained land" (Tibbets 1969). In Germany the 'peatland' limit was in former times 20 cm and is currently 30 cm (Schneider 1976), but also 25 cm has been used occasionally (Keppeler 1922). In Ireland the limit is 45 cm for undrained and 30 cm for drained areas (Bord na Mona 1985). In Europe a commonly used minimum peat depth for peatlands is 30 cm (cf. Kivinen 1980, Kivinen & Pakarinen 1980, 1981). This value and similar values have a practical background, both from an ecological (most roots are found in the uppermost 30 cm

Box 3.1: What are we talking about? (translated from Weber 1903)

'What is a 'Moor'? This question has been answered differently by those who have addressed the question. The botanist Sendtner and with him many other botanists understood and still understand 'Moor' as an association of living plants. Senfft declared 'Moore' to be peculiar accumulations of water that 'normally present the place of the thickest peat deposits'. Others took and take 'Moore' for a certain soil type, that is considered to be equivalent to peat in general or, like Ramann, at least for a certain kind of peat. In contrast, Wollny regarded 'Moor' as a location characterised by the occurrence of peat and I have expressed myself in the same way.

It is obvious that, depending on the position towards these concepts, ideas on the characteristics of 'Moore' must be very different. Effective communication is prohibited, as long it is not realised that other parties with the same term refer to completely different, although possibly causally related, objects. And complete confusion must arise, when a scientist uses the same word in different senses, without realising that different concepts are being mixed up completely, as one occasionally notices in the literature.

Such confusion is not only fatal for handling purely scientific, but also practical and technical questions. The uncertainty about the meaning of 'Moor' has above all obstructed one very important thing: reliable mapping of 'Moore' and accurate statistics on their size and occurrence'.

of soil) and from an agricultural point of view (somewhat deeper than standard plowing depth, Weber 1902). The criterion 'minimum peat depth of 30 cm' excludes many (sub)arctic and (sub)alpine areas with a shallow peat layer. The presence or absence of vegetation is not relevant for an area to be called a peatland.

According to FAO (2006) **organic soils** (**Histosols**) are soils having organic material, either:

1. 10 cm or more thick starting at the soil surface and immediately overlying ice, continuous rock, or fragmental materials, the interstices of which are filled with organic material; or
2. cumulatively within 100 cm of the soil surface either 60 cm or more thick if 75% (by volume) or more of the material consists of moss fibres or 40 cm or more thick in other materials and starting within 40 cm of the soil surface.

Organic material has one or both of the following:

1. 20% or more organic carbon in the fine earth (by mass); or
2. if saturated with water for 30 consecutive days or more in most years (unless drained), one or both of the following:
   a. (12 + [clay percentage of the mineral fraction × 0.1])% or more organic carbon in the fine earth (by mass); or
   b. 18% or more organic carbon in the fine earth (by mass).

The FAO (2015) definition of histosols is almost the same, that of organic material is slightly different and simplified.

The 2006 IPCC (Eggleston et al. 2006) definition of organic soil follows the 2006 FAO definition of histosol, but refrains from defining a minimum thickness of the organic layer to allow for country specific approaches. The same approach is taken by in the 2014 Wetland Supplement of IPCC (Hiraishi et al. 2014), who included 'peatland' in '**(land with) organic soil**', but omitted the thickness criterion, thus permitting often historically determined, country-specific definitions of organic soils.

Peat is sedentarily accumulated material consisting of at least 30% (dry mass) of dead organic material.

The concept "sedentära bildningar" ('sedentary formations') was introduced by von Post (1922) to distinguish peats from sediments. Sedentary ('sitting') means in this context 'formed on the spot and not transported after its formation and death'. Peat differs in this respect from organic sediments such as lake deposits (gyttjas, cf. von Post 1862, Grosse-Brauckmann 1961) and folisols (Blattmudde, 'Waldtorf', Kühn 1929), which originate from organic matter 'falling' from above (planktonic material, resp. leaves and branches; 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 (Succow & Stegmann 2001a).

The sedentary character of peat was brilliantly described by Gough (1793): "If we examine its structure, it will be discovered to consist principally of flexible, branched fibres, variously interwoven, and twisted together. Their arrangement proves, that they grew where they are lodged; and that they were not brought into their present situation by any extraordinary agent, such as an inundation; for, had this been the case, instead of a compact substance, we should have found an incoherent mass of heterogeneous things, thrown loosely together without texture or connection." (In fact the peat produced at a specific moment does not stay at exactly the same level, but slowly moves downward as a result of decomposition of the peat below that level, Frolking et al. 2014.)

Varying with country and scientific discipline, peat has been defined as requiring a minimal content by dry weight of 5, 15, 30, 50, or 65% of organic material (Andrejko et al. 1983, Agriculture Canada 1987, Driessen & Dudal 1991, Succow & Stegmann 2001b). In this book we use– unless otherwise stated – a minimum value of 30%, which is often encountered in definitions of peats and organic soils in European literature. This 30% is a practical criterion, because between 8% and 30% it is impossible to assess the organic matter content in the soil manually in the field (Volker Schweikle, pers. comm. 2003). Because clastic materials (sand, silt, clay) and organic matter have particle densities of 2.2–2.9 g cm^{-3} and 1.0–1.5 g cm^{-3} respectively (Rühlmann et al. 2006), 30% dry mass of organic material means that – apart from the water – more than half of the soil volume consists of organic matter. The fact that the organic matter content is expressed as a percentage of total dry mass leads to the counterintuitive situation that peat with about 50% of organic matter (and the rest sand or clay) has the same density of organic matter (mass per volume) as pure peat (100 % of organic matter) (Barthelmes et al. 2015a).

A **mire** is a peatland with a vegetation that forms peat.

A term for an ecosystem with active peat formation is useful, because peat forming ecosystems differ strongly from non-peat forming ecosystems (including degrading peatlands), especially with respect to their climatic and hydrologic regulation functions (Joosten & Clarke 2002) and biodiversity. The use of the term 'mire' for such concept in English was proposed by Godwin & Conway (1939): "No word at present exists in English to convey the sense of the Nordic 'myr', which is a term meaning both any kind of peatland, and at the same time the vegetation type characteristic of such land. It is proposed to attempt to establish the use of the English word 'mire' in this general sense, as a term embracing all kind of peatlands and all kinds of peatland vegetation."

An important point of discussion (and confusion) has always been, whether a 'mire' necessarily has to be a 'peatland', i.e. an area with peat. Weber (1902, p. 226) very explicitly rejects the notion of Sendtner (1854) that there are 'mires' without peat. Sjörs writes (1948, English summary p. 279): "Most mire communities form peat (or mire peat), but there are also mire communities without or with very poor peat-formation." Later he defined mires as "wetlands with a vegetation which usually forms peat" (Rydin et al. 1999, p. 91). The term 'usually' in this definition is unclear, as "swamp forests with alder […] are not treated as mires", even though peat accumulation rates in some alder (*Alnus glutinosa*) forests exceeds that of the best *Sphagnum* bogs (Barthelmes et al. 2006). The confusion arises, because the focus is apparently purely on the vegetation cover. A vegetation that is 'usually' (i.e. most of the time) peat accumulating should, however, have resulted in the presence of peat, unless the vegetation is very young. Du Rietz (1954, cf. Du Rietz 1957) defines a mire as 'any naturally delimited unit of (at least largely) peat forming vegetation on (at least temporarily) wet peat soil and containing a number of species characteristic for such vegetation, including the peat formed since the beginning of peat formation.' We think it is fair to restrict the term 'mire' to a peat accumulating peatland. All other wet lands with a potentially peat producing vegetation but without peat (or with a peat layer that does not comply with the minimum thickness criterion for calling them 'peatland') are included under the term 'swob'.

A **swob** is a wetland with a vegetation that may produce peat.

In some countries with abundant peat accumulating wetlands, the concept of 'land with a peatland vegetation' (i.e. with the "mire communities" of Sjörs 1948) is widespread. The most important examples are the Finnish 'suo' and the Russian 'болото'. Both terms are largely referring to areas where a type of vegetation occurs that *may*, but not necessarily *does* produce peat. Here we use 'swob' as a general term for this concept.

The difference between a swob and a wetland is that the latter may also encompass land with vegetation that does not produce peat, e.g. wetlands dominated by *Juncus* or *Typha*. Other examples of swobs are 'fen meadows', i.e. humid fens with wetland plants where as a result of superficial drainage slow peat degradation is taking place (Klimkowska et al. 2015), and calcareous spring ecosystems where calcium carbonate precipitation is so rapid that the resulting deposit does not qualify as peat (Stegmann & Succow 2001).

3.3 Peatland terms: origins and relations

3.3.1 Introduction

We asked the authors of the country chapters (Part II of this book) to provide an overview of the peatland terms in the language(s) of their country and to define these terms as clearly as possible. Aim was to expose (subtile) differences in meaning that would be lost by translation into English. Having collected so many words from so many languages, the temptation arises to further analyse the material: to what extent do terms and concepts relate to each other, from where did they originate, how did form and meaning change during the evolution of vocabularies and languages?

Regretfully only few semantic and etymologic studies into peatland terms exist (e.g. Crompvoets 1981, Crompvoets & van de Wijngaard 1987, Jansma 2004, Aapala & Aapala 2006, Thier 2007) and none of them addresses the full linguistic richness of the languages of Europe (cf. Annex). The scarcity of comparative linguistic studies, especially with respect to historical relationships beween languages and peatland words, and our own lack of expertise in that field hold the risk of naively establishing associations between words on the basis of form, sound, and meaning, while disregarding inflection, age, and sound changes to which terms may have been subject (Hock & Joseph 2009). Our tentative attempt hopefully serves as an invitation to correct and complement.

In the following chapters, we shortly describe the history and diversity of peoples (Chapter 3.3.2) and languages (Chapter 3.3.3) in Europe. In Chapter 3.3.4, we present a selection of important peatland terms/concepts and some ideas on their relationship and descent. Further information on the use of terms in various languages, their possible root(s), and their non-peatland 'relatives' can be found in the Annex (p. 87 ff.).

3.3.2 The diversity and history of peoples in Europe

The ancestors of contemporary Eurasians are believed to have left Africa some 60,000 to 50,000 years ago (60 to 50 ka; Seguin-Orlando et al. 2014). By 40 ka *Homo sapiens sapiens* had spread over large parts of Europe, from present-day Russia to the United Kingdom (Fu et al. 2016). Between 8 and 5 ka, Near Eastern Neolithic groups brought farming to Europe and partly replaced the genetically distinct resident hunter-gatherers (Skoglund et al. 2012, Seguin-Orlando et al. 2014, Mathieson et al. 2015). Then, around 5 ka (3000 BCE), the Neolithic farming cultures in temperate Eastern Europe were largely replaced by the Early Bronze Age Yamnaya culture, which rapidly spread from its homeland in the Pontic-Caspian steppe to occupy an area from what is now Hungary to the Urals. By 2800 BCE the Yamnaya culture had also expanded westward and shaped the Corded Ware culture, which replaced the Neolithic farmers in northern and central temperate Europe (Allentoft et al. 2015), concurrent with substantial declines in population (Hinz et al. 2012). Genomics demonstrate that in Bronze Age Europe and Asia large-scale population movements took place, which brought a strong 'Caucasian' genetic input in the population of hunter-gatherer and Neolithic farmer groups (Allentoft et al. 2015, Haak et al. 2015). These genetic changes were accompanied by profound social and economic changes, including the spread of domesticated horses and wheeled transport (Anthony 2007, Kristiansen & Larsson 2005, Callaway 2015b). Concurrent with its westward expansion, the Yamnaya culture also spread out further eastward across the steppes into Asia (Allentoft et al. 2015). The intensity and geographical extent of Yamnaya migration is not yet completely understood, but DNA data suggest "a massive migration into the heartland of Europe from its eastern periphery" with steppe migrants replacing 75% of the population of central Europe (Haak et al. 2015, Callaway 2015a).

The low genetic diversity in contemporary West-Eurasians results from population growth after the Bronze Age, combined with continuing gene flow between populations (Allentoft et al. 2015). Today, all European populations can be genetically characterised as various mixtures of 'western European hunter-gatherer', Early Neolithic, and Yamnaya components, with some outlier populations showing additional genetic influence from populations from Siberia and the Near East (Haak et al. 2015). The migration and mixing of peoples and cultural developments have shaped the languages of Europe.