Peatlands are important natural ecosystems with high value for biodiversity conservation, climate regulation and human welfare. This Main Report of the global Assessment on Peatlands, Biodiversity and Climate Change was prepared over three years by a team of experts. It reviews the key scientific information on peatlands in relation to biodiversity and climate change. The Assessment has been welcomed by the Parties to the Convention on Biological Diversity.

Selected overall findings of the assessment include:

> Peatlands are the most efficient terrestrial carbon-storing ecosystems. While covering only 3% of the World's land area, their peat contains twice as much carbon as all global forest biomass.
>
> Peatlands are critical for biodiversity conservation and support many specialised species and unique ecosystems, and can provide a refuge for threatened species.
>
> Degradation of peatlands is a major and growing source of anthropogenic greenhouse gas emissions. Carbon dioxide emissions from peatland drainage, fires and exploitation are estimated to currently be equivalent to at least 3,000 million tonnes per annum or equivalent to more than 10% of the global fossil fuel emissions.
>
> Climate change impacts are already visible through the melting of permafrost peatlands and desertification of steppe peatlands. Impacts of climate change on peatlands are predicted to significantly increase in the future.
>
> Conservation, restoration and wise use of peatlands are essential and very cost-effective measures for long-term climate change mitigation and adaptation as well as biodiversity conservation.
>
> There is an urgent need to strengthen awareness, understanding and capacity to manage peatlands in most countries - to address peatland degradation and biodiversity conservation and climate change.

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assessment on peatlands, biodiversity and climate change

main report

UNEP GEF Global Environment Centre WETLANDS INTERNATIONAL

About Global Environment Centre

The Global Environment Centre is a Malaysia-based non-profit organization with activities at local, national and global level to address environmental issues of global concern. It was established in 1998 and supports field programmes in more than 15 countries mainly in the Asia Pacific region as well as information exchange and policy work at the global level. It works primarily through multi-stakeholder partnerships and collaboration with networks of like-minded organisations.

Its work includes:

- Integrated management of peatlands for biodiversity and climate change
- Forest and wetland conservation
- River restoration and management
- Community-based natural resources management
- Awareness and Capacity Building on global environment issues

It has been recognized by the Parties to the Convention on Biological Diversity for its work on peatlands and also river basin management. It is a founding partner of the ASEAN Peatland Management Initiative endorsed by the ten ASEAN member Countries. It coordinates many networks and partnerships at local and international level.

About Wetlands International

Wetlands International works to sustain and restore wetlands and their resources for people and biodiversity. It is an independent, not-for-profit, global organisation. Based mostly in the developing world, it has 20 regional, national or project offices with a presence in all continents and a headquarters in Wageningen, the Netherlands.

It works in over 100 countries to tackle the most pressing problems affecting wetlands. With the support of governmental and NGO members and donors, it promotes and demonstrates the positive role that wetlands can play in addressing biodiversity loss, poverty and climate change. Its work ranges from research and community-based field projects to advocacy with governments, corporates and international policy fora and conventions. Wetlands International works through partnerships and is supported by contributions from an extensive specialist expert network and tens of thousands of volunteers.

Foreword by the Secretariat of the Convention on Biological Diversity

The seventh meeting of the Conference of the Parties to the Convention on Biological Diversity (CBD), held in Malaysia in 2004, welcomed the proposed Assessment on Peatlands, Biodiversity and Climate Change. It is with great pleasure to see this significant undertaking present its final conclusions.

The Assessment has demonstrated the importance of the biodiversity associated with these ecosystems, the services they provide and their critical role in sustaining livelihoods, especially in tropical areas. The role of peatlands in greenhouse gas regulation has also been clearly articulated.

We now need to raise the profile of these ecosystems in the debate on linkages between wetlands, biodiversity and climate change for the conclusions drawn in this assessment demonstrate one of the clearest opportunities for win-win outcomes. We have already moved in this direction. The twelfth meeting of the Subsidiary Body on Scientific, Technical and Technological Advice, held in Paris in July 2007, noted the importance of the outcomes of this assessment and requested that the Secretariat of the CBD, in collaboration with the secretariats of relevant multilateral environment agreements and other relevant partners, review opportunities for further action to support the conservation and sustainable use of the biodiversity of tropical forested peatlands, as well as other wetlands, and to report on progress to the ninth meeting of Conference of the Parties in Bonn in May 2008. These concrete steps demonstrate that at Convention level we are serious about paying attention to the issues identified. But the most important need is for this progress to be reflected in real changes to the policies, management and use of peatlands on the ground.

The Assessment has helped put these important ecosystems on the map, addressed the important issues and identified the responses that are needed. I would like to thank all of the people involved in contributing to this assessment. I have every confidence that it will make a major difference to improving the long-term sustainability of peatlands and therefore go down in history as a significant contribution towards the achievement of the 2010 biodiversity target.

Ahmed Djoghlaf
Executive Secretary
Convention on Biological Diversity (CBD)

Foreword by the United Nations Environment Programme

Climate change is emerging as the defining political, as well as environmental, concern of our era. But, while emerging issues, such as avoided deforestation, are increasingly on the agenda, peatlands have been largely left out of formal negotiations under such instruments as the UN Framework Convention on Climate Change (UNFCCC) and its associated Kyoto Protocol, as well as the UN Convention on Biological Diversity (CBD).

Tropical peat swamps, boreal forests and arctic permafrost regions, as well as temperate bogs, are a true global heritage, occurring in more than 180 countries. Although they cover only 3 percent of the land area, they store nearly 30 per cent of all global soil carbon. They hold approximately as much carbon as is found in the atmosphere or as in the total of terrestrial biomass.

As such, peatlands currently present a significant unrealized opportunity for cost-effective measures in mitigating and adapting to climate change. However, time is running out. The continued burning, degradation, drainage and exploitation of peatlands all over the globe, and particularly in Southeast Asia due to forest fires, constitute a 'time bomb' of massive amounts of below-ground stored carbon ready to be released in the atmosphere. This will not only undo much of the mitigation effort already achieved, but also go against the principles and goals of global greenhouse gas emission reduction.

As well as being the most important long-term carbon store in the terrestrial biosphere, peatlands have broader significance. They provide water resources regulation and a wide range of other valuable goods and services to industrial as well as agricultural societies. Peatland ecosystems are diverse and unique, and often provide the last refuge for endangered species.

This timely Global Assessment of Peatlands, Biodiversity and Climate Change has been produced as part of the UNEP/GEF Integrated Management of Peatlands for Biodiversity and Climate Change project, led by Wetlands International and the Global Environment Centre, and funded by the Global Environment Facility and various other donors. Both lead agencies and their partners have been instrumental in putting peatlands and their wise use high on the agenda of the CBD Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA) and of the Conferences of Parties (CoP) to both the CBD and the UNFCCC, as well as the Ramsar Convention on Wetlands of International Importance.

UNEP is glad that this publication's policy recommendations have been adopted by the CBD SBSTTA July 2007 Recommendation No XII/5 'Proposals for Integration of Climate Change Activities within the Program of Work of the [CBD] Convention', to advise the upcoming CBD CoP 9 , and request the CBD Executive Secretary to convey its message to the UNFCCC CoP 13. This assessment helps to strengthen the political agenda, both on peatlands and on Reduced Emissions from Deforestation and Degradation (REDD). It provides options for the sustainable management of peatlands, and builds a case for a cost effective contribution to averting further increases in carbon emissions worldwide, in developing as well as developed countries.

It also complements previous UNEP-supported work, such as the GEF Soil Organic Carbon project, developing measurement methodologies on carbon stock and fluxes, and the Assessments of Impacts and Adaptations to Climate Change project (AIACC), developed with the UNEP/WMO Intergovernmental Panel on Climate Change (IPCC) and funded by the GEF, to advance scientific understanding of climate change vulnerability and adaptation options in developing countries. The Carbon Benefits Project (CBP) – Modeling, Measurement, and Monitoring, a planned UNEP/World Bank initiative, supported through the GEF, will further benefit peatland and REDD climate mitigation programming by developing additional methodologies specifically to determine the carbon benefits of GEF programme investments. UNEP looks forward to working even more intensively with global partners in the future to incorporate peatlands and their dominant role in carbon emission mitigation into international agreements and programmes.

Achim Steiner
United Nations Under-Secretary-General
Executive Director, UNEP

Foreword by Global Environment Centre and Wetlands International

Peatlands are one of the world's most important ecosystems covering over 400 million ha and representing about a third of the estimated area of the world's wetlands. The global Assessment on Peatlands, Biodiversity and Climate Change brings together vital information for the first time in one volume. It includes analyses of information from numerous studies through out the world on different aspects of peatland functions, values and management and their importance to both biodiversity conservation and global climate regulation. The Assessment has revealed that peatlands are the most important terrestrial ecosystem for carbon storage and hence for regulating climate. It has also documented the key role that peatlands play in conservation of biodiversity at genetic, species and ecosystem levels. It emphasizes that peatlands also play a critical role in water resource management and provide critical resources and livelihood to millions of poor people around the world.

The Assessment has concluded that the current status and use of peatlands in most parts of the world is not sustainable. Peatlands are degrading worldwide - releasing their stored carbon and losing their value for biodiversity conservation and water resource management at an alarming rate. Millions of people are now negatively affected in different regions by fires, floods and water shortages as a result of peatland degradation. As the world's climate changes – the situation is predicted to worsen, as increased temperatures and more frequent extreme events have further impacts on peatlands, further reducing our adaptive capacity.

However, the Assessment also provides evidence that relatively simple changes in peatland management can limit and even reverse negative impacts. Optimisation of water management in peat, especially by reducing drainage is the most important measure to reduce greenhouse gas emissions while reducing degradation and biodiversity loss. It makes a strong case that conservation and rehabilitation of peatlands is a major, cost-effective tool to address climate change while providing co-benefits for poverty reduction and biodiversity conservation.

Wetlands International and the Global Environment Centre – the two lead partners in the development of this assessment are pleased to report these findings to the global community. We hope that this will stimulate further debate and action both within the frameworks of the global environmental conventions (including CBD, UNFCCC, UNCCD and the Ramsar Convention) as well as direct action by all sectors at the country and local level in each region of the world. We commit to continue our work together and with other partners to seek global action to conserve and sustainably use our peatland resources.

Jane Madgwick
Chief Executive Officer
Wetlands International

Faizal Parish
Director
Global Environment Centre

Executive Summary

This Executive Summary presents the key findings of the global Assessment on Peatlands, Biodiversity and Climate Change. The Assessment was prepared through a review of scientific information on the nature and value of peatlands in relation to biodiversity and climate change, the impact of human activities and potential sustainable management options. It responds to decisions by a range of global environmental conventions, including the Convention on Biological Diversity (CBD) (programmes of work on inland water, forest and mountain biodiversity as well as the cross cutting issue on biodiversity and climate change), the Ramsar Convention on Wetlands (Guidelines for global action on peatlands). It is also a contribution to the UN Framework Convention on Climate Change (UNFCCC) and the UN Convention to Combat Desertification (UNCCD). The Assessment has been specifically welcomed by the Conference of Parties of the CBD.

The Assessment was prepared in the period 2005-2007 under the coordination of a multidisciplinary international team of peatland, biodiversity and climate change specialists. Its preparation was supported by UNEP-GEF and a range of other supporters.

Major overall findings

Peatlands are important natural ecosystems with high value for biodiversity conservation, climate regulation and human welfare. Peatlands are those wetland ecosystems characterized by the accumulation of organic matter (peat) derived from dead and decaying plant material under conditions of permanent water saturation. They cover over 4 million km^2 worldwide, occur in over 180 countries and represent at least a third of the global wetland resource.

Inappropriate management is leading to large-scale degradation of peatlands with major environmental and social impacts. Rehabilitation and integrated management of peatlands can generate multiple benefits including decreasing poverty, combating land-degradation, maintaining biodiversity, and

mitigating climate change. Concerted action for the protection and wise use of peatlands should therefore be a global priority linking work at global regional and local levels.

Some of the major overall findings of the assessment are:

- Peatlands are the most efficient terrestrial ecosystems in storing carbon. While covering only 3% of the World's land area, their peat contains as much carbon as all terrestrial biomass, twice as much as all global forest biomass, and about the same as in the atmosphere.
- Peatlands are the most important long-term carbon store in the terrestrial biosphere. They sequester and store atmospheric carbon for thousands of years.
- Peatlands are critical for biodiversity conservation and support many specialised species and unique ecosystem types, and can provide a refuge for species that are expelled from non-peatland areas affected by degradation and climate change.
- Peatlands play a key role in water resource management storing a significant proportion of global freshwater resources. Peatland degradation can disrupt water supply and flood control benefits.
- Degradation of peatlands is a major and growing source of anthropogenic greenhouse gas emissions. Carbon dioxide emissions from peatland drainage, fires and exploitation are estimated to currently be equivalent to at least 3,000 million tonnes per annum or equivalent to more than 10% of the global fossil fuel emissions.
- Peatland degradation affects millions of people around the world. Drainage and fires in SE Asian peat swamp forests jeopardise the health and livelihood of millions of people in several countries in

the region. The destruction of mountain peatlands in Africa, Asia and Latin America threatens the water and food supply for large rural and urban populations.

- Climate change impacts are already visible through the melting of permafrost peatlands and desertification of steppe peatlands. In the future, impacts of climate change on peatlands are predicted to significantly increase. Coastal, tropical and mountain peatlands are all expected to be particularly vulnerable.
- Conservation, restoration and wise use of peatlands are essential and very cost-effective measures for long term climate change mitigation and adaptation as well as biodiversity conservation.
- Optimising water management in peatlands (i.e. reducing drainage) is the single highest priority to combat CO_2 emissions from oxidation and fires as well as address peatland degradation and biodiversity conservation.
- There is an urgent need to strengthen awareness, understanding and capacity to manage peatlands in most countries – to address peatland degradation, biodiversity conservation and climate change.

Key characteristics of peatlands

Peatlands are wetland ecosystems that are characterized by the accumulation of organic matter (peat), which is derived from dead and decaying plant material under conditions of permanent water saturation. There are many different types of peatland, depending on geographic region, terrain and vegetation type. A major distinction is between bogs (which are fed only by precipitation and are nutrient-poor) and fens (which are fed by surface or ground water as well as precipitation and tend to be more nutrient rich). Peatlands may be naturally forested or naturally open and vegetated with mosses, sedges or shrubs. Peat formation is strongly influenced by climatic conditions and topography. In northern latitudes or high altitudes the temperature may be high enough for plant growth but too low for vigorous microbial activity. Significant areas of peatlands are found in tropical and sub-tropical latitudes where high plant productivity combines with slow decomposition as a result of high rainfall and humidity. In some cases peatlands were formed during wetter climatic periods thousands of years ago but, in the drier prevailing climate, no longer accumulate peat.

- The major characteristics of natural peatlands are permanent water logging, development of specific vegetation, the consequent formation and storage of peat and the continuous (upward) growth of the surface.
- Peatland distribution and peat formation and storage are primarily a function of climate, which determines water conditions, vegetation productivity and the decomposition rate of dead organic material.
- Peatlands are found in almost every country, but occur primarily in the boreal, subarctic and tropical zones as well as appropriate zones in mountains. More detailed assessment of their extent, nature and status is needed. Many peatlands are not recognised as such but are classified as marshes, meadows, or forests.
- As a result of different climatic and biogeographic conditions, a large diversity of peatland types exists. However because of similar ecohydrological processes, they share many ecological features and functions.
- In northern regions and highlands, peatlands and permafrost are mutually dependent.
- The complex relationship between plants, water, and peat makes peatlands vulnerable to a wide range of human interference.

Peatlands and people

Peatlands and people are connected by a long history of cultural development. Humans have directly utilised peatlands for thousands of years, leading to differing and varying degrees of impact.

For centuries, some peatlands worldwide have been used in agriculture, both for grazing and for growing crops. Large areas of tropical peatlands have in recent years been cleared and drained for food crops and cash crops such as oil palm and other plantations. Many peatlands are exploited for timber or drained for plantation forestry. Peat is being extracted for industrial and domestic fuel, as well as for use in horticulture and gardening. Peatlands also play a key role in water storage and supply and flood control.

- Many indigenous cultures and local communities are dependent on the continued existence of peatlands, but peatlands also provide a wealth of valuable goods and services to industrial societies such as livelihood support, carbon storage, water regulation and biodiversity conservation.
- The many values of peatlands are generally poorly recognised and this is one of the root causes of degradation or avoidable conflicts about uses.
- The main human activities that impact peatlands include drainage for agriculture and forestry, land clearing and burning, grazing, peat extraction, infrastructure and urban development, reservoir construction, and pollution.
- Deterioration of peatlands has resulted in significant economic losses and social impacts, and has created tensions between key stakeholders at local, regional and international levels.
- Peatlands are often the last expanses of undeveloped land not in private ownership, so they are increasingly targeted by development that needs large areas of land, such as airports, plantations, windfarms and reservoirs.

Peatlands and past climate change

The form and function of peatlands and the distribution of peatland species depend strongly on the climate. Therefore climate exerts an important control on ecosystem biodiversity in peatlands.

Climate change is a normal condition for the Earth and the past record suggests continuous change rather than stability. The last 2 million years of Earth history (the Quaternary period) are characterised by a series of cold glacial events with warmer intervening interglacial periods. Peatlands expanded and contracted with changes in climate and sea-level. Many current peatlands started growth following the warming after the last glacial maximum. The initiation of new peatlands has continued throughout the postglacial period in response to changes in climate and successional change.

- Climate is the most important determinant of the distribution and character of peatlands. It determines the location and biodiversity of peatlands throughout the world.
- The earth has experienced many climate changes in the past, and peatland distribution has varied in concert with these changes. Most peatlands began growth during the current postglacial period. Peatland extent has increased over the course of the last 15,000 years.
- In the constantly accumulating peat, peatlands preserve a unique record of their own development as well as of past changes in regional vegetation and climate .
- Records show that the vegetation, growth rate (carbon accumulation) and hydrology of peatlands were altered by past climate change. This information helps in making predictions of future impacts of climate change.
- Peatlands affect climate via a series of feedback mechanisms including: sequestration of carbon dioxide, emission of methane, change in albedo and alteration of the micro- and mesoclimate
- Natural peatlands were often resilient to climate changes in the past. However, the rate and magnitude of predicted future climate changes and extreme events (drought, fires, flooding, erosion) may push many peatlands over their threshold for adaptation.
- Some expected impacts of recent climate change are already apparent in the melting of permafrost peatlands, changing vegetation patterns in temperate peatlands, desertification of steppe peatlands, and increased susceptibility to fire of tropical peatlands.
- Human activities such as vegetation clearance, drainage and grazing have increased the vulnerability of peatlands to climate change.

Peatlands and biodiversity

Peatlands are unique, complex ecosystems of global importance for biodiversity conservation at genetic, species and ecosystem levels. They contain many species found only or mainly in peatlands. These species are adapted to the special acidic, nutrient poor and water-logged conditions of peatlands. They are vulnerable to changes resulting from direct human intervention, changes in their water catchment and climate change, that may lead to loss of habitats, species and associated ecosystem services. The biodiversity values of peatlands demand special consideration in conservation strategies and land use planning.

Peatlands play a special role in maintaining biodiversity at the species and genetic level as a result of habitat isolation and at the ecosystem level as a result of their ability to self-organise and adapt to different physical conditions.

- Although species diversity in peatlands may be lower, they have a higher proportion of characteristic species than dryland ecosystems in the same biogeographic zone.
- Peatlands may develop sophisticated self-regulation mechanisms over time, resulting in high within-habitat diversity expressed as conspicuous surface patterns.
- Peatlands are important for biodiversity far beyond their borders by maintaining hydrological and micro-climate features of adjacent areas and providing temporary habitats or refuge areas for dryland species.
- Peatlands are often the last remaining natural areas in degraded landscapes and thus mitigate landscape fragmentation. They also support adaptation by providing habitats for endangered species and those displaced by climate change.
- Peatlands are vulnerable to human activities both within the peatland habitats themselves and in their catchments. Impacts include habitat loss, species extinction and loss of associated ecosystem services.
- The importance of peatlands for maintaining global biodiversity is usually underestimated, both in local nature conservation planning and practices, as well as in international convention deliberations and decisions.

Peatlands and carbon

Peatlands are some of the most important carbon stores in the world. They contain nearly 30 percent of all carbon on the land, while only covering 3 percent of the land area. Peatland ecosystems contain disproportionately more organic carbon than other terrestrial ecosystems.

Peatlands are the top long-term carbon store in the terrestrial biosphere and - next to oceanic deposits – Earth's second most important store. Peatlands have accumulated and stored this carbon over thousands of years, and since the last ice age peatlands have played an important role in global greenhouse gas balances by sequestering an enormous amount of atmospheric CO_2.

Peatlands in many regions are still actively sequestering carbon. However the delicate balance between production and decay easily causes peatlands to become carbon sources following human interventions. Anthropogenic disturbances (especially drainage and fires) have led to massive carbon losses from peatland stores and generated a significant contribution to global anthropogenic CO2 emissions. Peatland restoration is an effective way to maintain the carbon storage of peatlands and to re-initiate carbon sequestration.

- While covering only 3% of the World's land area, peatlands contain at least 550 Gt of carbon in their peat. This is equivalent to 30% of all global soil carbon, 75% of all atmospheric C, equal to all terrestrial biomass, and twice the carbon stock in the forest biomass of the world. This makes peatlands the top long-term carbon store in the terrestrial biosphere.

- Peatlands are the most efficient carbon (C) store of all terrestrial ecosystems. Peatlands contain more carbon per ha than other ecosystems on mineral soil: in the (sub)polar zone, 3.5 times, in the boreal zone 7 times, in the tropical zone 10 times as much.
- Peatlands store carbon in different parts of their ecosystem (biomass, litter, peat layer, mineral subsoil layer), each with their own dynamics and turn-over.
- The peat layer is a long-term store of carbon. Peatlands have accumulated and stored this carbon over thousands of years. Permanent waterlogging and consequent restricted aerobic decay is the main prerequisite for continued long-term storage of carbon in peatlands.
- Most coal and lignite and part of the 'mineral' oil and natural gas originated from peat deposits in previous geological periods.
- Peat growth depends on a delicate balance between production and decay. Natural peatlands may shift between carbon sink and source on a seasonal and between-year time scale, but the accumulation of peat demonstrates that their long-term natural balance is positive.
- Human interventions can easily disturb the natural balance of production and decay turning peatlands into carbon emitters. Drainage for agriculture, forestry and other purposes increases aerobic decay and changes peatlands from a sink of carbon to a source. Peat extraction (for fuel, horticulture, fertilizers, etc.) transfers carbon to the atmosphere even more quickly.
- Peatland drainage also facilitates peat fires, which are one of the largest sources of carbon released to the atmosphere associated with land management.
- Fluxes of dissolved (DOC) and particulate (POC) organic carbon constitute important carbon losses from peatlands that may substantially increase as a result of human impact and climate change
- Carbon dioxide emissions from peatland drainage, fires and exploitation are estimated to currently be at least 3000 million tonnes a year equivalent to more than 10% of the global fossil fuel emissions.
- Peatland conservation and restoration are effective ways to maintain the peatland carbon store and to maximise carbon sequestration with additional benefits for biodiversity, environment and people.

Peatlands and greenhouse gases

The world's peatlands influence the global balance of three main greenhouse gases (GHG) – carbon dioxide, methane and nitrous oxide (CO_2, CH_4, and N_2O). In their natural state, peatlands remove CO_2 from the atmosphere via peat accumulation and they emit methane. The long-term negative effect of methane emissions is lower than the positive effect of CO_2 sequestration. By sequestering and storing an enormous amount of atmospheric CO_2 peatlands have had an increasing cooling effect, in the same way as in former geological eras, when they formed coal, lignite and other fossil fuels.

When peatlands are disturbed, they can become significant sources of carbon dioxide and at the same time do not totally stop emitting methane which is still intensively released from drainage ditches and under warm wet conditions even from milled peat surfaces and peat stockpiles. Drained peatlands, especially after fertilization, can become an important source of nitrous oxide. Peatland restoration reduces net GHG emissions to the atmosphere, certainly in the long-term.

- Natural peatlands affect atmospheric burdens of CO_2, CH_4 and N_2O in different ways and so play a complex role with respect to climate.
- Since the last ice age peatlands have sequestered enormous amounts of atmospheric CO_2.
- GHG fluxes in peatlands have a spatial (zonal, ecosystem, site and intersite) and temporal (interannual, seasonal, diurnal) variability, which needs to be considered in assessment and management.
- Small changes in the ecology and hydrology of peatlands can lead to big changes in GHG fluxes through influence on peatland biogeochemistry.

- In assessing the role of peatlands in global warming, the different time frame and radiative forcing of continuous CH_4 emission and CO_2 sequestration should be carefully evaluated rather than using simple global warming potential calculations.
- Anthropogenic disturbances (especially drainage and fires) have led to massive increases in net emissions of GHG from peatlands, which are now a significant contribution to global anthropogenic emissions.
- Peatland drainage leads to increased CO_2 emissions in general and a rise of N_2O release in nutrient rich peatlands. It may not always significantly reduce CH_4 emissions.
- Because of the large emissions from degraded peatlands, rewetting and restoring them is one of the most cost-effective ways of avoiding anthropogenic greenhouse gas emissions.

Impacts of future climate change on peatlands

The strong relationship between climate and peatland distribution suggests that future climate change will exert a strong influence on peatlands. Predicted future changes in climate of particular relevance to peatlands include rising temperatures, changes in the amount, intensity and seasonal distribution of rainfall, and reduced snow extent in high latitudes and in mountain areas. These changes will have significant impacts on the peatland carbon store, greenhouse gas fluxes and biodiversity.

- Global temperature rises of 1.1-6.4°C will be higher in northern high latitudes where the greatest extent of peatlands occurs.
- High latitudes are likely to experience increased precipitation while mid latitudes and some other regions may have reduced precipitation at certain times of the year. All areas may be susceptible to drought due to increased variability in rainfall.
- Increasing temperatures will increase peatland primary productivity by lengthened growing seasons. Decay rates of peat will increase as a result of rising temperatures, potentially leading to increased CH_4 and CO_2 release. Changes in rainfall and water balance will affect peat accumulation and decay rates.
- Tree lines in northern peatlands will shift poleward as a result of higher summer temperatures, and hydrological changes may result in increased forest extent on open peatlands. The resulting reduced albedo will positively feed back on global warming.
- Increased rainfall intensity may increase peatland erosion. This may be amplified by anthropogenic drainage and overgrazing.
- Greater drought will lead to an increase of fire frequency and intensity, although human activity is expected to remain the primary cause of fire.
- Hydrological changes, combined with temperature rise, will have far-reaching effects on greenhouse gas exchange in peatlands. Drier surfaces will emit less CH_4, more N_2O and more CO_2, and the converse for wetter surfaces.
- Melting permafrost will probably increase CH_4 emissions and lead to increased loss of dissolved organic carbon in river runoff.
- Inundation of coastal peatlands may result in losses of biodiversity and habitats, as well as in increased erosion, but local impacts will depend on rates of surface uplift.
- The combined effect of changes in climate and resultant local changes in hydrology will have consequences for the distribution and ecology of plants and animals that inhabit peatlands or use peatlands in a significant part of their life cycles.
- Human activities will increase peatland vulnerability to climate change in many areas. In particular, drainage, burning and over-grazing will increase the loss of carbon from oxidation, fire and erosion.

Management of peatlands for biodiversity and climate change

The sustainable management of peatlands requires the integration of approaches for biodiversity, climate change and land degradation and close coordination between different stakeholders and economic sectors.

The Assessment has found that:

- The current management of peatlands is generally not sustainable and has major negative impacts on biodiversity and climate.
- Strict protection of intact peatlands is critical for the conservation of biodiversity and will maintain their carbon storage and sequestration capacity and associated ecosystem functions.
- Changes in peatland management (such as better water and fire control in drained peatlands) can reduce land degradation and can limit negative impact on biodiversity and climate.
- Optimising water management in peatlands (i.e. reducing drainage) is the single highest priority to combat carbon dioxide emissions from peat oxidation and fires as well as address peatland degradation and biodiversity conservation.
- Restoration of peatlands can be a cost-effective way to generate immediate benefits for biodiversity and climate change by reducing peatland subsidence, oxidation and fires.
- New production techniques such as wet agriculture ('paludiculture') should be developed and promoted to generate production benefits from peatlands without diminishing their environmental functions.
- A wise use approach is needed to integrate protection and sustainable use and to protect peatland ecosystem services from increasing pressure from people and changing climate.
- Peatland management should be integrated into land use and socio-economic development planning by a multi-stakeholder, ecosystem, river basin and landscape approach.
- Enhancing awareness and capacity, addressing poverty and inequity, and removing perverse incentives are important to tackle the root causes of peatland degradation.
- Local communities have a very important role as stewards of peatland resources and should be effectively involved in activities to restore and sustain the use of peatland resources.
- The emerging carbon market provides new opportunities for peat swamp forest conservation and restoration and can generate income for local communities.
- Plans for integrated peatland management should be developed at local, national and regional levels as appropriate.

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Glossary

Aapa mire: A mire complex with minerotrophic peat layer and pronounced surface pattern of wet **flarks** and **hummocky** mostly oligotrophic dwarf-shrub strings.

Acrotelm: Upper peat producing layer of mire with a distinct hydraulic conductivity gradient in which water level fluctuations and most of horizontal water flow occur.

Blanket bog: Bog in a very humid climate, which forms a blanket-like layer over the underlying mineral soil.

Bog (raised bog): Mire raised above the surrounding landscape and only fed by precipitation.

Catotelm: The lower permanently water saturated layer in a peatland, with relatively low hydraulic conductivity and rate of decay.

Cut-away peatland: What remains of a peatland after all the peat which can be economically removed has been extracted.

Fen: Peatland receiving inflow of water and nutrients from the mineral soil. Distinguished from **swamp forest** by a lack of tree cover or with only a sparse crown cover. Indistinctly separated from **marsh** (which is always beside open water and usually has a mineral substrate). **See also minerotrophic peatland.**

Flark: Elongated wet depressions with sparse vegetation (mud-bottom) in string mires; most of the time waterlogged or even flooded. Also called rimpi (Finnish).

Flood mires: Mires in which periodical flooding by an adjacent open water body (sea, lake, river) enables peat accumulation.

Fluvial mires: Mires associated with rivers.

Geogenous peatland: Peatland subject to external flows.

Hummock: Peatland vegetation raised 20-50 cm above the lowest surface level, characterized by drier-occurring mosses, lichens, and dwarf shrubs.

Infilling, terrestrialization: The process whereby peat develops on the margins and into the centers of ponds, lakes, or slow-flowing rivers.

Lagg: A narrow fen or swamp surrounding a bog, receiving water both from the bog and from the surrounding mineral soil.

Limnogenous peatland: Geogeneous peatland that develops on the ground along a slow-flowing stream or a lake.

Marsh: Develops mostly on mineral soil, but could be a peatland. Beside open water, with standing or flowing water, or flooded seasonally. Submerged, floating, emergent, or tussocky vegetation.

Mesotrophic peatland: Intermediate peatland between minerotrophic and ombrotrophic.

Minerotrophic peatland: Peatland receiving nutrients through an inflow of water that has filtered through mineral soil.

Mire: Synonymous with any peat-accumulating wetland. A peatland where peat is currently forming and accumulating.

Mire complex: An area consisting of several hydrologically connected, but often very different, mire types; sometimes separated by mineral soil uplands.

Mixed mire: A mire type with **bog** and **fen** features or sites in close connection.

Moor: Synonymous of mire (Europe).

Muskeg: Large expanse of peatlands or bogs (Canada and Alaska).

Oligotrophic peatland: Peatland with poor to extremely poor nutrient levels.

Ombrogenous peatland: Peatland receiving water and nutrients only from atmosphere. Also called ombrotrophic. See **Bog.**

Palsa mire: Peatland complex of the discontinuous permafrost region, with palsas (peat mounds or plateaus usually ombrotrophic) swelling out above the adjacent unfrozen peatland (usually fen).

Paludification: The formation of marsh or waterlogged conditions: also refers to peat accumulation which starts directly over a formerly dry mineral soil.

Peat: Fibric organic sedentarily accumulated material with virtually all of the organic matter allowing the identification of plant forms; consists of at least 30% (dry weight) of dead organic material.

Peat extraction: The excavation and drying of wet peat and the collection, transport and storage of the dried product.

Peatland: An area with or without vegetation with a naturally accumulated peat layer at the surface of at least 30 cm depth.

Polygon mire: Permafrost peatland patterned complex which consists of closed, roughly equidimensional polygons bounded by cracks, with high or low centers, and often with ridges along the margins.

Primary peat formation: The process whereby peat is formed directly on freshly exposed, wet mineral soil.

Pristine mire: Mire which has not been disturbed by human activity in a way which damages its ecosystem.

Quaking bog (quagmire, quaking mat, floating mat, Schwingmoor): Mire in which the peat layer and plant cover is only partially attached to the basin bottom or is floating like a raft.

Raised bog: Deep peat deposits that fill entire basins, develop a dome raised above ground water level, and receive their inputs of nutrients from precipitation.

Riparian peatland: Peatland adjacent to a river or stream, and, at least periodically, influenced by flooding.

Sloping mire: Mire with a sloping surface.

Soligenous peatland: Geogenous peatland that develops with regional interflow and surface runoff.

Spring mire: Mire that is mainly fed by spring water.

String: Elongated ridges in patterned fens and bogs arranged perpendicularly to the slope with **hummock** or **lawn** level vegetation.

Swamp: Usually forested minerotrophic peatland. Separate from wooded fens due to a denser tree canopy. Also peat swamp forest.

Terrestrialisation: The accumulation of sediments and peats in open water. See **infilling**.

Topogenous peatland: Geogenous peatland with a virtually horizontal water table, located in basins.

Wetland: Land with the water table near the surface. Inundation lasts for such a large part of the year that the dominant organisms must be adapted to wet and reducing conditions. Usually includes shallow water, shore, marsh, swamp, fen, and bog.

Wetland (Ramsar definition): Areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static, flowing, fresh, brackish or salt, including areas of marine water, the depth of which at low tide does not exceed six meters.

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Contents

1 Introduction

Lead authors: Faizal Parish, Andrey Sirin, David Lee, Marcel Silvius

The Assessment on Peatlands, Biodiversity and Climate Change aims to provide a synthesis of knowledge on the important functions and roles of peatland ecosystems in relation to biodiversity conservation, sustainable use and climate change mitigation and adaptation. It has been prepared over the period 2005–2007 by a team of specialists on peatland assessment and management, biodiversity, climate change and other fields. This chapter provides an introduction to the importance of peatlands and presents more details on the process by which the assessment was developed.

1.1 Rationale for the Assessment

Peatlands are key natural ecosystems. Peatlands are one of the most important natural ecosystems in the world. They are of key value for biodiversity conservation and climate regulation, and provide important support for human welfare. They cover over 400 million ha in about 180 countries and represent a third of the global wetland resource. Currently they are being degraded in many regions as a result of land clearance, drainage, fire and climate change. This not only causes a reduction in biodiversity and direct benefits for people; it also generates further problems. The protection and wise use of peatlands should be a global priority.

Peatlands are wetland ecosystems that are characterised by the accumulation of organic matter called "peat" which derives from dead and decaying plant material under high water saturation conditions. In peatlands, water, peat and the specific vegetation that lives in these ecosystems are strongly interconnected. If any one of these components is removed, or should the balance between them be significantly altered, the nature of the peatland fundamentally changes.

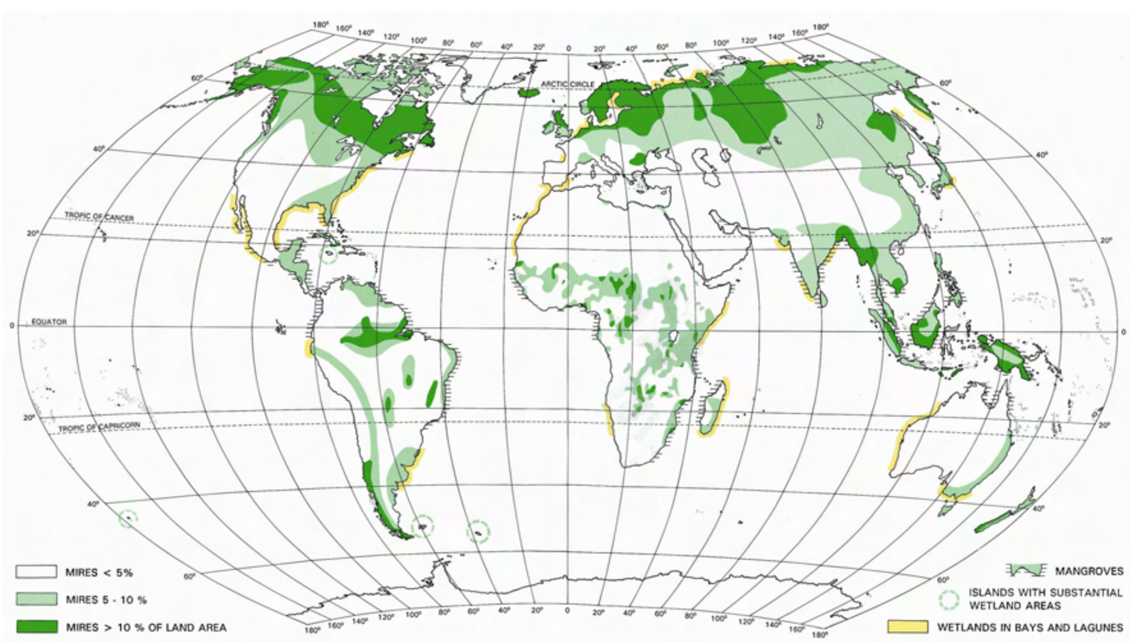


Figure 1.1: Distribution of mires/peatlands in the world (After Lappalainen 1996 [1]).

[1] Lappalainen E. (Ed.). Global Peat Resources. International Peat Society and Geological Survey of Finland, Juskä.

There are two major types of peatland: bogs (which are mainly rain-fed and nutrient-poor) and fens (which are mainly fed by surface or ground water and tend to be more nutrient rich). However there are many different variations of peatland type, depending on geographic region, altitude terrain and vegetation. Peatlands may be naturally forested or naturally open and vegetated with mosses or sedges. Another distinction that can be made is between peatlands where peat is currently being formed – these are known as mires – and areas which formerly had peat formation, but due to human interventions or climate change, peat is no longer developing.

Peat

Peat accumulates where plant growth exceeds decay. Water is the most important factor limiting decay. A permanently high water table can be provided by high precipitation or by ground or surface water flow. Diversity in bedrock and water flow conditions is responsible for the large variety of peatland types. A second cause of slow decay rates are the low temperatures that occur at high latitudes and altitudes.

Peat accumulates at a rate of about 0.5 – 1 mm per year (or 5-10m over 10,000 years) with locally strong variation.

Peat can be formed from mosses, sedges, grasses, trees, shrubs, or reeds. In northern regions, mosses are the main peat-forming plants while trees are the main species in the tropics. Most peatlands that exist today formed in the last 10,000 years since the last ice age.

Peatlands can be found in all parts of the world, but their distribution is concentrated in specific zones. Peat formation is strongly influenced by climatic conditions and topography. This may be in areas in northern latitudes or high altitudes where the temperature is high enough for plant growth but too low for vigorous microbial activity. Significant areas of peatlands are also found in tropical and sub-tropical latitudes where high plant growth rates combine with slow decomposition as a result of high rainfall and water-logged conditions. In some cases peatlands were formed during wetter climatic periods thousands of years ago, but peat may no longer accumulate due to recent climate changes.

Kenya

Sweden

Canada

Malaysia

Peatlands can be found in almost all geographic areas – from the Arctic to the Tropics. Suitable conditions for the formation of peatlands occur in many parts of a landscape – they can be found on watersheds and in river valleys, around lakes, along seashores, in high mountains and even in the craters of volcanoes.

*Table 1.1: Peatland Uses & Functions**

Agriculture	For centuries, peatlands in Europe, North America and Asia have been used for grazing and for growing crops. Large areas of tropical peatlands have been cleared and drained for food crops and cash crops such as oil palm and other plantations in recent years. However large-scale drainage of peatlands for agriculture has often generated major problems of subsidence, fire, flooding, and deterioration in soil quality.
Forestry	Many peatlands are exploited for timber harvesting. In northern and eastern Europe and Southeast Asia, peatlands have been drained for plantation forestry, whereas in North America and Asia some timber extraction takes place from un-drained peatlands. The peat swamp forests of Southeast Asia used to be an important source of valuable timber species such as Ramin (*Gonostylus bancanus*), but over-exploitation and illegal trade have led to trade restrictions under CITES (the Convention on International Trade in Endangered Species, drawn up in 1973).
Peat Extraction	Peat has been extracted for fuel, both for domestic as well as industrial use, particularly in Europe but also in South America. Peat extraction for the production of growing substrates and gardening is a multi-million dollar industry in North America and Europe. For instance, the Netherlands import 150 million Euros worth of peat every year as a substrate for horticulture.
Subsistence use	Peatlands play a central role in the livelihoods of local communities. In the tropics peatland-related livelihood activities include the harvesting of non-timber forest products such as rattans, fish, Jelutung latex (a raw material used in chewing gum), medicinal plants and honey. In parts of Europe and America the collection of berries and mushrooms is important for some rural populations. All over the world we can find indigenous peoples whose livelihoods and cultures are sustained by peatlands.
Water regulation	Peatlands consist of about 90% water and act as vast water reservoirs, contributing to environmental security of human populations and ecosystems downstream. They play an important role in the provision of drinking water, both in areas where catchments are largely covered by peatlands, and in drier regions where peatlands provide limited but constant availability of water.
Biodiversity	Peatlands constitute habitats for unique flora and fauna which contribute significantly to the gene pool. They contain many specialised organisms that are adapted to the unique conditions. For example, the tropical peat swamp forests of Southeast Asia feature some of the highest freshwater biodiversity of any habitat in the world and are home to the largest remaining populations of orangutan.
Research, education and recreation	Peatland ecosystems play an important role as archives. They record their own history and that of their wider surroundings in the accumulated peat, enabling the reconstruction of long-term human and environmental history. Because of their beauty and often interesting cultural heritage, many peatlands are important for tourism.
Carbon storage	Peatlands are some of the most important carbon stores in the world. They contain nearly 30% of all carbon on the land, while only covering 3% of the land area. Peatlands in many regions are still actively sequestering carbon. However, peatland exploitation and degradation can lead to the release of carbon. The annual carbon dioxide emission from peatlands in Southeast Asia by drainage alone is at least 650 million tonnes, with an average of 1.4 billion tonnes released by peatland fires. This represents a major portion of global carbon emissions and causes significant social and economic impacts in the ASEAN region.

* Each of the uses and functions described above is elaborated in more detail in the different chapters of the Assessment.

Russia

Argentina

Peatlands are closely linked with the economy and welfare of society. Peatlands are important to human beings due to their unique role in environmental regulation, aesthetic values, and the wide range of goods and services they provide. Humans have directly utilised peatlands for thousands of years, leading to varying degrees of impact. In many areas of the world, peatlands are beautiful landscapes with a unique biodiversity. They are deeply integrated into socioeconomic processes and have become an historical arena of conflicts and contradictions in land use. Inappropriate or short-sighted exploitation of the functions and services from peatlands have often negatively affected the livelihoods of local communities and created broader threats to society through increasing floods, water shortages and air pollution from fires.

Peatlands and Climate Change. Peatlands play an important role in climate regulation. Over the past 10,000 years peatlands have absorbed an estimated 1.2 trillion tonnes of carbon dioxide, having a net cooling effect on the earth. Peatlands are now the world's largest terrestrial long-term sink of atmospheric carbon storing twice as much carbon as the biomass of the world's forests.

However in the last 100 years, clearance, drainage and degradation of peatlands have turned them from a net store to a source of carbon emissions. This, combined with large-scale emissions from use of fossil fuels and forest clearance, has contributed to significant global increases in the concentration of carbon dioxide and other greenhouse gases – the root cause of global climate change. Current predictions by the Intergovernmental Panel for Climate Change (IPCC) of significant changes in global temperature and rainfall regimes have significant implications for peatland ecosystems. In many cases the predicted changes are expected to have a negative impact on peatlands and to exacerbate the rate of degradation and release of stored carbon.

Peatlands and global environment conventions. In the global arena of international environment conventions, peatlands are of growing concern within the deliberations of the UN Framework Convention on Climate Change (UNFCCC), the Convention on Biological Diversity (CBD), the Convention to Combat Desertification (UNCCD), and the Ramsar Convention on Wetlands. The UNFCCC (See Box below) is primarily concerned with the implications of peatland loss and its impact on the global greenhouse gas emissions, as well as in possible mitigation and adaptation options. The CBD and the Ramsar Convention have focused on the importance of peatlands for biodiversity conservation and the potential for the sustainable use of biological resources. Parties to the UNCCD have raised concerns about the degradation of peatland in the dryland regions and the loss of associated ecosystem services such as water supplies. As peatlands are one single ecosystem, it is important that their management is addressed in an integrated manner. The challenge will be to find new management methods that simultaneously generate benefits for biodiversity and climate change, while also addressing the important needs of local communities.

1.2 Purpose of the Assessment

The Assessment on Peatlands, Biodiversity and Climate Change aims to provide a synthesis of knowledge on the important functions and roles of peatland ecosystems in relation to biodiversity conservation and sustainable use and climate change mitigation and adaptation. One of the most pertinent reasons for the preparation of the Assessment is because peatlands are very often inadequately recognised as specific and valuable ecosystems in relation to either climate change or biodiversity. The Assessment has brought together diverse knowledge on peatland features, functions and services from different sources, through a multidisciplinary international task force of peatland, biodiversity and climate change experts.

Why do we need an assessment? The assessment aims to contribute to international decision-making processes relating to global problems such as biodiversity conservation, climate change, desertification, pollution, poverty and health. It will enable the identification of appropriate management and adaptation strategies for peatlands which will bring both biodiversity and climate benefits. It is intended to provide information to feed into the deliberations of the global environment conventions as well as contribute to deliberations at regional and national levels.

It also provides recommendations on the development and planning of peatland use that could be used as an information source in policy making and in the drafting of laws and regulations. For some countries with significant areas of peatland, this Assessment could be used to provide guidance and reference in the development of sustainable strategies for peatland management and to help foster understanding about the need for stakeholder interaction related to peatland management.

Recognition of the Assessment process. In February 2004, the Seventh Conference of the Parties to the Convention on Biological Diversity formally recognised the preparation of the Assessment through decision VII/15 on Biodiversity and Climate Change. This decision *"welcomes the proposed assessment on peatlands, biodiversity and climate change and encourages the involvement of parties in this assessment and in preparations for the consideration of its findings by SBSTTA prior to the ninth CBD Conference of Parties [in 2008]"*. This decision formally links the Assessment with the decision-making process of the Convention on Biological Diversity. In July 2007, the CBD SBSTTA considered and welcomed the results of the Assessment and recommended its further consideration by CBD COP 9 in May 2008. The CBD SBSTTA also mandated the Executive Secretary of the CBD to formally convey the outcomes of the Assessment to the UNFCCC COP 13 in December 2007.

Peatlands and Environmental Conventions

United Nations Framework Convention on Climate Change (UNFCCC)

In recent years there has been increasing reference to peatland in the deliberations of the UNFCCC, although there have not yet been specific decisions relating to peatlands. Peatlands and other organic soils are now assessed separately in the national assessments of greenhouse gas emissions by Annex 1 Parties. The relevance of peatlands to climate change adaptation and mitigation as well as in reducing emissions from deforestation in developing countries has been recognised by some of the parties to the convention.

Convention on Biological Diversity (CBD)

The CBD, through its decision on Biodiversity and Climate Change at COP 7 (Kuala Lumpur, 2004), has supported action to minimise peatland degradation, as well as promote the restoration of peatlands due to their significance as carbon stores and/or ability to sequester carbon. The CBD also welcomed the current Assessment on Peatlands Biodiversity and Climate Change and has incorporated peatland-related issues into its Programme of Work on Inland Water Biodiversity.

Ramsar Convention on Wetlands

The Ramsar Convention on Wetlands recognises the need for increased attention to be paid to peatland conservation and wise use, as well as addressing the climate-related functions of peatlands. In 2002 it established a Coordinating Committee to monitor progress on the implementation of its Guidelines for Global Action on Peatlands (CC-GAP), which sought to develop an implementation plan for further action and to identify priority actions for the promotion of the wise use of peatlands. The Resolution on Climate Change and Wetlands in 2002 gave specific recognition to the need to protect and restore peatlands in relation to their role in carbon storage.

Wise Use approach concerning peatlands

Conflicts between different groups arise because some significant peatland functions can only be provided by intact peatlands, while other uses lead to total transformation. To address this issue, the International Mire Conservation Group and the International Peat Society, together with other partners, have been working to promote the wise use of peatlands since 1997. The principal objective of the Wise Use process is to protect peatlands in a manner that respects the positions of all stakeholders, contributing to sustainable life for humankind. This effort has brought together those who exploit peatlands through agriculture, forestry, peat extraction and other uses with those who wish to promote non-extractive benefits such as biodiversity, freshwater, climate stability and beauty.

1.3 Outline of the Assessment

The Assessment contains a number of key synthesis chapters (2–7). These provide basic facts in relation to the following questions:

Chapter 2: What are peatlands?
Chapter 3: What is the relationship between people and peatlands?
Chapter 4: How have peatlands responded to climate changes in the past?
Chapter 5: What is the importance of peatlands in the maintenance of biodiversity?
Chapter 6: What is the role of peatlands in carbon storage and sequestration?
Chapter 7: What is role of peatlands in the flux of greenhouse gases?
The information in chapters 2-7 is synthesised and applied in chapters 8 and 9 to answer the following questions:

- What are the possible impacts of climate change on peatlands (carbon storage, GHG, biodiversity) and peatland responses to future climate change?
- How can we manage peatlands in an integrated manner to generate benefits for biodiversity and climate change?

1.4 Process of preparation of the Assessment

The overall preparation of the Assessment has been overseen by the Global Environment Centre and Wetlands International. These institutions are the joint implementers of the UNEP-GEF supported project on Integrated Management of Peatlands for Biodiversity and Climate Change. Guidance was also provided by the project steering committee comprising representatives from UNEP, GEF-STAP, IMCG, CBD and participating countries.

The Assessment was initiated just prior to CBD COP7 in February 2004, when a small expert meeting prepared a concept paper. Following the formal expression of support for the process by the CBD Conference of Parties, a request for expressions of interest was circulated to all parties to the CBD and to a broad range of peatland and climate change experts and organisations. Based on the feedback received, a number of experts from a range of disciplines and regions were identified. A first coordination meeting was held in October 2004 in Wageningen, the Netherlands, to discuss in detail the possible topics, contents and author teams. An initial outline of the Assessment was then circulated to a range of experts related to peatlands, biodiversity and climate change as well as policy makers and managers, to elicit further expressions of interest in involvement as contributing authors and reviewers. The drafting of the different chapters was initiated in 2005. Initial drafts were prepared by lead authors and were then circulated to contributing authors for specific inputs. A series of meetings of lead authors were organised in June, October and November of 2006 to review and refine the draft and address areas of overlap and synergy between the various chapters. Drafts were then circulated, reviewed and refined and the overall Assessment finalised. Key findings of the Assessment were presented to the SBSTTA meeting of CBD in July 2007. A meeting in October 2007 finalised the content and design/layout of an Executive Summary to highlight the key findings from the overall Assessment. The overall assessment report was distributed at the UNFCCC COP 13 in December 2007.

1.5 Scope and limitations

The scope and objective of the Assessment as mentioned above is rather specific. Its main aim is to focus on the assessment of two very important issues of climate change and biodiversity in relation to peatlands. In order to undertake a manageable process it was necessary to restrict the inclusion of some other related topics. In particular, two important topics which were identified for inclusion in the initial scoping could not be included in the final Assessment. These were an assessment of the function of peatlands in relation to water resources and the social and economic implications of peatland management and development. These issues are only addressed briefly in the current Assessment and it is proposed that these are subjects of separate future assessment reports.

The Assessment faced some constraints in gathering information on peatlands from different regional and scientific disciplines. The global knowledge on peatlands cuts across a number of scientific and social scientific disciplines and geographic areas. This knowledge is highly dispersed among publications in various languages and scientific schools, as well as being found amongst indigenous populations that have traditionally managed the peatlands. Despite the large body of knowledge, there are also still significant gaps. The strongest levels of inputs for the assessment came from experts from Europe, Asia and to a lesser extent North America – regions that together contain the majority of the world's peatlands and where there has been a relatively long history of peatland studies. A lower level of input was received from Africa, Latin America and the Pacific region – these parts of the world have smaller areas of documented peatlands and fewer detailed scientific studies. It is hoped that in future coverage of information from these regions can be enhanced. Nevertheless, the Assessment attempts to be as globally relevant as possible by including examples from a variety of different regions.

In the process of preparing the Assessment, efforts have been made to gather and accumulate as much available information from as wide a variety of sources as possible. Information related to the links between climate change, biodiversity and peatland have been concisely presented in the hope of raising readers' awareness of the need for a more integrated approach between different sectors to address common issues.

2 What are peatlands?

Lead author: Hans Joosten

Summary points

- A peatland is an area with a layer of dead organic material (peat) at the surface.
- The major characteristics of natural peatlands are the formation and storage of peat, permanent water logging, and the continuous upward growth of the surface.
- These characteristics determine the specific goods and services that peatlands provide. Of global importance is the long-term storage of 550 Gigatonnes of carbon as peat.
- Peatland distribution and peat formation and storage are primarily a function of climate.
- Covering 4 million km^2, peatlands are found in almost every country, but primarily in the boreal, subarctic and tropical zones. Their inventory status is (largely) insufficient.
- As a result of climatic and biogeographic differences, a large diversity of peatland types exists.
- In peatlands "plants", "water", and "peat" are mutually interdependent, making peatlands vulnerable to a wide range of human impacts.
- As a result of long development, peatlands reach a high level of internal coherence and autonomy.
- In northern regions and highlands, peatlands and permafrost are mutually dependent.
- Peatlands deserve more attention as ecosystems with special characteristics and values.

2.1 Definition

A peatland is an area with a naturally accumulated layer of dead organic material (peat) at the surface. In most natural ecosystems the production of plant material is counterbalanced by its decomposition by bacteria and fungi. In those wetlands where the water level is stable and near the surface, the dead plant remains do not fully decay but accumulate as *peat*. A wetland in which peat is actively accumulating is called a *mire* (Figure 2.1, Joosten and Clarke 2002). Where peat accumulation has continued for thousands of years, the land may be covered with layers of peat that are metres thick.

A **wetland** is an area that is inundated or saturated by water at a frequency and for sufficient duration to support emergent plants adapted for life in saturated soil conditions. The Ramsar Convention 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" concept.

Peat is dead organic material that has been formed on the spot and has not been transported after its formation.

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

A **mire** is a peatland where peat is being formed.

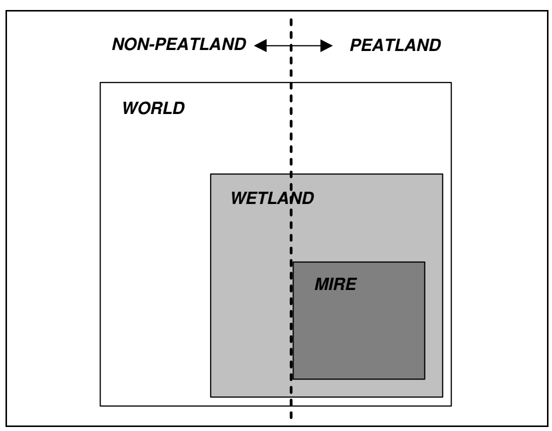


Figure 2.1: The relation between "peatland", "wetland", and "mire" (adapted from Joosten and Clarke 2002).

Dramatic examples of overlooked peatlands are the high-altitude peatlands in Central and North-East Asia, for example, in Mongolia, China, and Kyrgyzstan. These highland sedge fens (often on deep peat) are not recognized as peatlands by land users and decision makers, and are often overlooked even by specialists and experts. The peatlands are mainly used as pastures and are managed as meadows, yet they regulate river water flow by storing large amounts of ice and water (Minayeva *et al*. 2005). Local people are often not aware of the key hydrological functions of these highland peatlands.

In the Arctic regions, peatlands are often called tundra and people do not care if vegetation grows on peat or mineral soil, whereas these different ecosystems need different types of management.

Wetlands can occur both with and without peat and, therefore, may or may not be peatlands. A mire is always a peatland. Peatlands where peat accumulation has stopped, for example, as a result of drainage, are no longer mires. When drainage has been particularly severe, they are no longer wetlands (Figure 2.1, Joosten and Clarke 2002).

Peatlands are highly diverse and the peatland character of various ecosystem types is often not recognized. Peatlands are often unrecognized and overlooked. This is especially the case for mangroves, salt marshes, paddies/rice fields, boreal paludified forests, cloud forests, elfin woodlands, tropical swamp forests, highland sedge fens (pastures), spring mires, páramos, dambos, and cryosols, all of which may form peat and may have a peat soil (Joosten 2004). Peatlands may constitute almost 20 wetland categories in the Ramsar Convention Classification System, over 40 habitat types of the EU Habitat Directive, and over 60 types of Endangered Natural Habitats of the Bern Convention.

2.2 Peatland characteristics

The major characteristics of natural peatlands are permanent water logging, the formation and storage of peat, and the continuous upward growth of the surface. These characteristics determine the specific goods, services, and functions associated with peatlands. Of global importance is the long-term storage of carbon and water within peatlands. Worldwide, peatlands contain 550 Gtonnes of carbon (see chapter 6) and 10% of the global fresh water in their peat (cf. Ball 2000). Carbon storage is made possible by the permanent water-logging of the peat body. Water-logging and the continuous upward growth of the surface further determine the special and extreme site conditions to which peatland organisms are exposed. These conditions typically include:

- A scarcity of oxygen and the presence of toxic ions such as Fe^{2+}, Mn^{2+}, S^{2-} in the root layer (Hook and Crawford 1978, Sikora and Keeney 1983)
- Continuously rising water levels that can suffocate perennial plants (Van Breemen 1995, Grosse-Brauckmann 1990, Malmer *et al*. 1994)
- Spongy soil that makes trees fall over easily or drown under their own weight (Joosten and Clarke 2002)
- A scarcity of nutrients. This is the result of peat accumulation (by which nutrients are fixed in the peat), a limited nutrient supply (as in rainwater-fed mires) and chemical precipitation (as in groundwater-fed peatlands, where phosphates are bound by calcium and iron (Boyer and Wheeler 1989). The scarcity of ions in the water further complicates osmoregulation (an organism's control of the balance between water and ions) in submerged organs and organisms (Burmeister 1990)
- A generally cooler and rougher climate than the surrounding mineral soils, with stronger temperature fluctuations (Joosten and Clarke 2002)
- Acidity caused by organic acids and cation exchange (Ross 1995, Van Breemen 1995)
- The presence of toxic organic substances produced during decomposition (Verhoeven and Liefveld 1997, Salampak *et al*. 2000)
- The humus rich water, which can complicate orientation and recognition in aquatic animals.

As a result of these extreme conditions, natural peatlands are generally species-poor compared with mineral soils in the same biographic region. However, many peatland species are strongly specialised and not found in other habitats, highlighting the biodiversity value of peatland areas (see Chapter 5).

2.3 Peat formation

The accumulation of peat implies an imbalance in the production and the decay of dead organic (plant) material. Such imbalance may be caused by both the production side and the decay side of the process. A high production rate is stimulated by ample availability of plant nutrients (CO_2, P, K, N), water and warmth. A high CO_2 concentration in the atmosphere has probably been responsible for the enormous accumulation of peat in the Carboniferous and Tertiary periods that has been passed on to us as coal and lignite (Lyons & Alpern 1989, Cobb & Cecil 1993, Demchuk *et al.* 1995). While NPK-fertilization and higher temperatures may lead to higher production, decay rates generally are even higher. This therefore frustrates peat accumulation (Clymo 1983).

Differences in the chemical and structural composition of the plant material mean that some plant species and plant parts may produce peat, whereas others do not (Koppisch 2001). The most important reason for peat accumulation, however, is retarded decay due to the abundance of water (Clymo 1983, Koppisch 2001).

Water is the single most important factor enabling peat accumulation. Water-logging is a prerequisite for the creation and preservation of peat. The large heat capacity of water and the large energy demand for vaporization induce lower than ambient temperatures, whereas the limited diffusion rate of gases in water leads to a low availability of oxygen (Ball 2000, Denny 1993). The resulting relatively cold and anaerobic conditions inhibit the activities of decomposing organisms (Moore 1993, Freeman *et al*. 2001).

Coal is former peat from 300 million years ago. Lignite is former peat from 50 million years ago. Both originated probably under elevated atmospheric CO_2 concentrations.

Peat accumulation only takes place when the water level is just under, at, or just over the surface over the long-term. When water levels are too low, plant remains decay too rapidly to allow accumulation. Water levels that are too high obstruct the production of plant material because the submersed plant parts are suffocated through lack of oxygen and carbon dioxide (Ivanov 1981, Ingram and Bragg 1984**,** Alexandrov 1988, Sjörs 1990, Lamers *et al.* 1999). Peat accumulation therefore only takes place in the range of water "availability" (both in space, with regard to water levels, and time, with regard to seasons), in which the decay of organic material is inhibited more than its production. In areas with deeper and fluctuating water levels a larger part of the organic material decays. This leads to less peat accumulation and more strongly humified peat. Activities that substantially lower or raise the water level in peatlands negatively affect their peat accumulation capacity and their associated functions (Ivanov 1981).

In different parts of the world, different plant groups and plant parts are the main peat

Table 2.1: Characteristic peat forming plants in different parts of the Earth (Prager et al. 2006).

Climatic zones and sections	Dominant peat formers (physiognomy)	Dominant peat formers (taxonomy)	Dominant peat forming plant parts
Arctic / Boreal/ Oceanic	Mosses	Sphagnaceae, Hypnales	Stems, branches, leaves
Temperate / Subtropic	Reeds	Poaceae, Cyperaceae, Equisetaceae	Rhizomes, rootlets
Tropic	Trees	Angiospermae/ Dicotyledoneae	Roots

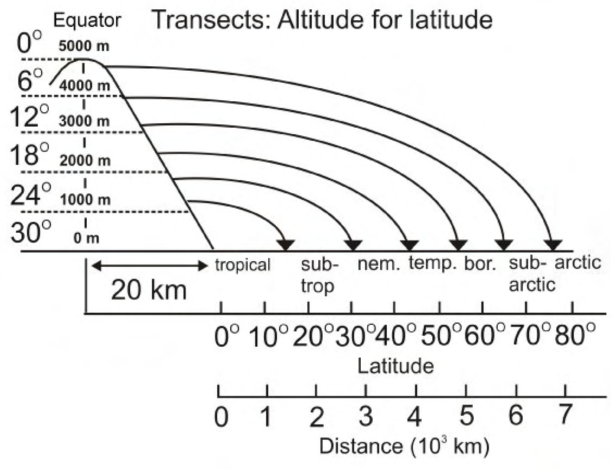


Figure 2.2: Altitude for latitude: in mountains the climate across vast latitudinal distances is represented over short elevational distances (from Körner 2003).

formers. Mosses (Bryophytes) determine peat growth in cold (e.g. boreal and subarctic) and wet-and-cool (e.g. oceanic) places (Table 2.1). A lack of water-conducting organs enables peat formation by mosses only where water loss by evapotranspiration is restricted. In these areas, where most peatlands are concentrated, peatland science came into being. Therefore moss growth is the central model of peatland development, to the extent that the same words refer to tiny Bryophyte plants and to the extensive peatlands of e.g. Flanders Moss, Lille Vild Mose, and Katin Moch (Prager *et al.* 2006). This north/west European bias has hampered the recognition of peatlands that are not dominated by mosses.

In more temperate and continental parts of the world, the drier climate forces peat formation to "go underground". There, peat is formed from the downward growing rhizomes and rootlets of grasses (Poaceae) and sedges (Cyperaceae). Peat accumulates in the first 10–20 cm below the surface, as new root material is injected into the older peat soil matrix. In tropical lowlands peat is forms even further under the surface by the roots of tall forest trees (Prager *et al.* 2006).

In natural peatlands peat typically accumulates with a long-term rate of 0.5-1 mm and 10 – 40 tonnes C per km^2 per year, with locally strong variation (see chapter 6). These general rates may be slower under less favourable climatic or hydrological conditions such as in the Arctic tundra, or faster, particularly in the tropics (Lavoie *et al.* 2005, Prager *et al.* 2006). The peatlands existing today largely originated from the end of the Late-Glacial and in the first part of the Holocene (Halsey *et al.* 1998, Campbell *et al.* 2000, MacDonald *et al.* 2006).

2.4 Peatland distribution

Peat formation is primarily a function of climate. Peatland distribution is therefore concentrated in specific climatic regions. Climate determines the amount of water available in the landscape via the amount of net precipitation, while temperature affects both the production and decay of organic material. Accumulation and maintenance of peat is only possible when the balance between production and decay is positive. Peatlands are therefore especially abundant in cold (i.e. boreal and sub-arctic) and wet (i.e. oceanic and humid tropical) regions (Figure 1.1). In areas where the precipitation/evaporation balance is less favourable for accumulation, peatlands are only found where landscape features enable water to collect. The scarcity of peatlands in the southern hemisphere is due to the absence of land in the relevant climatic zones. In mountains, zonation in altitude reflects the zonation in latitude (Figure 2.2).

Peatlands prevail on flat surfaces. As water-logging requires a flat surface, large peatlands prevail on extensive flat land areas, such as western Siberia, the Hudson Bay Lowlands (Canada), the Southeast Asian coastal plains, and the Amazon Basin (see Figure 1.1). In areas with abundant water supplies and limited water loss, peatlands may also occur on slopes. It is these conditions that can produce blanket bogs and hill slope peatlands.

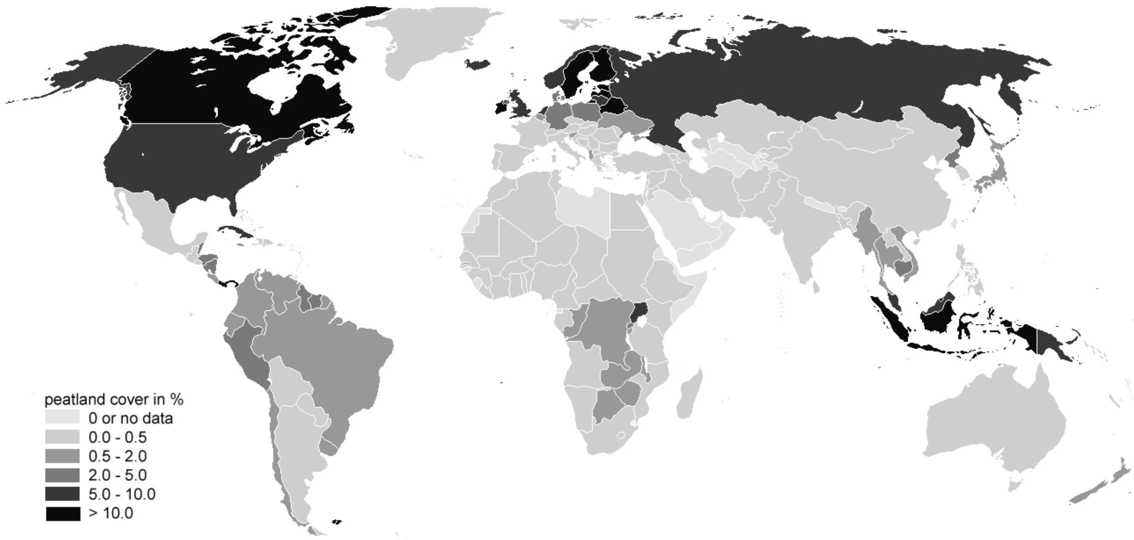


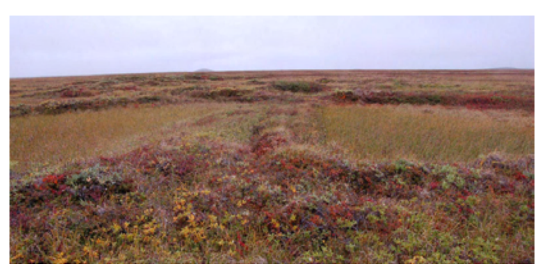
Figure 2.3: Percentage of the area covered with peatland per country (after Van Engelen and Huting 2002).

Approximately 4 million km² of the Earth (some 3% of the land area) is covered with peatland (with >30 cm of peat). Peatlands are found in almost every country of the world. Peatlands (with >30 cm of peat) cover approximately 4 million km² (Joosten and Clarke 2002, Lappalainen 1996, cf. Rubec 1996, Zoltai and Martikainen 1996). Peatlands with less than 30 cm of peat may cover an additional 5 - 10 million km² (Tjuremnov 1949, Vompersky *et al.* 1996) and are largely situated in the permafrost regions (Vompersky *et al.* 1996). Countries with the most extensive peatland area include Russia, Canada, the USA and Indonesia. Together, these countries hold over 60 % of the global peatland area (Joosten and Clarke 2002). No peatlands are as yet known in Libya, Somalia, Saudi-Arabia, Yemen, Oman, Jordan, and Turkmenistan (Figure 2.3, IMCG Global Peatland Database: www.imcg.net/gpd/gpd.htm). The distribution of peatlands across the continents is shown in Table 2.2.

The general inventory status of peatlands is (largely) inadequate. For some regions almost nothing is known about peatlands. This is the case, for example, for large parts of Africa and South America and for the mountain areas of central Asia. Major problems preventing a consistent global overview include a lack of awareness and capacity, typological differences between countries and disciplines, different inventory scales and the use of outdated data.

Eighty per cent of the global peatland area is still pristine (i.e. not severely modified by human activities). Sixty per cent of the global peatland area still actively accumulates peat. The pristine peatlands are concentrated in the (sub)arctic and boreal zones; the modified peatlands in the temperate and (sub)tropic zones (Joosten and Clarke 2002). However, part of the pristine area no longer accumulates peat because of climatic changes. This especially concerns permafrost peatlands and peatlands in the tropics (Vitt and Halsey 1994, Oechel *et al.* 1993, 1995, Malmer and Wallén 1996, Vompersky *et al.* 1998, Sieffermann *et al.* 1988).

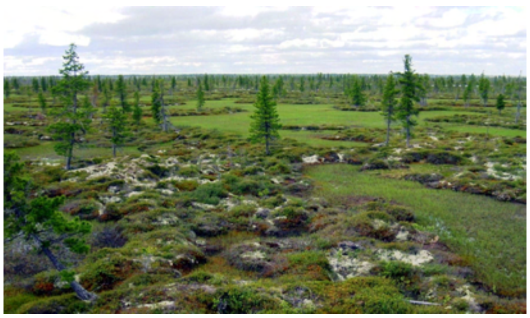
Globally, natural peatlands are destroyed at a rate of 4,000 km² per year; the global peat volume decreases by 20 km³ per year. These losses (Immirzi and Maltby 1992, Joosten and Clarke 2002) largely occurred (and occur) in the temperate and tropical zones. Fifty per cent of natural peatland loss has been attributable to agriculture, 30% to forestry and 10% to peat extraction (Joosten and Clarke 2002).



Polygon mire

Table 2.2: Distribution of peatlands (> 30 cm of peat) over the continents (after Joosten and Clarke 2002).

Continents	Total area in 10^6 km^2	% of global land area	Peatlands in km^2	% of land area	% of global peatland area
Africa	30.37	20.3	58,534	1.9	1.4
Antarctica	13.72	9.2	1	0.0	0.0
Asia	43.81	29.3	1,523,287	3.5	36.7
Australasia (Oceania)	9.01	6.0	8,009	0.1	0.2
Europe	10.40	7.0	514,882	5.0	12.4
North America	24.49	16.4	1,884,493	7.7	45.3
South America	17.84	11.9	166,253	0.9	4.0
	149.64	100.0	4,155,459	2.8	100.0



Peat plateau mire

Sedge mire

Forested fen

2.5 Peatland ecology and peatland types

In peatlands plants, water, and peat are very closely connected and mutually interdependent (Figure 2.4). These interdependencies make peatlands vulnerable to a wide range of human impacts. Plants determine the type of peat that will form as well as its hydraulic properties. The water (hydrology) determines which plants will grow, whether peat will be stored and how much decomposition will take place. The peat structure determines how the water will flow and fluctuate. These close interrelations imply that when any one component changes, the others will change too (Ivanov 1981, Davis *et al*. 2000). These changes do not necessarily all happen at once, but in the longer run, they inevitably occur. As changes take place in the different components, the mire services may change (Figure 2.5).

Raised bog

Blanket bog

Aapa mire

Papyrus swamp

Tropical peat swamp forest

Water flow connects the larger catchment area with the peatland, and various parts of a peatland with each other. A change in the water flow of the catchment or of part of the peatland may therefore influence every part of a peatland (Kulczyński 1949, Ivanov 1981, Wassen and Joosten 1996, Glaser *et al.* 1997, Couwenberg and Joosten 1999, Edom 2001b). Such interconnections may function over many kilometres (Schot 1992, Van Walsum and Joosten 1994, Glaser *et al.* 1997, Wetzel 2000).

Globally, peatlands are highly diverse, especially with respect to species and community composition (see Chapter 5). They have, however, much in common with respect to their ecohydrological functioning. A classical distinction is between *bogs* – which lay higher than their surroundings ("high mires") and are only fed by precipitation – and *fens* in landscape depressions ("low mires") – which are also fed by water that has been in contact with mineral soil or bedrock (Figure 2.6). Bogs prevail in wet climates whereas fens are ubiquitous.

Acidity and nutrient availability particularly determine plant diversity in natural peatlands. Precipitation water is poor in nutrients and somewhat acidic. Through contact with the mineral soil/bedrock the chemical properties of the water may change. As a result, peatlands in different hydro-geological settings receive water inputs of different quality (Joosten and Clarke 2002). On the basis of acidity (base saturation) and nutrient availability (trophic conditions) different "ecological peatland types" are distinguished (Table 2.3, Figure 2.7). The mesotrophic buffered (slightly acid and calcareous) peatland types are particularly threatened worldwide. Rare and threatened peatland plants mostly occur under carbonate-rich/subneutral and oligo-/mesotrophic conditions (mostly with P limitation (Wassen *et al.* 2005)). The dependence of local peatland conditions on the quality of the incoming groundwater necessitates a thorough assessment of the relationship between the hydrology and the surroundings.

Table 2.3: Ecological mire types and their pH characterization after Sjörs (1950). The pH trajectories are largely determined by chemical buffer processes and therefore probably have a worldwide validity.

Peatland type	**pH range**
Bog	3.7 – 4.2
Extremely poor fen	3.8 – 5.0
Transitional poor fen	4.8 – 5.7
Intermediate fen	5.2 – 6.4
Transitional rich fen	5.8 – 7.0
Extremely rich fen	7.0 – 8.4

The functions and functioning of peatlands are strongly dependent on their hydrological and genetic features (including their position in the landscape and the conditions of peat formation). Classically a distinction is made between *terrestrialization*, when peat develops in open water, and *paludification*, when peat accumulates directly over a formerly dry mineral soil (Figure 2.8). In *terrestrialization* *peatlands* peat formation takes place in floating mats (e.g. *Papyrus* islands) or under water on the bottom of the lake (e.g. many *Phragmites* stands). Peatlands may also form on formerly dry soils when the water level in the catchment rises slowly due to external reasons (*water rise peatlands*). *Flood peatlands* are periodically flooded by rivers, lakes or seas. Without externally induced water level rise (due to climate change, changes in land use, rising sea levels, rising river beds, beaver dams, the origin of stagnating layers in the soil and so on) all these *horizontal* peatlands only accumulate peat for a limited time.

Of special importance for carbon sequestration and water regulation are sloping peatlands. These have an inclining surface plane and mainly horizontal water movement. In sloping peatlands the laterally flowing water is retarded by vegetation and peat. As a result, vegetation growth and peat accumulation cause a continuous rise of the water table in the peatland and often also in the catchment area. In this way these peatlands maintain their peat sequestration capacity autonomously. Sloping peatlands are subdivided into percolation, surface flow, and acrotelm peatlands. These are discussed in more detail below.

Percolation peatlands are found in areas with a large water supply that is very evenly distributed over the year. Percolation peatlands are characterized by weakly decomposed or coarse peats (due to roots) that are highly permeable. Consequently, the water flows via a considerable part of the peat body (Wassen and Joosten 1996). Percolation peatlands are normally groundwater-fed because only large catchment areas can guarantee a large and continuous water supply in most climates. Groundwater-fed percolation mires are characteristic of the temperate zones. In steadily humid climates such as in the Kolchis lowlands (Georgia) ombrogenous *Sphagnum*-dominated percolation peatlands (percolation bogs) exist (Haberl *et al.* 2006).

Surface flow peatlands are found in areas with an almost constant water supply but with short periods of net water losses. In the short periods of water deficit, oxygen penetrates the peat. The resulting stronger decomposition and compaction make the peat less permeable, forcing the water to overflow the mire surface. Because of the low hydraulic conductivity of their peat and the large water supply, surface flow peatlands can occur on, and with, steep slopes. Three subtypes of natural surface flow peatlands can be distinguished: *Blanket bogs* – these are solely fed by rainwater and only occur under very oceanic conditions. *Hill slope peatlands* – these are additionally fed by (near-) surface run-off from the surrounding mineral slopes. S*pring peatlands* – these are largely fed by artesian groundwater; their peat often includes carbonates and silicates that have precipitated from or washed in with the groundwater.

Acrotelm peatlands occupy an intermediate but very special position. The plant material they produce is very resistant to decay and so the top decimetres of the peatland are little decomposed, open and permeable. Water flow is largely confined to these top layers. The distinct gradient in hydraulic conductivity in the top layers, combined with its large storage capacity, constitutes a very efficient water-level regulation device, the so-called *acrotelm*. Globally, the *Sphagnum*-dominated *raised bog* is the most important acrotelm peatland type.

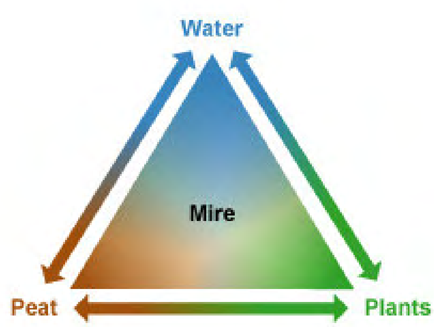


Figure 2.4: The interrelations between plants, water and peat in a mire.

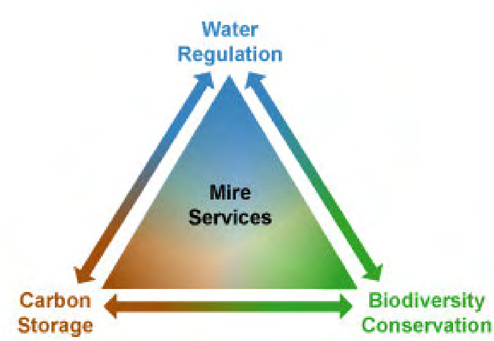


Figure 2.5: Important services of mires and peatlands.

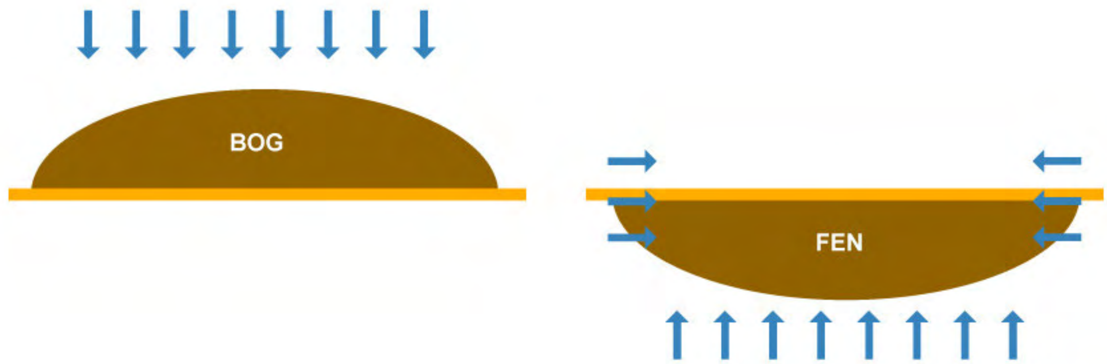


Figure 2.6: The classical difference between "bog" and "fen" peatlands. Shaded = peat; Arrow = water flow.

The global distribution of raised bogs, far beyond the area where percolation and surface flow peatlands may exist, illustrates the effectiveness of the acrotelm regulation mechanism (Joosten 1993). Also many tropical swamp peatlands may be assigned to this type (Joosten submitted).

As a result of water, vegetation, and peat interacting over an extensive period of time ("self-organisation"), sloping peatlands develop high levels of internal coherence and autonomy, reflected in their typical shapes and sophisticated surface patterns. Peatlands are not merely a type of land cover. Many sloping peatlands develop high levels of internal coherence, self-regulation, and autonomy and almost organismatic properties (Ivanov 1981, Joosten 1993).

This is expressed in the development of sophisticated patterning, such as those in string mires/aapa fens, plateau bogs, concentric bogs (Figure 2.9), and eccentric bogs (Glaser 1999, Couwenberg 2005, Couwenberg and Joosten 1999, 2005).The presence of such patterns has

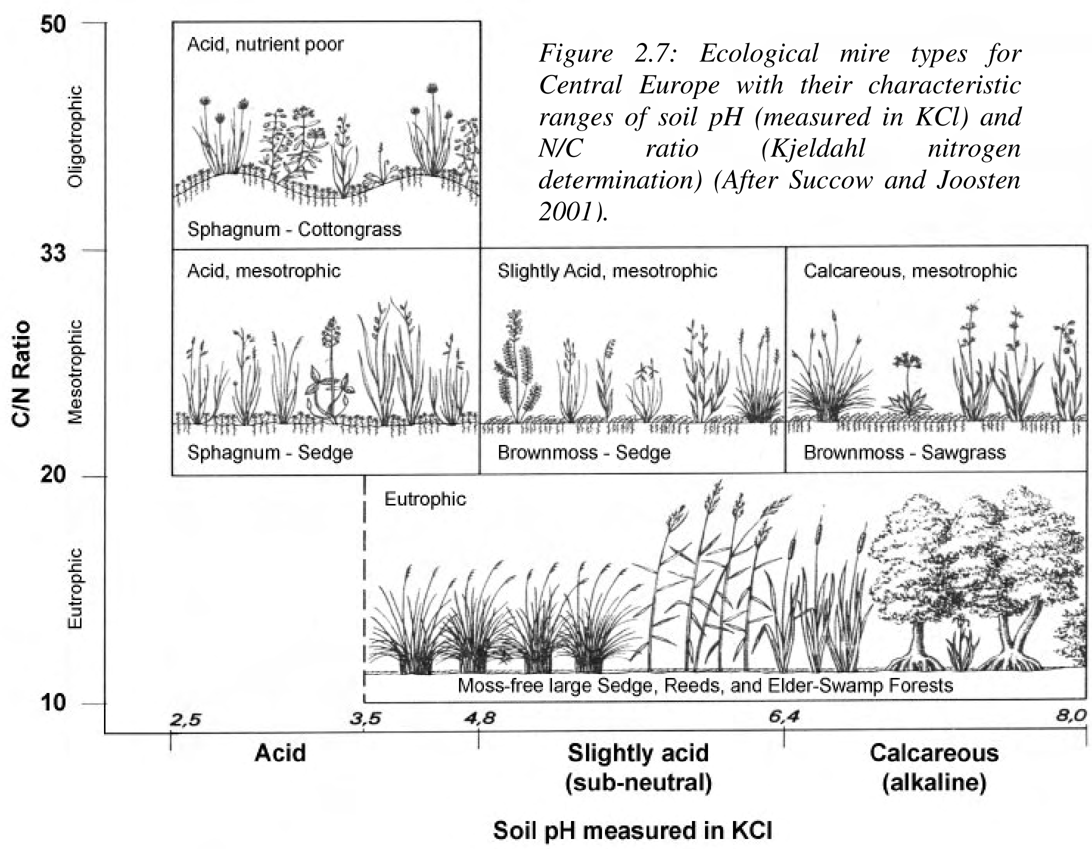


Figure 2.7: Ecological mire types for Central Europe with their characteristic ranges of soil pH (measured in KCl) and N/C ratio (Kjeldahl nitrogen determination) (After Succow and Joosten 2001).

important consequences for biodiversity, water flow and greenhouse gas emission

External mechanisms, specifically ice formation and permafrost, may contribute to the configuration of peatland macro- and micro-patterns. Ice formation in the Arctic, subarctic and boreal zones give rise to specific morphological peatland types (Tarnocai and Zoltai 1988, Zoltai and Pollet 1093, Zoltai *et al.* 1988). These include *polygon mires* in areas with continuous permafrost (Minke *et al.* 2007) and *palsa* (frost mound), and *peat plateau mires* in areas of discontinuous permafrost. The relationship between peatlands and permafrost is reciprocal: specific peatland types are created by permafrost, whereas peatlands cause the development of permafrost in the zone of discontinuous permafrost.

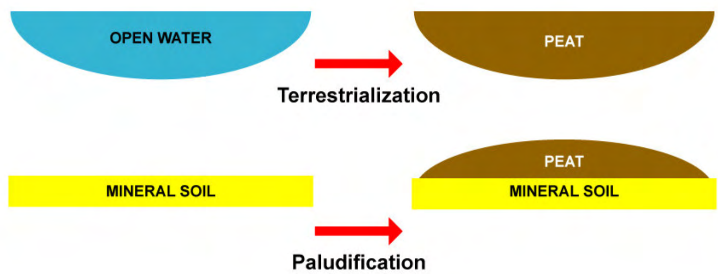


Figure 2.8: The difference between terrestrialization and paludification.

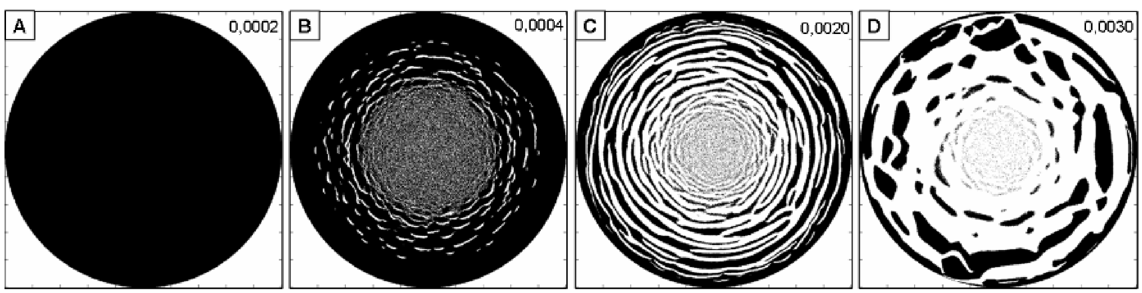


Figure 2.9: Bogs change their surface patterns but not their overall functioning as a consequence of climate change. The sequence shows the effect of increasing precipation (from Couwenberg and Joosten 2005).

Peatlands are ecosystems with extraordinary characteristics for biodiversity conservation, water regulation and carbon storage/ sequestration, and deserve more attention.

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3 Peatlands and People

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Summary points

- Peatlands and people are connected by a long history of cultural development; the livelihoods of substantial parts of rural populations in both developed and developing economies still significantly depend on peatlands.
- From the tropics to the Arctic the environmental security and livelihoods of indigenous cultures and local communities depend on peatland ecosystem services and the steady supply of natural peatland resources.
- The value of peatlands as an ecosystem providing crucial ecological, hydrological and other services has generally been disregarded.
- People have commonly treated peatlands as wastelands, using them in many destructive ways, without taking the long-term environmental and related socio-economic impacts into account.
- The main human impacts on peatlands include drainage for agriculture, cattle ranching and forestry, peat extraction, infrastructure developments, pollution and fires.
- Deterioration of peatlands has resulted in significant economic losses and social detriment, and has contributed to tensions between key stakeholders at local, regional and international levels.
- Lack of awareness and insufficient knowledge of peatland ecology and hydrology have been major root causes of peatland deterioration.
- The key economic, cultural and environmental role of peatlands in many human societies calls for a "wise use" approach that minimises irreversible damage and sustains their capacity to deliver ecosystem services and resources for future generations.

3.1 Human – peatland interactions

Peatlands and people are connected by a long history of cultural development. Peatlands have always been part of human history. Since pre-history, hunter-gatherers and traditional farmers have exploited peatlands by harvesting plants, game, fish, forage, fuel and other useful products. Bog bodies, tools, ornaments, weapons and other archaeological remains found in abundance in peatlands, are testament to the long and intimate relationship between people and peatlands during the whole Holocene (Joosten in press). Historical accounts describe people who lived in and depended almost entirely on wetlands, from the "half amphibious" Fen Slodgers in the English Fenlands (Wheeler 1896) to the wetland peoples of recent times, such as the Marsh-Arabs (Ma'dan) of Southern Iraq (Thesinger 1964) and the Kolepom people in Irian Jaya, Indonesia (Serpenti 1977). Large-scale human modification of peatlands for agriculture started with the origin of rice cultivation in China about 6000 years BC (Glover and Higham 1996). The Minyans drained and subsequently cultivated the Kopais basin in Greece 3,500 years ago (Knauss *et al.* 1984). Some centuries later, the Babylonians established municipal reedbeds and harvested bulrushes for construction purposes (Boulé 1994). Peat bogs were also a primary source of bog iron, used since the Iron Age.

Generally peatlands have often been considered as wastelands that are of no use unless they are drained, logged or excavated. In the past, peat landscapes were both feared and respected as wilderness areas and often linked to traditional culture, rituals and worship. Moreover, until modern times their ecosystem services and their very peat-land character, being unobtrusive and sub-surface, have generally remained unnoticed. This has resulted in a lack of appreciation of the need for cautious development. As peatlands are "too wet to plough and too dry to fish" most people avoided them. Their limited accessibility protected them against large-scale human interventions and often turned them into political, cultural and language borders.

Interactions between humans and peatlands can create far-reaching environmental and economic impacts. Whereas many peatland development activities are considered on the basis of short- to medium-term economic interests, the environmental, social and economic impacts can be far reaching and may span many generations. In many cases this is related to the gradual nature of the impacts of changes in peat hydrology and the related soil subsidence and carbon emissions, which places the burden of impacts on future generations.

> In the Netherlands, extensive drainage of peatlands for agriculture began in the 8th century, providing excellent yields of cereals. The availability of cheap energy from peat contributed substantially to the development of Holland as a major trade area in the 17th century. However, subsidence of the peat surface was inevitable (despite water control efforts using polder technology), eventually leading to the end of peatland-based arable agriculture. Peatland use changed since then towards dairy production (Borger 1992).
>
> Over the last 50 years, the main developments on peatland in the Netherlands have been urban expansion and nature conservation. Large parts of the country are now lying below sea level, requiring major investments in flood protection along both the coast and rivers.
>
> This history illustrates the far-reaching impacts that peatland drainage, mining and agriculture can have both on the environment and on human society. The changes made to the natural environment, especially the increased vulnerability to flooding, were irreversible. To cope with these impacts, trade profits and the increased availability of labour due to declining agriculture triggered technological developments, water management and the search for new sources of income (Gerbens-Leenes and Schilstra 2004). Dutch water management skills have consequently become a major export product.
>
> Peatlands are becoming a key part of the ecological networks of the Netherlands and provide opportunities for nature tourism and recreation.

The history of peat development in the Netherlands provides a clear example (see box). It will be interesting to consider how future generations will look upon the current peatland degradation and related greenhouse gas emissions in the light of climate change impacts that they may experience, or perhaps the new opportunities that will emerge.

Interest in peatland resources may fluctuate and re-emerge suddenly in times of crisis or opportunity. Whereas the use of peatlands for agriculture and as fuel resource has significantly declined over recent decades, in situations of economic crisis, interest in peatland may increase again. For example, the use of peat as fuel intensified in Ireland during World War II when the supplies of coal from Great Britain almost ceased. Currently, interest in peat as fuel is increasing in parts of the world where there is limited access to other fuels.

Large-scale development of Southeast Asia's peatlands started only in the 1960s as a result of population pressures, geopolitical interests and access to loans for large-scale land-use development projects. Many peatlands were the subject of official and spontaneous transmigration schemes (Silvius *et al.* 1984). Timber extraction of peat swamp forests has been a major – albeit ecologically unsustainable – cash earner, providing temporary employment, local income, jobs and business opportunities.

Over the last few decades the tropical lowland peat swamp forests of Malaysia and Indonesia have been the target of rapid and large-scale developments of oil palm and pulpwood plantations, driven by both local and global demands for these resources. Global policy changes in 2006/2007 demanding increased use of biofuels in transport and energy sectors has augmented these pressures, despite the fact that palm oil produced on peat actually leads to higher overall CO_2 emissions than the burning of fossil fuels (Hooijer *et al.* 2006).

3.2 Benefits of peatlands

Peatlands are of considerable value to human societies due to the wide range of goods and services they provide. Peatlands help to maintain food and other resources and have functional significance far beyond their actual geographical extent. The benefits provided are:

- **a.** Regulation functions (ecosystem services)
- **b.** Production functions
- **c.** Carrier functions
- **d.** Information functions

The following sections provide a brief overview of these benefits.

3.2.1 Regulation functions (ecosystem services)

Peatlands play a significant role in regulating the global climate, being one of the major sinks of atmospheric carbon as well as a source of greenhouse gases including carbon dioxide, methane and nitrous oxide. Peat accumulation involves the sequestration and storage of carbon from the atmosphere. The amount of carbon currently stored in peatlands equals approximately 75% of the total amount of atmospheric CO_2 (see Chapter 6). Both pristine mires and re-wetted peatlands can emit methane. Almost all types of agricultural and forestry management of peatlands require drainage, which results in peat oxidation and the release of the stored carbon back into the atmosphere as CO_2. Human-induced fires in the degraded Indonesian peatlands may release amounts of carbon equivalent to 40% of the global annual emissions from fossil fuels (Page *et al.* 2002). Peatlands used for agriculture are important sources of nitrous oxide. Thus, the way in which people manage peatlands plays a significant role in managing climate change.

Peatlands regulate local climates. The specific mesoclimate of peatlands influences regional and local climates through evapotranspiration and the associated alteration of heat and moisture conditions. The influence on micro- and meso-climate is larger in warmer or drier climates and smaller when the regional climate is colder or more humid. Consequently, in areas with extensive peatlands, the regional climate is cooler and more humid (Edom 2001). Drainage of mires in the boreal zone leads to a reduction in minimum temperatures and a shortening of the yearly frost- free period; a process that is reversed by subsequent afforestation (Yiyong and Zhaoli 1994, Solantie 1999). Similarly, the large-scale conversion and drainage of the Ruwenzori mountain peatlands at the Uganda/Rwanda border may have resulted in increased local temperatures and increased occurrences of malaria at higher altitudes.

Peatlands play an important role in catchment hydrology with respect to water storage, water quality, the support of groundwater levels and flood and drought mitigation. Peatlands often form major components of local and regional hydrological systems and have the ability to purify water by removing pollutants (Joosten and Clarke 2002). Large peatland bodies may regulate the surface- and groundwater regime and mitigate droughts and floods. For example, tropical peat swamp forests serve as overflow areas in flooding periods, while in the dry season the stored water is slowly released (Klepper 1992). Riparian peatlands such as in the floodplain of the Pripyat River in Belarus store floodwaters, resulting in a downstream reduction of velocity and volume of peak discharges (Belakurov *et al*. 1998). Coastal peat swamps act as a buffer between salt- and freshwater systems, preventing saline intrusion into coastal lands. Scenario studies of the Air Hitam Laut river basin (Sumatra) demonstrate that reclamation of upstream peatland areas will dramatically reduce water flow to downstream and coastal areas. This can lead to increasing droughts, salt water intrusion and acidification of potential acid sulphate soils downstream (Silvius 2005, Wösten *et al.* 2006).

The water storage and retention function of peatlands is locally important for the supply of drinking water and for the irrigation of agricultural lands. In regions where catchment areas are largely covered by peatlands, as well as in drier regions where peatlands indicate a rare but steady availability of water, they can play an important role in maintaining water supplies for drinking and irrigation water. For example, much drinking water in Scotland is derived from peat-dominated catchments. Where or when other water resources are rare (e.g. in the dry season), mires and peatlands can be important as sources of water, for example, in the Andes, KwaZulu-Natal, Sarawak, Kalimantan, and Sumatra (Hooijer 2003, Silvius *et al.* 1984). In the Sarawak coastal peatlands, some 25 Public Works Department supplies rely on stream water draining from the peat swamps, providing 70,000 people with high quality potable water (Rieley and Page 1997). Such water resources can also be important for the irrigation of agricultural areas.

3.2.2 Production functions

The capacity of peatlands for agricultural production is generally low in the absence of intensive management (e.g. drainage, fertilization). In their natural state, peatlands have only marginal agricultural capability (Melling 1999, Rieley and Page 1997), thus restricting their use. Important characteristics that inhibit agriculture are the very high groundwater table, the low bulk density and bearing capacity, the high acidity, the low availability of nutrients, and their subsidence upon drainage. Conventional agriculture involves drainage, fertilizing, tilling, compaction and subsidence, which eventually cut short the sustainability of peatland agriculture (Succow and Joosten 2001).

Table 3.1: Peatland used for agriculture in selected countries (After Joosten and Clarke 2002, Hooijer et al. 2006, JRC 2003).

	Peatland used for agriculture (km^2)	% of total peatland
Europe	124 490	14
Russia	70 400	12
Germany	12 000	85
Poland	7 620	70
Belarus	9 631	40
Hungary	975	98
Netherlands	2000	85
USA	21 000	10
Indonesia	60 000	25
Malaysia	11 000	45

Much of the small-scale but widespread agricultural encroachment in tropical peatlands is linked to severe poverty. Large-scale encroachment is mainly linked to palm oil development. Agricultural development of tropical peatlands in South-east Asia only started a few decades ago. On shallow peat these developments have led to the disappearance of the shallow peat layers as a result of drainage and ensuing oxidation. The agricultural successes are mainly due to the qualities of the surfacing sub-soil. As a result of continuous land hunger however, even the deeper peatland areas have become the target of agricultural development. Only a few commercial crops grow well on peatlands, including pineapple and oil palm. More recently the dryland species *Aloe vera* has been introduced in Indonesia to the desiccated peatlands and is falsely propagated as a "sustainable" crop. New commercial and sustainable crops may include the indigenous Jelutung tree (*Dyera* sp., also known as the chewing gum tree, as it produces the latex that is used in chewing gum), which can grow under non-drained conditions. The development of fishponds in closed drainage canals offers interesting commercial potential for local communities. In addition, many tropical black-water fish species are of interest to the aquarium industry. New development opportunities are very much needed as poverty levels in Indonesian peatlands are generally higher than in non-peatland areas.

Recent poverty-induced agricultural encroachment has left over 80% of South Africa's coastal peat swamp forests denuded of its original vegetation. Communities have nowhere else to go and after the soil nutrients have been depleted, they move on to the next patch of remaining peat swamp forest (Marcel Silvius, pers.obs.).

Agricultural development is also taking place in the high mountain peatlands of the Andean Paramos at over 3000 m altitude. Also in these "high mountain water towers", agriculture goes hand in hand with drainage and fires, and the practices are clearly not sustainable. The resulting decreasing water retention capacity may jeopardise the water supply to agricultural communities and cities downstream (Bermudes *et al*. 2000, Hofstede *et al*. 2002).

Peatlands are used for forestry all over the world. Extensive commercial forestry operations have been established on peatlands in many nations. Exploitation of naturally forested peatland is practiced in northern boreal mires throughout Scandinavia and Canada. The dominant species are mostly coniferous (Black Spruce *Picea mariana*, Scots Pine *Pinus sylvestris*). The growth of these commercially useful species is limited by waterlogging. Therefore, drainage has been used in many areas to provide greater economic returns. Afforestation of open mires is a more fundamental alteration of the peatland system. It involves major change to the physical and hydrological conditions due to ploughing and drainage, major structural alteration to the vegetation, and the introduction of non-native species. Afforestation is especially common in the blanket and raised mires in oceanic western Europe (British Isles, northern Scotland). Tropical peat forests include substantial quantities of commercial tree species and yield some of the most valuable tropical timbers. Ramin (*Gonystylus bancanus*) and Agathis (*Agathis dammara*), for example, constitute almost 10% of Indonesia's exports of forest products. Also in Malaysia, logging of peat swamp forest plays a very important role in the economy, especially in Sarawak which has major peat swamp forest reserves. More recently, large tracts of peat swamp forest in Sumatra have been granted in concession to pulp-and-paper companies, like Asia Pacific Resources International Ltd (APRIL) and Asian Pulp and Paper Ltd (APP). The establishment of the pulp plantations (*Acacia sp.*) involves the deforestation of the original peat swamp forests, soil compaction and drainage.

Approximately 14% of European peatlands are currently used for agriculture, mainly as meadows and pastures. Also in North America, extensive areas of peatlands are cultivated for agriculture, as pastures and for sugar cane, rice, vegetables and grass sods. The commercial production of cranberries on peatlands in North America is a major business enterprise with the production of 6 million barrels. Large-scale cultivation in Southeast Asia is largely for estate crops (mainly palm oil, coconut and some sago) and rice. Sarawak is now the world's largest exporter of sago, exporting annually about 25,000 to 40,000 tonnes of sago products. Indonesia and Malaysia are the world's largest palm oil exporters, each producing about 43% of the global production (Basiron 2007).

Peat as an energy source is only important for regional or domestic socio-economic reasons, because it is more expensive and emits more CO_2 per unit energy than other fossil fuels. Peat has been used as an energy source for at least two millennia. At present peat only contributes marginally to worldwide energy production, but at the local and regional scale, it can still be an important energy source, particularly in Finland, Ireland, and Sweden. It also continues to be important in the Baltic States, Belarus and Russia. In recent years technical developments have led to lower, more competitive peat prices.

As peat is more expensive and emits more CO_2 per unit energy than other fossil fuels, it is only of interest as an energy source for regional or domestic socio-economic reasons. In Finland and Ireland employment in rural areas is the most important motive for peat energy, whereas in Eastern European and Central Asian countries, independence from Russian oil and gas imports and the lack of foreign currency are important driving factors.

Logging

The IPCC Guidelines (IPCC 2006) provide a default calorific value for peat of 9.76 GJ/t peat and an emission factor of 28.9 kgC/GJ = 106 $kgCO_2$/GJ (compared to <100$kgCO_2$/GJ for various types of coal). Countries may adjust these values to national circumstances. There is not much room for adjustment however, as the emission factor for peat is largely determined by chemical properties that cannot be altered (Couwenberg 2007, Joosten and Couwenberg 2007).

Peat is widely used as a growing medium in horticulture and as a soil conditioner. Peat substrates are used particularly in glasshouse horticulture for the cultivation of young plants, pot plants and for the growing of vegetable crops. They are also sold to amateur gardeners as a soil conditioner. In Europe, approximately 95% of all growing media for the professional and amateur markets are peat-based. The total global production amounts to around 30 million tonnes of peat per annum, of which approximately one-third is used for agriculture and one-third for energy (Joosten and Clarke 2002). Although alternative materials are emerging, these are not yet of sufficient quality, nor available in large enough quantities, to replace peat.

Peat is also extracted for small-scale uses. In addition to fuel and horticulture, there is a variety of other uses of peat that involve the extraction of smaller amounts. These include: raw materials for chemistry, bedding material, filter and absorbent material, peat textiles, building and insulation material, therapeutic uses (balneology), and peat as a flavour enhancer (e.g. in whisky) (Joosten and Clarke 2002).

Agriculture

Peat extraction machine

Peatlands provide many plant species that are utilized for food, fodder, construction and medicine. One of the oldest and most widespread uses of wild peatland plants is as straw and fodder for domestic animals. For example, in Poland 70% of the peatlands were used as hay meadows and pastures. A second important use, especially in the temperate and boreal zones of Eurasia, is the collection of wild edible berries and mushrooms. Cloudberries (*Rubus chamaemorus*) are an important dietary supplement for many Arctic residents as well as a source of cash income. In Finland, the estimated yield at the turn of the 20th century amounted to 90 million kg. In the north, wild plants are used for a great variety of purposes. Their use today is, however, declining, as is the knowledge required to find, identify and gather such plants.

Tropical peat swamp forests provide a wide range of products, such as edible fruits, vegetables, medicinal and ritual plants, construction material (wood, rattans, bamboo), fibres and dyeing plants, firewood and traded products like rattans, timber and animals. Important timber species are Ramin (*Gonostylus bancanus*) and Meranti (*Shorea* sp.). Both timber and non-timber forest products (NTFPs) are, besides providing employment and contributing to state and federal revenues, central to the well-being and livelihood of local indigenous communities, such as the Dayak and Iban. Socio-economic studies indicate that in Indonesia local communities may depend on the peat swamp forest for over 80% of their livelihoods, rather than depending on agriculture. NTFPs provide cash income to supplement daily expenses or are a 'safety net' in time of need. Moreover, they represent an essential part of subsistence, culture and heritage. To the Dayak, the forest landscape is not only viewed as a collection of biodiversity, but also as a meaningful object for their social, economic, politic, and cultural lives (the concept of "*Petak Ayungku*"). The forest functions are a strong chain that binds together all members of the Dayak communities of the past, present, and future (Colfer and Byron 2001).

Picking berries

Peatlands and tundra with shallow peat are crucial habitats for reindeer throughout the circumpolar region. They serve as a refuge from predation and, more importantly, as a source of forage. Reindeer are very selective foragers. During spring and early summer, they depend greatly on peatland plant species such as early sprouts of cotton grass (*Eriophorum vaginatum*) or bogbean (*Menyanthes trifoliata*). This food source plays an important role in the growth of calves because of its high protein content. Later on, other species also become important, such as herbs (*Eriphorum angustifolium, Equisetum fluviatile, Rubus chamaemors, Carex* sp.), willow (*Salix* spp.), deciduous trees and shrubs (*Vaccinium myrtillus*). Summer forage significantly affects the condition of reindeer and their survival over winter. Ground lichens (*Cladina* sp., *Cetraria* sp. *and Cladonia sp.*) are a major winter food source (Márell *et al*. 2005).

The use of wild plants among Nenets nomadic tundra communities
(Källman 2002)

Present patterns of plant use still follow the old tradition of a reindeer-herding culture. Few plants are used as food, whereas medicinal plants and plants for other practical purposes are more important. The Nenets (Gyda Peninsula, northern Siberia) have names for all species of importance for the reindeer and themselves. All other species are just called "plant" (*namted*). Some 30 species of plants are used. Most important are *Betula nana* and *Salix* spp. for firewood. *Salix* and graminoids are collected for making covering mats used in the tipi (*chum*). *Cladonia arbuscula* is used for cleaning wounds, while *Ledum palustre* is used as tea, in washing water after childbirth, in cleaning rituals after burials, and as a ceremonial drug by the shamans. Another important medicinal plant is *Veratrum album* which is used against intestinal worms. Moxibustion (medicinal burning) with a fungus (possibly *Piptoporus betulinus*) is popular among the Nenets and the fungus is also used in tea as a healing drink. Peat mosses *Sphagnum* are among the most important plants. They are divided into "white", "red" and "brown" moss. The white moss is used for absorbing fluids, for example, as nappies, in shoes or for cleaning tables. The red moss is used as bandages, whereas the brown moss indicates drinkable water in small ponds. The most popular use of wild plants is in tea made from the leaves of *Comarum palustre*. Other popular food plants are the leaves of *Oxyria digyna* and *Rumex*, and roots of *Pedicularis*. Berries, especially *Rubus chamaemorus* (cloudberry), are picked mostly by children. Thin *Betula pubescens* carvings are used in baby cradles and are often traded in the nomads' winter locations.

Peatlands may also be significant for hunting and fishing. Fur-bearers such as coyote, racoon, mink and lynx, and game species such as grouse, ducks, geese and moose, are often found in peatlands. In North America, black bears, hunted for food, fur, and traditional medicine (bladders), are also frequently found in peatlands. Wild reindeer (caribou in North America) are hunted for meat for local markets as well as for subsistence. An estimated 250,000 people in the Eurasian Arctic depend on reindeer as a major food source. Caribou meat and hides are marketed in Canada on a small scale and in both Alaska and Canada caribou are hunted recreationally, generating income for guides, outfitters, and the service industry. For animal species that do not directly depend on peatlands, the habitat may contribute substantially to their continued presence in populated regions where few areas other than peatlands provide safe havens away from direct human disturbance.

Peatland waters harbour many fish species, which in some regions, in addition to providing an important protein source to local communities, can be an object of sports fishing, generating income through the sales of fishing equipment and licences. Tropical black water fish diversity is extremely high. Black water species are attractive to sport fishing and the often very colourful species are attractive for the aquarium industry.

3.2.3 Carrier functions

Peatlands provide space for urban, industrial and infrastructural development. Peatlands are generally uninhabited which makes them attractive for a wide variety of land use options including building construction, waste disposal and even military exercises. Substantial peatlands are located in coastal areas, where over 50% of the world's population lives. Major cities like Amsterdam and St. Petersburg are largely built on peat. Their location near to coastlines makes it tempting to convert mires and peatlands to provide infrastructure for towns and harbours, as can currently be observed in Southeast-Asia. Being often related to low relief, peatlands provide suitable locations for water reservoirs.

Infrastructure construction

Vast areas of peatlands in Western Siberia and Alaska (Prudhoe Bay) have been affected by expanding infrastructure for oil exploration, exploitation, and transport. In Georgia (Caucasia) new harbours and railroads are currently being constructed in protected mires that are of international importance for biodiversity conservation, in order to carry oil from Azerbaijan to the Black Sea (Krebs and Joosten 2006).

> Tasik Bera, or Bera Lake, is the largest freshwater swamp in Peninsular Malaysia. It sustains the livelihoods of the Semelai, the indigenous people inhabiting the wetlands. The majority of Semelai (total population around 2000) live in Pos Iskandar, a settlement area with five main villages, where they cultivate hill rice, cassava, vegetables, fruit and rubber trees. Traditional Semelai homes are built from forest products such as bamboo (for flooring) and tree bark (for walls). Dependent on the lake and forests, the Semelai fish, hunt and trap wildlife (mainly wild boar and deer) to supplement their income. Wetland and forest products are used to make traps, spears, and canoes. They also practise the traditional collection of "minyak keruing", the resin from the Keruing tree, which is used for making torches, sealing boats and as an ingredient in perfume. Medicinal species, usually planted near the home, are used to fend off fever and other ailments. Their extensive knowledge of both the forest and lake habitats makes them a popular choice as guides among sport fisherman (Santharamohana 2003).

Peatlands in the UK, Ireland and the USA are increasingly targeted for wind and hydro-electric energy development. The production of such "green" energy may have negative environmental impacts on the peatlands, including significant greenhouse gas emissions that should be taken into account.

3.2.4 Information functions

Peatlands are major contributors to the natural diversity of the temperate, boreal and sub-arctic regions of both hemispheres, as well as in some tropical areas. The variety of peatland types provides a rich source of ecosystem diversity. Whereas their species diversity in general is low compared to mineral substrate habitats, they are important sources of genetic richness, as they contain specialized organisms including many rare or endangered species. Peatlands are also important refuge areas, with many relict species. For animal species that for their survival do not directly depend on them, peatlands may contribute substantially to their continued presence in populated regions where few areas other than peatlands provide safe havens away from human disturbance. For example, Southeast Asian tropical peat swamp forests are important for the survival of many species that have become rare in other habitats. These include the Sumatran Rhino, Sumatran Tiger, Malayan Tapir, Storm's Stork and White-winged Duck. See Chapter 5 for further information on peatland biodiversity.

Peatlands contain important information on environmental and cultural history. Peatlands are valuable for education and research, since they contain important archives of cultural and environmental history reaching back more than 10,000 years. Fossils in the peat matrix, including pollen, plant remains, archaeological artefacts and even human sacrifices, reveal the ecological and cultural history of the peatland itself, its surroundings, and even more distant regions (Joosten and Clarke 2002, see also Chapter 4).

Peatlands provide significant aesthetic, artistic, cultural, and spiritual values. Relatively few people live entirely from and in peatlands. For many more people, peatlands provide for part of their livelihoods. In addition, they are part of their traditions and have a special place within the ancestral land area, being part of their spiritual and aesthetic world, frequently occurring in folklore, literature, paintings, and other art (Joosten and Clarke 2002).

The cultural and aesthetic values of natural and cultural peatlands offer high potential for ecotourism and recreation. The limited accessibility of mires and peatlands does not make them particularly suitable for mass recreation. Where facilities are available, however, large numbers of people may visit peatland reserves, e.g. the Everglades NP (USA), North York Moors NP (UK), and Spreewald Biosphere Reserve (Germany) (Joosten and Clarke 2002). In many other countries peatlands are an important part of the national park or protected area networks that attract tourists, such as in Canada, Finland, the Baltic countries, and the Netherlands. Many more mires are used for low- intensity recreation.

Such ecotourism can provide additional income, such as in the Tasek Bera Ramsar site in Peninsular Malaysia where local communities earn additional income by selling traditional handicrafts and guiding boat tours through the swamps (Santharamohana 2003). In Indonesia, Orangutan rehabilitation centres in some peat swamp forest reserves (e.g. Tanjung Putting, Central Kalimantan) attract local and international tourists. Much of the potential of peatlands as special and intriguing habitats remains unexplored, perhaps also because there is limited experience with the special facilities that could make them more accessible and attractive to visitors.

Nature protection and Ecotourism

3.3 Peatlands and livelihoods

Many peatlands have considerable value in supporting local communities for subsistence. Human cultures can be substantially dependent on the productivity and/or the ecological and hydrological functions and values of peatlands. These include for example, the reindeer herding cultures of nomadic tribes that almost fully depend on Arctic and sub-arctic peatland landscapes, central Asian nomads whose livestock mostly depends on pastures on peat soils, small-scale subsistence farming communities in the peaty páramos of the high Andes, and the nomadic yak herding cultures on the Tibetan plateau.

More often, human communities depend on peatlands for only part of their subsistence. Examples are the Semelai in Peninsular Malaysia (Tasek Bera Ramsar site) or local people eking out a living on the coastal valley peats in Maputaland, South Africa. Other examples include the traditional agricultural systems in central and eastern Europe involving low intensity agricultural use of fens as pastures and hay meadows, the rattan gardens of the Dayak people in the peat swamp forests of Kalimantan, or the widespread subsistence fisheries of riverine communities in the black waters of southeast Asia.

Peatlands are often poverty traps. Whereas peatlands are valuable in many respects, they can also be poverty traps for local people. Many indigenous people in peatlands are living in isolation from the modern economic mainstream. While there is value in the traditional lifestyle, it may also come with hardships, in terms of lack of access to schooling, medical facilities and many other services and facilities that modern society regards as synonymous with wealth and/or development. Nevertheless, attempts to push these communities into modern life often creates more poverty and may be more related to interests in the natural resource base than in the livelihoods and development of these people.

Raised island culture of Kimaam Island

Pulau Kimaam is a 1,146,000 ha large deltaic island in South-east Irian Jaya. Swamps (both tidal and seasonal) cover 98% of the total area. During the wet season, the island is almost completely inundated. The inhabitants (10,200 in total) are highly adapted to this extreme, swampy environment. They have developed a unique system of agriculture, which is the primary means of subsistence. Except for some sandy reefs along the coast, all agricultural ground, as well as the ground needed for dwelling houses has to be artificially obtained. For this purpose, long and narrow islands made of clay, drift grass and mud are raised in the marsh to a certain level, depending on the crop to be grown. On these islands coconuts, papaya, root crops, fruit trees etc. are planted. Around the islands, floating grass beds are cultivated which are used to regularly build up the continuously declining islands. The garden islands are fertilized by spreading alternate layers of drift-grass and clay. This intensive agricultural use is a practical necessity, since the environment would not permit a system of shifting cultivation. In fact, the possibility to pursue intensive agriculture was the main reason for the natives to choose the swamp instead of cultivating on dry land. Their diet is supplemented with a wide variety of edible plants, eggs from magpie geese, and by fishing and hunting. The gardens are still in use even by people who moved to dry land in translocation schemes (Serpenti 1970, Silvius 1989).

In some cases the opposite has happened: people who have been unsuccessful in modern

High altitude peatlands	
Yak and sheep herding in Tibet. High altitude peatlands often represent key resources for livestock production because in such particularly scarce and dry environments, peatlands provide relatively high biomass production and water resources. One example is the Ruoergai Plateau in Western China; a relatively flat plateau at 3300-3800m above sea level in the northeast part of the Qinghai-Tibetan Plateau. This area is rich in peat resources (total peat area of 490,000 ha) and has abundant water resources. Its rangelands rank among China's most productive areas for livestock production. Tibetan pastoralists have depended on the peatlands to support their herds and families for thousands of years. The population of the plateau at present is about 125,000 people, mostly Tibetan pastoralists with vast herds of sheep, yaks and horses. The livestock population of the plateau currently comprises 800,000 yaks, 1,300,000 sheep and 50,000 horses. In recent decades, traditional nomadic pastoralism has been replaced by semi-nomadic and settled systems that have a larger impact on the fragile grasslands and wetlands. Industrial and agricultural output from the peatland is valued at US$15.6 million, of which animal husbandry comprises 50%. The annual per capita income is about US$85. (Yan Zhaoli 2005, http://www.gefweb.org/wprogram/Jan99/undp/main2.doc, Wetlands International 2005)	**Peatlands in the Andean highlands.** The biomass-rich pastures of the *bofedales* (cushion peat bogs) in the Andean highlands, such as the 4000 m high Bolivian Tarija Altiplano, are a vital forage resource for livestock production, as the herbaceous vegetation of dry areas in this region has a very low productivity. The soils are rich in organic matter, have adequate moisture for year-round growth and are able to support quite high livestock densities. The perennial grasses *brama* (*Distichlis humilis*) and *bramilla* (*Muhlenbergia fastigiata*) grow quickly after rain and are important for grazing, as are other species such as *Chondrosum simplex*. Traditional alpaca herders (*Aymara*) have used the Tarija plateau for over 7,000 years to raise llamas and alpacas as a source of meat and wool. Pastoralism, combined with arable farming and seasonal migration, is also an important element of the livelihoods of other altiplano people. Livestock are important for minimizing risk within these livelihoods. Local people consider livestock as an ambulant bank and as a buffer against adversity. Elsewhere in the Andes, the peaty páramos are important to local communities and to some mega cities as water providers. Both traditional and intensive farmers depend on grazing areas in the páramos to feed the oxen needed to plough the steep slopes (Hofstede *et al*. 2003)

society are forced out and move into unoccupied and cheap land areas that are often peatlands. For example, in many transmigration projects in Indonesia, poor farmers from Java and Madura were moved to large-scale agricultural development projects on peatlands in Sumatra and Kalimantan.

As a result of some of these projects, local indigenous communities lost access to valuable resources and land that had been developed over centuries through enrichment planting, sustainable agriculture and fisheries. For example, the traditional agriculture and rattan gardens of Dayak communities in Central Kalimantan were affected by the large-scale misguided development of the centrally (nationally) organised Mega Rice Project.

These projects were often designed to improve development opportunities. However, the lack of experience with large-scale peatland development in the tropics exacerbated rather than reduced poverty. Poverty in Indonesian peatlands is estimated to be 2 to 4 times higher than in other parts of Indonesia. It is made worse by the recurrent problems of over-drainage and fires. According to data from CARE-Indonesia, around 30% of the children under the age of 5 living in fireprone Indonesian peatlands suffer from respiratory diseases caused by the annual smog of peat fires during the dry season.

Also in western Europe, poverty in peatlands is often higher than elsewhere, but the relative poverty of farming communities is often masked by agricultural subsidies.

Indigenous communities that depend on wild peatlands are most vulnerable to peatland degradation. Peatlands include some of the last remaining wilderness and vast natural resource areas of the world, with huge undisturbed stretches in the sub-arctic zone. Development in such areas often ignores the special hydrological and ecological characteristics that are central to the productivity of these peatland areas.

While developments may bring economic prosperity to some stakeholders, the poorer and marginalized local people who subsist on the natural productivity of peatlands are often excluded from the planning and development process and it is they who suffer most from the negative environmental impacts. For these communities, the degradation and loss of their peatlands is tantamount to losing their way of life. Currently, the potential for subsistence livelihoods is decreasing in many peatlands due to increasing population pressure as well as externally-induced development. Under such circumstances, local communities may find no other solution than to over-exploit what is left of the natural resource base.

Table 3.2: Present and former extent of mires in the non-tropical world (after Joosten and Clarke 2002).

Continent	Original mire area	Present mire area	Loss of mire area
	(x1,000 km^2)		(%)
Europe	617	295	52
Asia	1,070	980	8
Africa	10	5	50
North America	1,415	1,350	5
South America	25	20	20

Peatlands still play a key role in modern economies. Peatlands still play a key role in the economy in many first world countries. The economic value of peat as a substrate for modern horticulture in countries like the Netherlands and Germany is huge. This is one of the reasons why large areas of peatlands in western and central Europe remain a target of peat mining (Aerts 2005). In countries in economic transition, such as Russia and eastern European countries, the demand for agricultural products is decreasing, making traditional agriculture and grazing on peatlands no longer economically viable. This leads to large-scale abandonment of drained or extracted peatlands, with farmers and companies unable or unwilling to pay for restoration.

3.4 The root causes of human impacts on peatlands

The impact of humans on peatlands is increasingly negative and has locally resulted in the total annihilation of peatlands. Whereas the relationship between people and peatlands in the past may often have been balanced and mutually enriching, recent developments have resulted in huge areas of peatlands being degraded as a result of drainage (oxidation), deforestation, fire and pollution.

Human exploitation has destroyed almost 25% of the mires on Earth: of this destruction, 50% is by agriculture, 30% by forestry, 10% by peat extraction, and 10% by infrastructure development. Compared to other continents, Europe has suffered the greatest losses in mires, both in absolute and relative terms. Peat formation has stopped in over 50% of the original mire area, of which possibly 10-20% does not even exist any more as peatland (Joosten 1997). In Western Europe, many countries have lost over 90% of their peatland heritage, with the Netherlands leading with almost 100% of its natural peatlands being destroyed.

Asia and North America, including the vast extent of Siberian and sub-arctic peatlands, have incurred the least losses. Large-scale reclamation of tropical peat swamp forests in Southeast Asia which started only in the 1960s has destroyed over 120,000 km^2 of this habitat. Large areas have been left without peat soil as a result of oxidation and fires. Over 90% of peat swamp forests in Southeast Asia have been impacted by deforestation, conversion, drainage and legal or illegal logging, to the extent that they are significantly degraded and have turned from being carbon sinks into net sources of carbon (Hooijer *et al*. 2006).

On a global scale human exploitation may have destroyed 800,000 km^2 (20%) of mires on Earth: 50% of these losses are attributable to agriculture, 30% to forestry, 10% to peat extraction, and 10% to infrastructure development (Joosten and Clarke 2002).

As a result of continuing exploitation, the global mire resource is decreasing by approximately 1‰ per year, but in some regions (southern Africa, Southeast Asia, Central Asia) the current annual losses of peatlands can be counted in whole percentages and may result in the annihilation of the natural peatland habitat in this century (Silvius and Giesen 1992, Hooijer *et al.* 2006). Peat swamp forest area decline in insular South-east Asia is twice that of other forest decline (Hooijer *et al.* 2006). Most mire and peatland losses in future are expected to result from drainage and infrastructure development.

Peatland conservation and restoration: a new service market for local livelihoods

Developing carbon markets, both under the Clean Development Mechanism of the Kyoto protocol, as well as emerging voluntary markets, may in the near future, provide a price for Reduced carbon Emissions from Deforestation and Degradation (REDD). With current certified emission carbon prices under the CDM (10-20 Euro/tonne and voluntary market prices of around 5 – 10 Euro/tonne) the value of avoiding emissions from peatlands would be billions of Euros. These values may also represent a potential new service market that can be catered for by the local people. To avoid further emissions from deforestation, drainage and fires, the degraded peatlands require management, restoration and protection measures that can only be provided by these people. Such new global enviro-economic mechanisms may thus provide a way out of poverty. Internationally, there is a call for emerging carbon markets to link their environmental payments in developing countries to poverty reduction schemes.

Unsustainable use of peatlands can have significant environmental and socio-economical side effects. These may be exacerbated by externalities and feedback mechanisms such as climate change (El Niño, sea level rise). Exploitation of peatlands may bring short-term benefits, but the loss of peatland ecosystem functions involves irreversible changes with large long-term impacts, both on-site and off-site. On-site changes result in habitat destruction with significant implications for local biodiversity, productivity and ecosystem services. Off-site effects may be felt at local, regional and global scales.

Also peat fires can have major collateral impacts, including losses of timber and other natural resources, regional public health problems, as a result of the haze, and major economic losses in transport and tourism sectors (Tacconi 2003).

Even though far fewer mires have been destroyed by peat extraction than by agriculture and forestry, this practice is most damaging to bogs over the short-term. Peat extraction is still ongoing today, particularly in Europe, and remains a serious local threat.

Drainage of peat leads unavoidably to land surface subsidence and carbon emissions. Most land-use practices on peatlands require drainage. This results invariably in subsidence of the peat body owing to physical collapse and compaction of the dehydrated peat, together with lowering as a result of loss of organic matter by oxidation. Subsidence may be as much as 500 mm in the first year of drainage and proceeds at rates of 10-100 mm in subsequent years depending on local conditions (Wösten *et al.* 1997). Consequently drainage and overall site hydrology are very difficult to manage, which results in technical management difficulties, declining water quality and smaller harvests. The exposure of peat layers to oxygen leads to oxidation of the organic material, while drying out of peatlands also leads to increased occurrence of fires, causing huge emissions of CO_2 (see Chapter 7).

In some parts of the world, peatlands have developed on former mangrove soils with high pyrite contents. These Potential Acid Sulphate Soils (PAS Soils or sulphaquents) may become exposed after destruction of the peat layer, resulting in oxidation of the pyrite and the production of sulphuric acid. This leads to loss of nutrients and severe acidification of the land and water.

In the temperate and boreal zones drainage of pristine mires for forestry is declining. In some countries (e.g. Finland and Russia) current drainage activities are concentrated on maintaining ditches in already drained peatland

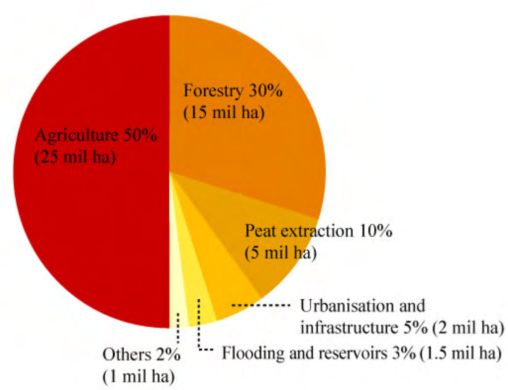

Figure 3.1: The contribution of different human activities to peatland losses (after Joosten and Clarke 2002).

> The largest recent example of disastrous drainage for agriculture is the Mega Rice Project in Kalimantan (Indonesia) where since 1995 over one million ha of peatlands were drained for rice production. Without taking the hydrological and hydromorphological properties of peatlands or their (un)suitability for rice cultivation into account, 4400 km of drainage canals were dug, leading to subsidence, desiccation, and huge carbon emissions as a result of peat oxidation and major fires. In 1997, immense, uncontrollable fires ravaged the area with enormous consequences for both the environment and human health. As a result of peat smog, thousands of people in Indonesia were hospitalized and half a million received out-patient treatment, causing a loss of millions of work and school days (Tacconi 2003).

forests. Partly in response to wildlife conservation arguments, large-scale commercial forestry is increasingly combined with management of wildlife and landscape values, for example by partial harvest management. This results in multi-purpose forests with improved aesthetic and recreational values and opportunities. In general, the area of agricultural peatlands in Europe is decreasing as a result of globalization (which makes agriculture on marginal lands in developed areas uneconomic). However, the opposite trend is occurring in Southeast Asia where over the last decades millions of hectares of peatlands have been deforested and drained. Deforestation rates in peat swamp forests are currently double of those in other tropical rainforests (Hooijer *et al.* 2006). Large areas have been converted to agriculture but in many areas these attempts have failed resulting in extensive areas of degraded idle land. More recently there has been a growing drive to develop pulp wood and oil palm plantations on peatlands.

The latter is augmented by recent European policies for increased use of biofuels for transport and energy generation. Europe is a major importer of palm oil, and this now stands to substantially increase, despite the fact that palm oil from peat may result in up to 10 times more carbon emission than is being sequestered in the crop. Currently about 20% of palm oil in South-east Asia is produced on peat, making it a product that negatively impacts on the global climate overall. Similarly, production of corn on peatlands in western Europe for bio-ethanol is increasing, despite the fact that the carbon balance of such production will be negative. Generally there is a lack of awareness amongst policy and decision makers of the significant climate change impacts of unsustainable (i.e. drained) uses of peatlands, creating the opportunity for adverse policies and development of perverse incentives.

Changes to the physical and chemical properties of peat soil caused by drainage increase the susceptibility of peatlands to soil erosion and fire. The changing land management practices in tropical peatlands have greatly increased the susceptibility to physical degradation (subsidence), chemical degradation (oxidation) and fire, with particularly extensive fires associated with ENSO-related droughts in Indonesia since 1982. Similar effects of peatland drainage have been observed in Europe, with large parts of Russia and major cities like Moscow being covered in peat smoke for months on end in some years. Huge fires were, in the past, also known from Western Europe.

Intensive grazing on temperate and highland peatlands leads to increased phosphate P-output to surface water (Tetzlaff and Wendland 2004). It creates compaction and the exposure of the peat soil results in oxidation and erosion.

Peatland conversion for different kinds of uses often leads to fragmentation of the remaining natural or semi-natural peatlands. Large-scale conversion and intensive use of peatlands has in various parts of the world led to anthropogenic landscapes with ‘islands’ of remnant peatland habitats. Even when these fragments are protected for their wildlife and aesthetic values, their long-term sustainability is questionable, when their ecohydrological system has been destroyed (Charman 2002).

3.5 Conflicts and wise use

The broad range of peatland values and functions underlines the variety in user groups of peatland systems. There are some people who wish to use peatlands for their production functions, and others who wish to preserve and manage these ecosystems for their regulating and non-material life-support functions. Conflicts may arise between these competing views of protection and production. For example:

- the drainage of peatlands may affect their flood control functions leading to damage of downstream valley farmland, bridges and buildings;
- drainage of peatlands for agriculture may lead to loss of carbon storage and climate change mitigation functions;
- drainage and afforestation of peatlands impacts upon biodiversity and constrains their use for recreation, berry picking and hunting;
- strict nature conservation may impact upon the local socio-economic situation, especially in developing countries.

The multiple functionality of peatlands can lead to trade-offs between different stakeholder groups and consequent conflicts over use options. Conflicts between production versus conservation uses and values often result in "win-lose" situations, with the more influential or powerful stakeholders "winning" and the less powerful "losing". An example of this can be seen in peat extraction that does not take peatland conservation or after-use into account. There can also be "lose-lose" situations in which all stakeholders lose, for example, the Indonesian Mega Rice Project. This project was cancelled in 1998 after drainage of over one million ha of peatlands and without producing any economically viable agricultural crops.

There are a number of reasons why peatlands continue to be lost, converted, or degraded. The individuals who benefit most from the conservation of peatland areas are often local residents, many of whom are not involved in policy development and decision-making processes. Decisions concerning the fate of their wetlands are often made through processes that are unsympathetic to local needs or that lack transparency and accountability.

Many services delivered by peatlands (such as flood mitigation, climate regulation, and groundwater recharge) are not marketed (i.e. do not generate income to local communities) and accrue to society at large at local and global scales. Individuals often do not have incentives to maintain the peatland services for the benefit of wider society. Furthermore, when an action results in the degradation of a service that harms other individuals, market mechanisms do not exist (nor, in many cases, could they exist) to ensure that these individuals are compensated for the damages they suffer.

Decision-makers at many levels are unaware of the existence of peatlands and their special management requirements. They fail to recognise the connection between peatland conditions and the provision of peatland ecosystem services. Decisions are generally not informed by assessments and evaluation of the total economic value of both the marketed and non-marketed services provided by peatlands.

The private benefits of peatland conversion are often exaggerated by subsidies such as those that encourage the drainage of peatlands for agriculture or the large-scale replacement of coastal wetlands by intensive aquaculture or infrastructure, including that for urban, industrial, and tourism development.

Community Development

Peat swamp forests in Indonesia are currently subject to relatively high population pressure from new immigrant communities that often combine their main agricultural livelihoods with use of forest and fishery resources. In many areas there are also still the villages of the original Dayak and Melayu communities. As a result of the many failed large-scale developments, both immigrant and native communities have a strongly reduced resource base left for pursuing further development. This creates the danger (and for them – in view of their poverty situation – often the necessity) of continuing or augmenting unsustainable practices. This vicious circle can only be broken by provision of alternative means of income generation.

In some cases, the benefits of conversion exceed those of maintaining the peatland, such as in prime agricultural areas or on the borders of growing urban areas. As more and more peatlands are lost, however, the relative value of the conservation of the remaining areas increases, and these situations become increasingly rare.

Economic and public health costs associated with damage to peatland ecosystem services can be substantial. Often significant investments are needed to restore or maintain non-marketed peatland ecosystem services.

Non-marketed benefits are often high and sometimes more valuable than the marketed benefits. Some examples include:

- Flood control functions of the Muthurajawela Marsh, a 3,100-hectare coastal peatland in Sri Lanka, provides an estimated $5 million in annual benefits ($1,750 per hectare) through its role in local flood control (Mahanama 2000).
- Economic and public health costs associated with damage to peatland ecosystem services can be substantial. The burning of 1.5 to 2.2 million hectares of Indonesia's peat swamp forests in 1997/98 came at a cost of an estimated $9.3 billion in increased health care, lost natural resources, lost production, and lost tourism revenues. It affected some 20 million people across the region (Tacconi 2003).
- Annual costs of replacing the life support services of the Martebo mire, Sweden, with human-made technology is calculated between $350,000 and $1million (Emerton and Bos 2004).

The multifunctional benefits from the maintenance of peatlands as intact ecosystems may far exceed the economic returns from single sector conversions, such as agriculture, forestry or mining. Despite this, such conversions may continue because of a lack of awareness of the wider economic, social, ecological and environmental benefits. However, this finding would not hold true in all locations. For example, the value of conversion of an ecosystem in areas of prime agricultural land or in urban regions often exceeds the total economic value of the intact ecosystem. (Although even in dense urban areas, the total economic value of maintaining some "green space" can be greater than development of these sites, e.g. the "Green Heart" in the densely populated area in the western Netherlands).

In many areas sustainable peatland conservation and restoration requires an integrated approach with sustainable development and poverty alleviation. Considering the decline in incomes from agriculture, there is a pressing need to enhance alternative income opportunities for rural populations. It is important to ensure that their lands and resources are no longer degraded. Environmentally sound economic development is the basis for sustainable development that creates livelihood options and employment opportunities for current as well as future generations.

Sustainable livelihood strategies to generate income include income from carbon trading, water, biodiversity, green energy and tourism. Profitable land use options, such as, in tropical peatlands, oil palm, could, under certain conditions, be part of a wise use of deforested and degraded areas in order to prevent further unproductive degradation. Another strategy, particularly relevant to countries with no substantial agricultural subsidies, is the development of innovative financial instruments, e.g. bio-rights that involve payments by the global community to local stakeholders for biodiversity conservation services, thus compensating for the opportunity costs of the sustainable use of their natural resources. Bio-rights allow the public value of key biodiversity wetland/peatland areas to be transferred to local stakeholders as a direct economic benefit.

Economic valuation provides an argument and a tool for promoting wise use approaches. Evidence has been accumulating that in many cases natural peatland habitats generate marketed economic benefits that exceed those obtained from habitat conversion. Also, non-marketed ecosystem services do have economic value, but these often only become obvious when they are missed.

Mechanisms for monetarising ecosystem functions such as flood prevention, biodiversity conservation and carbon storage are generally underdeveloped. While some ecosystem functions are difficult to value as their precise contribution becomes known only when they cease to function, other functions are difficult to price as there are no equivalents to be put in their place. Consequently, weighting can only be partial and many values, benefits or disadvantages may escape monetary evaluation.

Valuation studies of industrialized countries focus on recreational and existence values held by urban consumers (travel cost models, contingent valuation). In developing countries, ecosystem values related to production and subsistence are more important, although this is changing in regions characterised by rapid urbanisation and income growth.

Valuation of peatland ecosystem services	
Using replacement cost techniques to value life support services. The Martebo mire, on the island of Gotland, Sweden has been subject to extensive draining and most of its ecosystem-derived goods and services have been lost. A study to assess the value of these lost life-support services calculated the value of replacing them with human-made technologies. The services (and their replacements) included peat accumulation, maintenance of water quality and quantity (installing pipelines, well-drilling, filtering, quality controls, purification plants, treatment of manure, pumps, dams), moderation of waterflow (pumps and water transport), waste processing and filtering (sewage plants), food production (increased agricultural production and import of foods), fisheries support (fish farming), as well as certain goods and services that could not be replaced. Replacement costs were calculated at market prices. The results of the study indicated that the annual cost of replacing the peatland's services was between $350,000 and $1million.	**Using mitigative or avertive expenditure techniques to value wetland flood attenuation.** Muthurajawela is a coastal peatland that covers an area of some 3,100 hectares alongside the Indian Ocean, 10-30 km north of Colombo, Sri Lanka's capital city. One of its most important functions is the role it plays in local flood control. Muthurajawela buffers floodwaters from 3 rivers and discharges them slowly into the sea. The value of this service was calculated by looking at the flood control measures that would be necessary to mitigate or avert the effects of wetland loss. Consultation with civil engineers showed that this would involve constructing a drainage system and pumping station, deepening and widening the channels of water courses flowing between the marsh area and the sea, installing infrastructure to divert floodwaters into a retention area, and pumping water out to the sea. Cost estimates for this type of flood control measure were available for Mudu Ela, a nearby wetland that had recently been converted to a housing scheme. Here, infrastructure had been installed to ensure that a total of 177 ha of land remains drained. Extrapolating the capital and maintenance costs from Mudu Ela to Muthurajawela gave an annual value for flood attenuation of more than $5 million, or $1,750 per hectare (Emerton and Bos 2004).

Significant investments may be needed to restore or maintain non-marketed ecosystem services. In the Netherlands loss and subsidence of peatlands has created a situation in which a large part of the country can maintain dry feet only at the costs of considerable investments in dikes and other water management structures. Whereas this may be economically feasible in such a small and highly developed country, this will not be the case in regions with lower population densities and economic productivity.

A new but key issue for peatland valuation is climate change and the related emerging official (CDM) and voluntary carbon markets. With degraded peatlands now emitting more CO_2 than global deforestation (IPCC 2007 (Working Group 3 report)), avoiding emissions from peat swamp forests and peatlands in general is rapidly turning from a hypothetical value into a real commodity. The average annual emissions of 2000 million tonnes of CO_2 from Indonesian and Malaysian degraded peatlands represent a value of 10 to 40 billion Euros if compared to investments made elsewhere in innovative climate change mitigation solutions (such as the capturing of carbon from power stations and/or storage of carbon in old oil or gas fields as being experimented with in the Netherlands and Norway). The potential and relatively low costs of avoidance of these huge emissions from degraded peatlands also compares favourably with many conventional methods for decreasing emissions in transport and energy sectors. The additional spin-offs of combining peatland restoration (combating land degradation) with sustainable development, biodiversity conservation and poverty reduction creates a win-win option, and win for all three Rio conventions, as well as other international agreements.

In conclusion, there is more in peat than the eye can see. The relationship between people and peat is one of contradictions, sometimes it is a tense one where people eke out an unsustainable living based on an ever deteriorating peat resource, and sometimes it is symbiotic with both partners in the relationship benefiting. Where people respect the ecosystem services and the eco-hydrological limitations to sustainable development in peatland areas, they can provide an enduring resource base for physical, cultural and spiritual use.

Economic value of peat swamp forests of North Selangor, Malaysia

A study by Kumari (1995, 1996) of the peat swamp forests of in Peninsular Malaysia, analyses the various benefits of moving from an existing unsustainable timber management system (base option) to sustained forest management overall. Kumari concludes that adopting more sustainable methods of timber extraction from peat swamp forest is preferable in economic terms. Although shifting to a sustainable harvesting system reduces the net benefits of timber harvesting, the case study suggests that this is more than offset by increased non-market benefits, primarily hydrological and carbon storage values. The study evaluates the total economic value (TEV) of four options (one "unsustainable", three "sustainable") for logging a peat swamp forest in North Selangor. All three sustainable options have higher net present values than the unsustainable option, for which a TEV of about US$4,000 (M$10,238) per hectare was calculated. Over 90% of TEV in all cases is made up of timber and carbon storage benefits. Economic values considered include:

- direct use values associated with extraction of timber and Non-Timber-Forest Products (rattan and bamboo);
- indirect and direct use values associated with forest water regulation/purification services;
- direct use values associated with forest recreational benefits;
- indirect use values associated with forest carbon sequestration; and
- the existence and option values associated with wildlife conservation.

Summary Results on economic value of Peat Swamp Forest in Malaysia and cost for change from unsustainable to sustainable forest management.

			Change in TEV from Base Option to sustainable option:		
Forest Good/ Service	Base Option (unsustainable traxcavator and canal) (M$/ha)	Percent of Total Economic Value (TEV)	Sustainable Traxcavator and Canal (M$/ha)	Sustainable Traxcavator and Winch (M$/ha)	Sustainable Winch and Tramline (M$/ha)
Timber	2,149	21.3	-696	-399	-873
Hydrological - Agricultural	319	3.1	0	411	680
Wildlife Conservation	454	4.4	35	20	44
Carbon Sequestration	7,080	69.2	969	1,597	1,597
Rattan	22	0.2	88	172	192
Bamboo	98	1.0	0	-20	-20
Recreation	57	0.6	0	0	0
Domestic Water	30	0.3	0	0	0
Fish	29	0.3	0	0	0
TEV	10,238	100.0	396	1,782	1,620

(Source: Kumari 1995)

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4 Peatlands and Past Climate Change

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Summary points

- Climate is the most important determinant of the distribution and character of peatlands. It determines the location, typology and biodiversity of peatlands throughout the world.
- The Earth has experienced many climate changes in the past, and peatland distribution has varied in concert with these changes. Most existing peatlands began to grow during the current postglacial period. Peatland extent has increased over the course of the last 15,000 years.
- Peatlands preserve, in the constantly accumulating peat, a unique record of their own development as well as of past changes in climate and regional vegetation.
- Records show that the vegetation, growth rate (carbon accumulation) and hydrology of peatlands was altered by past climate change and this can help in making predictions for the future.
- Peatlands affect climate via a series of feedback effects including; sequestration of carbon dioxide, emission of methane, increased albedo and alteration of microclimate.
- Natural peatlands showed resilience to the climate changes that have occurred in the past. However, the rate and magnitude of predicted future climate changes and extreme events may push many peatlands over their threshold for adaptation.
- The effects of recent climate change are already apparent in the melting of permafrost peatlands, changing vegetation patterns in temperate peatlands, desertification of steppe peatlands, and increased burning of tropical peatlands during strong ENSO events. Other impacts may remain unrecorded.
- Human activities such as vegetation clearance, drainage and overgrazing have increased the vulnerability of peatlands to climate change.

4.1 Climate and peatland characteristics

Climate is the most important control on peatland distribution. The strong relationship between climate and peatland distribution suggests that any future climate change will exert a strong influence on the distribution of peatlands. Climate is self-evidently an important influence on the distribution and character of peatlands throughout the world. The occurrence of peatlands is controlled by water balance and they are therefore most abundant in areas with excess moisture (Chapter 2, Lappalainen 1996). Consequently, peatlands are dominant over large parts of the landscape in the mid-high latitudes of North America and Eurasia, where cool conditions led to peat development even in areas with relatively low precipitation. In more temperate locations, peatlands are most extensively developed in oceanic climates, where summer temperatures are lower than equivalent continental latitudes and precipitation tends to be higher. Peatlands in New England, USA, and the Atlantic seaboard of the British Isles and France are good examples of such locations. In some tropical regions, high potential evapotranspiration is counterbalanced by extremely high rainfall, so that there is still more than adequate soil moisture for peatland development. At very high latitudes and altitudes, peat growth may be limited by the shorter growing season and low plant productivity. For example, in Finnish Lapland where the growing season is short, severe winters exert a strong frost action and the subsoil is highly permeable, peat deposits are shallow compared to southern mires. Peatlands in this region therefore have a lower average growth rate than those found further south

(Mäkilä and Moisanen 2007). Climate is therefore the most important fundamental control on peatland distribution, although the geological and topographic settings are also significant.

seasonal ice formation within the peat (Allard and Rousseau 1999). In contrast, the most extensive ombrotrophic systems occur in oceanic regions with rainfall throughout the year and low summer temperatures leading to

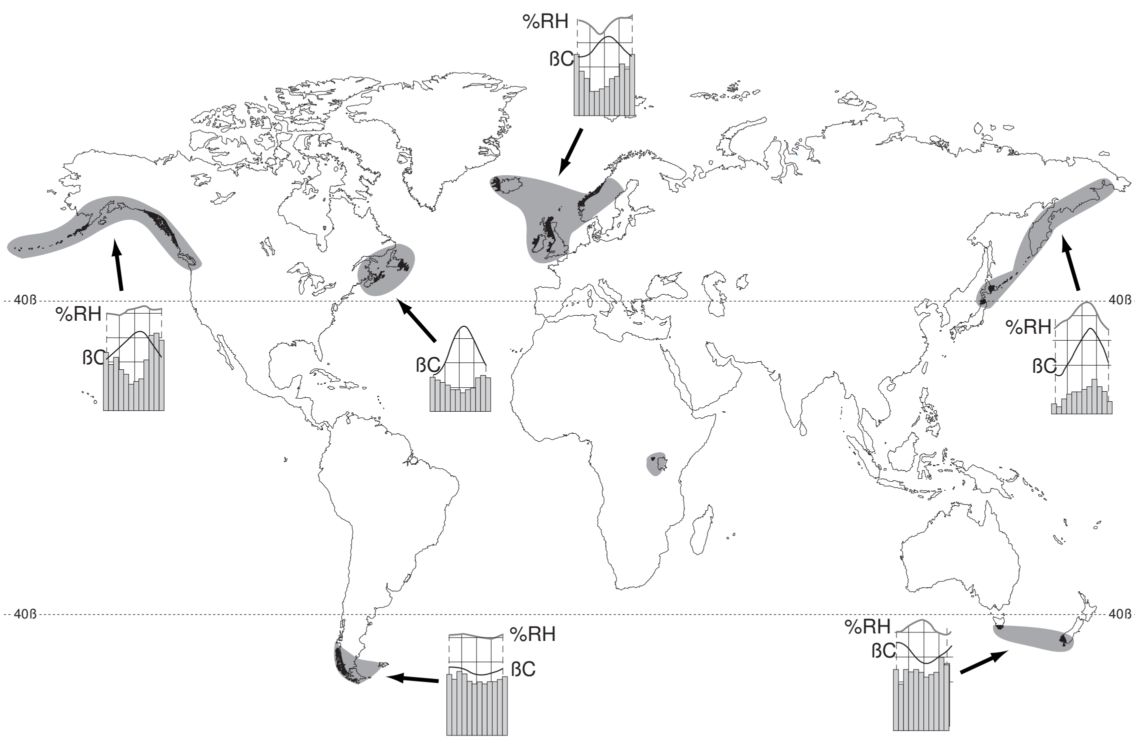


Figure 4.1: Climatically suitable areas for blanket mire formation (shaded). There is a strong association between areas with cool, wet summers and this peatland type, where peat covers most of the landscape. The inset climate graphs show the variation throughout the year of rainfall (bars), temperature and relative humidity (lines). See Chapter 2 for further description of this and other peatland types. Redrawn from Lindsay et al. (1988) and Charman (2002).

The form and function of peatlands depends strongly on the climate regime in which they occur. Typological diversity of is one of the most important characteristics of peatland biodiversity value and therefore climate exerts a fundamental control on ecosystem biodiversity in peatlands. Climate is one of the most important determinants of peatland types on a global scale. The peatland typologies described in chapter 2 are fundamentally controlled by factors such as the amount and seasonality of rainfall, mean annual and seasonal temperatures, winter minimum temperatures and freeze-thaw processes. For example, the formation of many of the landforms associated with arctic peatlands such as polygonal patterns and palsa formation are only possible where winter temperatures are low enough to produce permanent and year-round saturated ground (Lindsay *et al.* 1988, Figure 4.1). The control of climate on peatland typology is best expressed by the zonation of peatland types in relation to the main climate gradients through individual regions. This has been described for North America, Europe and Russia (Botch and Masing 1983, Eurola *et al.* 1984, National Wetlands Working Group 1988). Within Europe for example, the oceanic fringe from western Norway, western areas of the British Isles, and as far south as northeast Spain, is dominated by blanket mire. Eastward of this zone, there is an extensive and varied region where raised mires are the principal peat-forming systems. Raised mires extend throughout northern Europe into European Russia but change in form across this region, with the best developed raised domes of peat to the west and north and drier, flatter forms to the south and east. Moving north from this zone into much of Fennoscandia and northern European Russia (above approx. 60^{o}N), aapa mires are dominant. Then in the extreme north, palsa mires are found with arctic polygonal fens in even colder continental settings. Of course, there are transitional zones between regions and some local variability due to local topographic and climatic conditions, but these general patterns are striking in their clarity when viewed at the continental scale.

The distribution of peatland species is often closely related to climate. Many species of plants and animals are only found on peatlands and some are endemic to specific peatland regions, especially in the tropics. Some of these species are obligatory peatland taxa and only depend on climate to the extent that climate controls the distribution of their habitat. Other taxa show strong relationships with climate, but are not obligatory peatland taxa. In these cases, peatlands provide suitable microclimatic conditions within areas that are otherwise climatically unsuitable, thus extending their overall geographical range. For example, the dwarf birch (*Betula nana*) shows a strong relationship with maximum July temperatures. Dwarf birch and some other arctic species like Crowberry (*Empetrum nigrum*) and Labrador tea (*Ledum palustre*) are found only in peatlands in the southern part of their distribution where local temperature conditions are cooler, while in the Arctic they are a widespread species, not associated with peat.

Invertebrates are often more closely tied to temperature regimes than plants. For example, in the UK there is a strong altitudinal gradient of invertebrate taxa as a function of decreasing temperatures at higher elevations. Relationships between species distributions, diversity and climate are most apparent on continental scales. Glaser (1992) shows that species diversity increases with mean annual precipitation and annual freezing degree days (cumulative temperature below 0^{o}C). Sites with higher precipitation and less intensive and prolonged periods of winter freezing contained a greater range of peatland taxa.

On the other hand, some peatland plants and animals show surprisingly cosmopolitan distributions, especially for lower orders. A good example is the genus *Sphagnum*, a dominant component of ground flora and peat component in many peatlands. Some species such as *S. magellanicum* attain very widespread distribution in both hemispheres. However, at larger scales, even *Sphagnum* species are restricted to specific climatic spaces. For example, Gignac *et al*. (1991) show that taxa in North America occupy specific niches defined by temperature and precipitation (Figure 4.2).

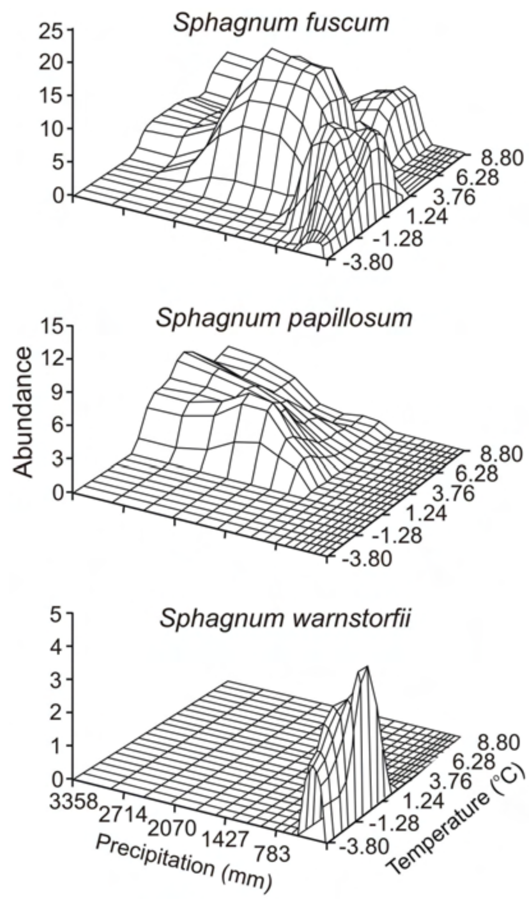


Figure 4.2: Relationships between temperature, precipitation and abundance of three species of Sphagnum in peatlands in western Canada. Sphagnum papillosum occurs only in areas with higher temperatures and high precipitation whereas S. warnstorfii is restricted to locations with low temperatures and low precipitation. Sphagnum fuscum is tolerant of a wider range of climate conditions. Redrawn from Gignac (1991) and Charman (2002).

4.2 Past climate variability and peatland distribution

Climate change is a normal condition for the Earth; the past record suggests continuous change rather than stability (Figure 3). Climate change is constant. There is no period of the Earth's history when the climate has been completely stable. Evidence from the geological record shows that climate varies over a range of timescales and with varying magnitude. Recent climate change recorded in meteorological records covering the last 150 years (see below) and future climate predictions should be seen in the context of longer term climate variability. Recent climate change may already be outside the range of natural climate variability. Climate is normally defined as average conditions over periods of 30 years or more. Variability on shorter timescales is usually referred to as changes in weather. However, this division is not a strict one; continuous trends in temperature within periods of 30 years may still constitute climate change. The details of very long-term climate changes are sketchy due to the incomplete and imperfect geological record. However, it seems likely that global temperatures have shown a slow decline from the beginning of the Cenozoic (approximately 65 million years ago) to the current period of geological time, the Quaternary (approximately the last 2 million years, Figure 4.3a). The climate changes on these very long timescales are controlled by various factors including the movement of the continents and tectonic uplift. These factors are insignificant over centennial to millennial timescales.

Peatlands have existed from the earliest periods of geological history, as soon as wetland plants evolved. Peatlands are a key component of the Earth system and peat formation has provided an important terrestrial carbon sink for hundreds of millions of years. Rather little is known about the changes in distribution and mass of peatlands over very long timescales, but peatlands have certainly existed for hundreds of millions of years. The early peatlands form the coal and oil deposits from a wide range of geological periods during a variety of climatic conditions and from all continents (e.g. Bojesen-Koefoed *et al.* 2001, Gastaldo *et al.* 2004, Sykes 2004). Many of these peatlands were formed in tropical or sub-tropical climates but we have to be careful about drawing direct parallels between these ancient peatlands and those in existence today, not least because many of the plants that formed them have become extinct. Estimates of the magnitude of the carbon stored in peat compared to the carbon stored in exploitable coal show that 'modern' peat holds almost as much carbon as is contained in exploitable global coal reserves.

The last 2 million years of Earth history (the Quaternary period) is characterised by a series of cold glacial events with warmer intervening interglacial periods. These large changes in climate are forced by predictable variations in the Earth's orbit around the sun. Sea level was around 120m lower than present during major glacial periods. There have been at least 20 glacial-interglacial cycles and the last 400,000 years has seen a regular pattern of change with glaciations lasting around 100,000 years and interglacials around 10-20,000 years (Figure 4.3b). The nature of this cyclicity has been demonstrated by changes in ocean sediments and ice cores (Petit *et al.* 1999, EPICA Community members 2004). The ultimate cause of these climate changes is the orbital variations of the Earth around the sun, which produce predictable changes in the amount and distribution of solar radiation received at the Earth's surface. However, orbital variations alone cannot account for the climate changes observed in the geological record, and amplification mechanisms in the Earth system must have been involved. These include changes in the carbon cycle and greenhouse gas concentrations, changes in albedo from ice, snow and vegetation, and variability in ocean circulation and heat transport.

During the 'ice-ages', peatlands expanded and contracted with changes in climate and sea-level. During glacial maxima, much of the current area of extensive peatlands would have been covered with ice or would have been too dry to support peat growth. However, suitable areas for peat formation would have existed on the continental shelf areas, exposed due to the lowering of sea level by around 120m. Peat would also have been present in tropical regions, and some existing peatlands from lower latitude areas contain sediments from during the last glacial, for example, Lynch's Crater in Australia (e.g. Turney *et al.* 2005)

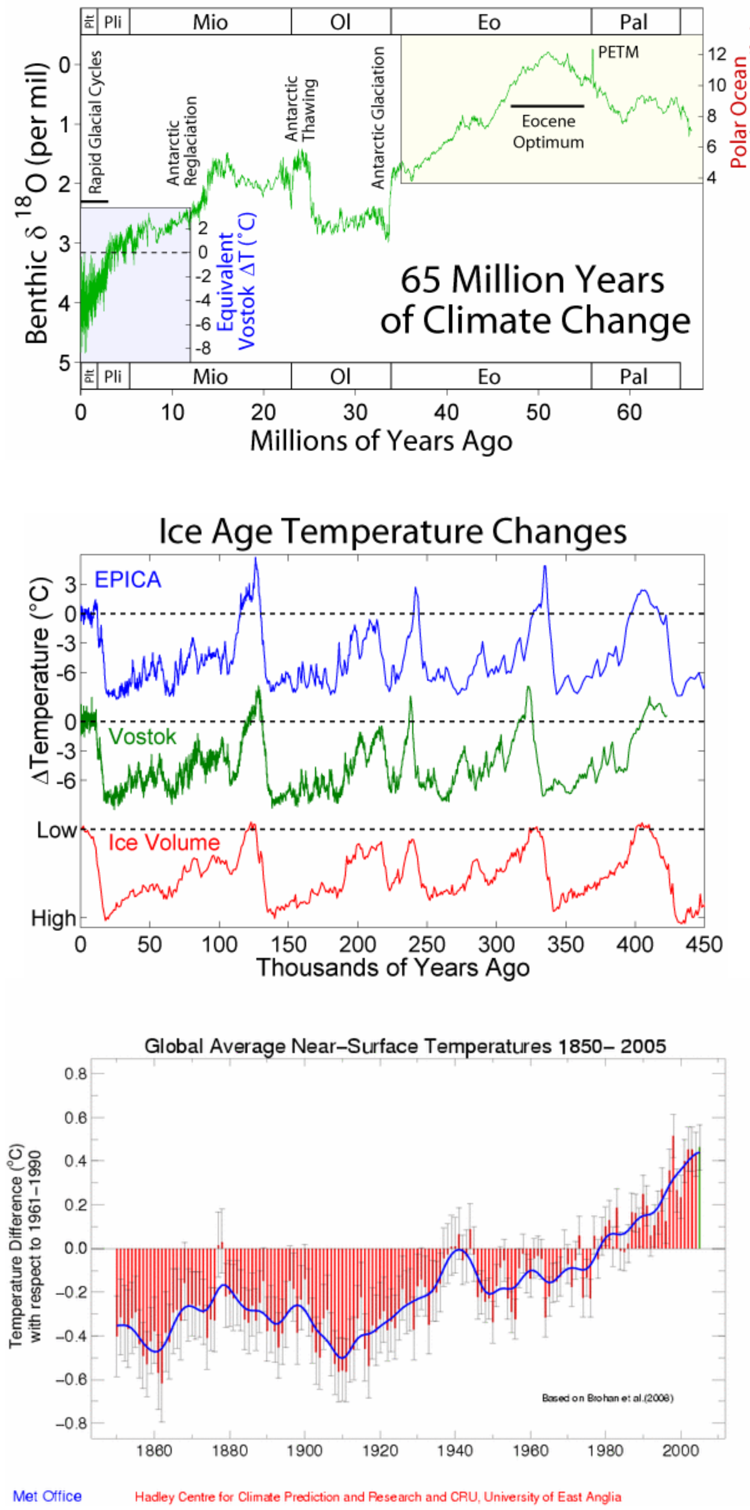


Figure 4.3: Global temperature change a) For the last 65 million years, as shown by oxygen isotopes in benthic foraminifera in ocean sediments b) for the last 450,000 years, as shown by oxygen isotope variations in ice cores c) since AD 1850 from instrumental meteorological records. Images from Global Warming Art (2006), based on original sources Zachos et al. (2001), 1 b). Petit et al. (1999), EPICA community members (2004), Lisiecki and Raymo (2005), 1 c) UK Meteorological Office Hadley Centre and Climate Research Unit, University of East Anglia, Brohan et al. (2006).

How big is the 'modern' peatland carbon store compared to the 'ancient' peatland carbon contained in coal?

Coal is one of the main fossil fuels for energy production. Coal formed in ancient peatlands represents a large carbon pool. Estimates of the accessible global coal reserve including bituminous, sub-bituminous coals, lignite and anthracite, are close to 1 trillion tonnes (1 x 10^{12} tonnes). One recent estimate is of about 900 Gigatonnes (1 Gt = 1 billion tonnes = 1 x 10^{9} tonnes) (EIA 2006). Assuming that the carbon content of this averages around 65% (high grade coal may be as much as 95%), the carbon held in fossil reserves is around 585 Gt. This is not too dissimilar to many estimates of the total carbon stored in modern peat today, which are usually around 500 Gt (Charman 2002). 'Modern' peat thus represents a similar carbon pool to the entire global exploitable coal reserves. Both coal and peat demonstrate the importance of peat accumulation and fossilisation as vital functions in removing and storing carbon from the atmosphere over millions of years. At current rates of use (roughly 5 Gt pa, equivalent to 3.25 Gt C pa), there is almost 200 years of coal supply left. Put another way, modern peatland carbon represents almost 200 years of coal burning at present rates.

and the Nakaikemi Wetland in south-west Honshu, Japan (Saito 2004). The deepest peat/lignite layer in the world is probably the Phillipi peatland in Greece, reputed to be 190 m deep (Kalaitzidis and Christanis 2002), and dating largely from the Pleistocene.

Fragments of peatlands that formed during previous warm phases (interglacials or interstadials) can also be found under glacial till in areas that were subsequently covered by ice. For example, in Finnish Lapland, peat from the last ('Eemian', c. 120,000 years BP) interglacial has been reported. The peat contains abundant pollen of spruce and *Sphagnum* spores, which together indicate that peatland was present across a wide area (Saarnisto *et al.* 1999). Further east, peat deposits formed during a later interstadial and dating from 33,300 to 41,900 years BP can be found in Southern Valday. These deposits lie outside the last glacial maximum and therefore avoided destruction by the ice sheet (Minayeva *et al*. 2005). Other old peat deposits occur in North America in sediments from below the Laurentide ice sheet, such as the Missinaibi beds in Ontario, Canada. These have been dated to 38,000 and 53,000 years BP (Terasmae and Hughes 1960). The extent of peatlands during previous interglacial and glacial periods cannot be estimated with any certainty because they have been subsequently eroded by ice or submerged under rising sea levels. However, refugia for peatland taxa must have existed during these phases and peatland development may have been very extensive in some locations.

Atmospheric carbon dioxide concentrations were much lower during glacial periods, and peatlands and other organic-rich soils may have still played a significant role as one of the enhanced sinks for CO_2 during these phases. Peat growth may also have played a role in the feedbacks controlling glacial-interglacial cycles, removing carbon during warm phases thus lowering atmospheric CO_2 levels and contributing to the climatic downturn to an ice age (Franzen *et al*. 1996).

Climate changes in the current postglacial (approximately the last 11,500 calendar years) occurred gradually as a result of changes in the Earth's orbit, and more rapidly due to changes in solar output, volcanic activity and internal ocean-atmosphere processes. The last 11,500 calendar years (= c. 10,000 radiocarbon years[1]) have been relatively stable compared to the glacial-interglacial cycles (Figure 3). However, it is increasingly realised that there were significant changes in global and regional climate during this time, and that some of these changes manifested as abrupt climate changes rather than as long-term, gradual shifts. Most importantly for peatlands, hydrological changes appear to have been some of the most marked changes during the Holocene, often occurring over short (decadal to centennial) timescales. In many continental regions there is abundant evidence for recurrent and severe drought episodes during the late Holocene, many of which were greater in magnitude and/or extent than those observed during historical times (Cook *et al.* 2004, Booth *et al.*

[1] Ages younger than 11,500 calendar years are all cited as calibrated radiocarbon ages unless they are historically documented ages, when they are cited in years AD/BC.

2005, 2006). For example, a widespread drought spanning several centuries about 4200 years ago has been documented throughout mid-continental North America and parts of the rest of the world (Booth *et al.* 2005). Similarly, tree-ring based drought reconstructions in western North America indicate recurring intervals of persistent, severe and widespread drought during the last 1000 years, most notably a series of multidecadal events during the Medieval Climate Anomaly (or Medieval Warm Period) (Cook *et al.* 2004). The causes of these and other centennial and sub-centennial scale fluctuations in water balance are not well understood, and the influence of orbital cycles on continental climate is only apparent over much longer timescales. However, variations in water balance over these shorter timescales may have been triggered by the dynamical response of the coupled ocean-atmosphere system to changes in solar and/or volcanic forcing. For example, sea-surface temperature anomalies (SSTs) appear to have played an important role in decadal to multidecadal drought episodes during historical time periods (Hoerling and Kumar 2003, McCabe *et al*. 2004, Schubert *et al.* 2004), and past changes in solar output and volcanic emissions may have amplified similar dynamics. However, mechanisms linking drought and SST anomalies are not clear and the response of the ocean-atmosphere system to changes in external forcing needs to be better understood.

Many existing peatlands started growth soon after the warming following the last glacial maximum. The initiation of new peatlands has continued throughout the postglacial period in response to changes in climate and successional change. After the recession of the large Eurasian and North American ice sheets, new land surfaces for peatland development were exposed. At the same time, other land was inundated by the rising seas. This process still continues at a much lower rate today. Many modern peatlands started growth almost as soon as the climate warmed. For example boreal peatlands began growth as early as 16,500 years ago (MacDonald *et al.* 2006) and the extensive western Siberian peatlands began their main period of growth 11,500 years ago (Smith *et al*. 2004). Other peatlands took longer to begin growth, either because of greater delays in the exposure of the land surface or because of climatic factors. For example, it is clear that large parts of the northern hemisphere were subjected to a short (around 1000 years) cold snap which interrupted the warming after the last glacial maximum. Extensive peat growth in the northern hemisphere may also have been delayed by the relatively warm conditions in the early Holocene. The extended retreat of the large ice sheets over the first 3000-4000 years of the Holocene in the northern hemisphere also delayed peat growth (e.g. Mäkilä 2006). However, in many regions, the initiation of new peatlands continued into the early Holocene and proceeded throughout the whole of the Holocene period. New peatlands are still beginning to grow on freshly exposed terrain such as the emerging land surface of the Gulf of Bothnia (Hulme 1994).

Holocene climate change led to a succession of new peatlands being formed in many parts of the world including Australia (Kershaw *et al.* 1997) and western Canada (Halsey *et al.* 1998). This is confirmed by the correspondence between dates of peat initiation and other independently derived records of past climate change (Campbell *et al.* 2000). Other factors clearly played a role in encouraging the growth of peat in some regions. In Britain, it has long been recognised that deforestation by humans probably altered the water balance sufficiently to allow the accumulation of organic matter and ultimately the development of deeper peat (Moore 1993). However, most peat initiation appears to be climatically driven rather than a result of human activity or other local factors.

Peatland expansion has been a constant process during the Holocene. Once peatlands became established, most of them continued to grow vertically and expand laterally throughout the Holocene period. It is not known whether some peatlands disappeared during this time because evidence for any former peatlands may have been eroded or completely decayed. For example, it is well known that sub-Saharan Africa experienced much wetter climates during the early Holocene, and it is likely that there were peat-forming wetlands in this region. Elsewhere, peatlands spread partly as a result of ecological and soil development processes and partly as a result of changing climate. Korhola (1995) attributes the spread of mires in Finland to climatic change, with phases of expansion

Peatland archives

Evidence of past change: To understand the way the 'Earth system' works, we need information on how the environment and climate have changed in the past. This information is provided by a range of natural 'archives' that range from ice cores, ocean and lake sediments, to tree rings and stalactites in caves. Peat also contains a variety of evidence of past environmental changes. These consist of plants, animals and microbes that once lived on the peatland, as well as material such as pollen, dust and pollution blown in from more distant areas. Studies of the biology and geochemistry of peat have taught us much about changes in the past. Some of the main indicators are:

- Pollen and spores. These provide us with information on the main changes in vegetation on and around the peatland, such as forest history
- Plant macrofossils. These are larger plant fragments usually from plants growing on the peatland itself. They tell us how the vegetation of the peatland has changed through time in more detail than pollen alone.
- Protozoa, diatoms and other microfossils. There is a huge variety of remains of small organisms preserved in peat, including amoebae, diatoms and other algae, fungi and a range of invertebrates. Particularly notable are the testate amoebae that allow us to reconstruct hydrological changes on peatlands.
- Peat humification or degree of decay of the peat. This provides information on past changes in decomposition.
- Heavy metals. These indicate changes in pollutant history and other disturbances to the peatland.
- Stable isotopes of carbon, oxygen and hydrogen. These can be used to help understand changes in hydrology and temperature.
- Biomarkers. These are complex chemicals associated with particular plants and are being developed as a new tool for reconstructing environmental changes from peat.

Finding out when changes took place: The evidence of past changes can be used to reconstruct what happened in the past, but they don't tell us *when* events took place. However, peat can be dated using various techniques. The principal technique is radiocarbon dating which depends on the presence of tiny amounts of radioactive carbon. This gradually decays at a known rate over time; more radiocarbon indicates the peat is young. Older peat contains much less radiocarbon and almost none at all after about 50,000 years. Other similar 'radiometric' techniques include lead (^{210}Pb), caesium (^{137}Cs), and Americium (^{241}Am) for peat formed in the last 150 years. We can also estimate the age of peat from other markers such as volcanic ash layers of known age, vegetation changes of known age detected by pollen analysis (e.g. plantation of non-native trees in Europe), and pollution markers of known age (e.g. increased use of fossil fuels in the 20th century).

occurring at times of increased moisture excess also reflected in lake level changes in the region.

4.3 Peatland archives of past climate change

Peatlands provide a record of their own development preserved in the peat itself. This means that it is possible to trace the changes in peatlands through time, in response to climate change and other influences such as succession and human activity. Peatlands are unique ecosystems because they preserve a record of their ecological and physical structure in water-saturated sediments, where decomposition rates are slower than production (Charman 2002). Peat is primarily formed from the dead remains of plants that once grew on the mire surface. However, when the layers of successive vegetation remains are laid down, they incorporate a range of other microscopic remains and geochemical signals of past environmental conditions. In fact, virtually everything living in or around a peatland has the potential to be preserved in the accumulating peat (Charman 2002), although there is a clear bias toward materials that are decay-resistant, such as structures rich in refractory compounds like lignin or chitin. The excellent preservation of materials in peat allows a variety of biological, physical, and geochemical techniques to be used to reconstruct past environmental conditions. Application of these methods provides a secure basis for understanding how peatlands have responded to past climate variability and change.

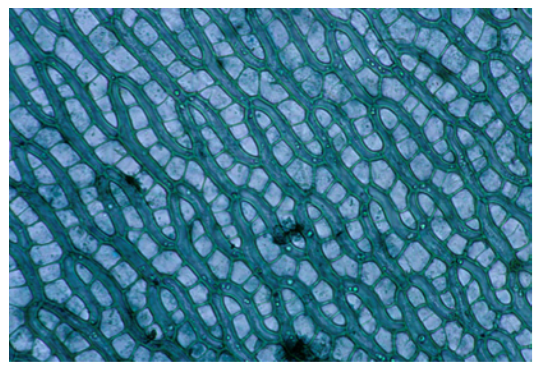
For example, evidence from plant macrofossils and relative peat decomposition (i.e. humification), indicates that many peatlands in Europe became much wetter around 2650 years ago following a change to a cooler and wetter climate (van Geel *et al.* 1996). Similar increases in moisture also occurred within many peatlands of Europe during the cooler and wetter Little Ice Age (Barber *et al.* 2000). These moisture increases were often associated with changes in peatland plant communities, particularly the relative abundance of

Sphagnum and vascular plants. In other circumstances, it is clear that past changes in peatland ecology and hydrology are attributable to human activity, such as the clearance of forest around peatlands. This can result in the flooding of peatlands that receive the runoff from the cleared areas. In southern Ontario, European settlement in the last few hundred years led to widespread deforestation of catchments and the formation of at least some of the 'floating bogs' that are found in the numerous surface depressions in the area (Warner *et al.* 1989).

Peatlands also provide records of past changes in the wider landscape and environment such as regional vegetation change, atmospheric pollution and climate change. Some peat characteristics are representative of the local peatland environment and structure, and others are derived from adjacent uplands or the wider region. Thus, landscape and regional perspectives can be provided by peat stratigraphy, and compared to the developmental history of the peatland itself.

Plant and other organic materials are very well preserved in the saturated peat.

For example, plant macrofossils can provide excellent records of peatland vegetation, and can be used to investigate local vegetational and hydrological dynamics within a peatland (McMullen *et al.* 2004). These local dynamics can be compared to temporal changes in macrofossils and pollen of upland plants, providing insight into the long-term linkages between peatlands and the surrounding landscape (e.g. Singer *et al.* 1996, Campbell *et al.* 1997, Wilmhurst *et al*. 2002, Booth *et al.* 2004). Recent and ongoing studies in the mid-continent of North America have been employing coupled studies of past peatland hydrology and upland vegetation to provide insight into the direct responses of upland tree populations to changes in water balance, providing insight into population dynamics at centennial timescales (Jackson *et al*. 2006). Peatlands also record changes in atmospheric deposition, and changes in heavy metal concentrations have been used to assess regional and sometimes global atmospheric pollution levels (Shotyk and Krachler 2004).



A close-up of Sphagnum cells from peat approximately 4000 years old.

Evidence from peatlands can be used to reconstruct past changes in climate, contributing to the growing archive of information on past climate changes, as well as providing information on the ways in which peatland systems respond and adapt to climate changes. Some of the earliest evidence for climate changes in the 'postglacial' period came from peatlands in Scandinavia, where changes in the structure and botanical content of the peat were used to describe a series of main climate periods. For example, a change to less decayed peat dominated by *Sphagnum* mosses marked the start of the 'Sub-Atlantic' period following on from the earlier relatively dry 'Sub-Boreal'. These Blytt-Sernander periods (named after the scientists who described them) are now known to over-simplify climate change over the past 12,000 years but some events are confirmed by more modern work, including the Sub-Boreal to

Sub-Atlantic transition at around 2600 years ago.

Peat stratigraphy may reflect past climate changes.

In many peatland systems, hydrological status is particularly sensitive to climate variability. These ombrotrophic peatlands receive all of their water from precipitation rather than from runoff or groundwater supplies and therefore changes in their surface wetness primarily reflect climate change from either precipitation or evapotranspiration variations (Blackford 2000). However, local changes in hydrology can also occur as a result of non-climatic factors such as successional processes and local vegetation dynamics. As a result, more reliable reconstructions of past climate can be gained from multi-core and multi-site reconstructions of hydrology (Figure 4.4, Charman *et al.* 2006). Climate change can also be inferred from other independent markers of climate change such as isotopes of carbon, hydrogen and oxygen (Pendall *et al.* 2001).

4.4 Peatland responses to past climate change

Peatlands change as a result of both internal ecological processes and external forcing such as climate change and human disturbance. The relative influence of these factors depends on the magnitude of forcing and the type and stage of development of the peatland. In the past, climate has been the most important influence on changes in peatlands. In their natural condition, peatlands behave almost like whole organisms – they grow upwards and expand outwards and go through successional stages over time. The detailed changes in vegetation and surface topography are also partly a result of competition, small-scale hydrological changes, and chance. Overlain on these 'internal' processes is the over-riding effect of climate variability. Changes in the character of the peatland and its continued existence are due to a combination of the complex internal mechanisms and climate change. Human influences are a further 'external' forcing factor that, when severe enough, may over-ride both internal ecological factors and climate change to alter the system. However, under natural conditions, climate is the most important determinant of changes over time (e.g. Barber 1981).

Peatlands have experienced many climate changes in the past and in their natural state, peatlands are often resilient to such changes. Changing climates over the Holocene have been a major influence on peatland condition. Because of the preservation of biological and geochemical evidence in peat, quite a lot is known about the responses of peatlands to climate change over several centuries and millennia. However, these studies are sometimes limited in the range of changes they can detect. In northwest Europe, a series of fluctuations from wet to dry conditions have occurred in response to past climate changes. The most easily observed and dramatic change is the switch from dark peat to lighter peat at the so-called 'Grenzhorizont' dating from approximately 2500 years BP. This widespread feature reflects changes from dry to wet conditions at this time. Throughout the Holocene period there has been a series of such changes from dry to wet and back to dry conditions recorded in many peatlands (Barber and Charman 2003). This suggests that in their natural state, peatlands can persist through a variety of climate regimes. Extreme dry periods may in some cases result in a cessation of peat growth but accumulation resumes once conditions become wetter again, for example, in peatlands of north-west Europe and mid-continental North America. In some circumstances, climate change is sufficient to

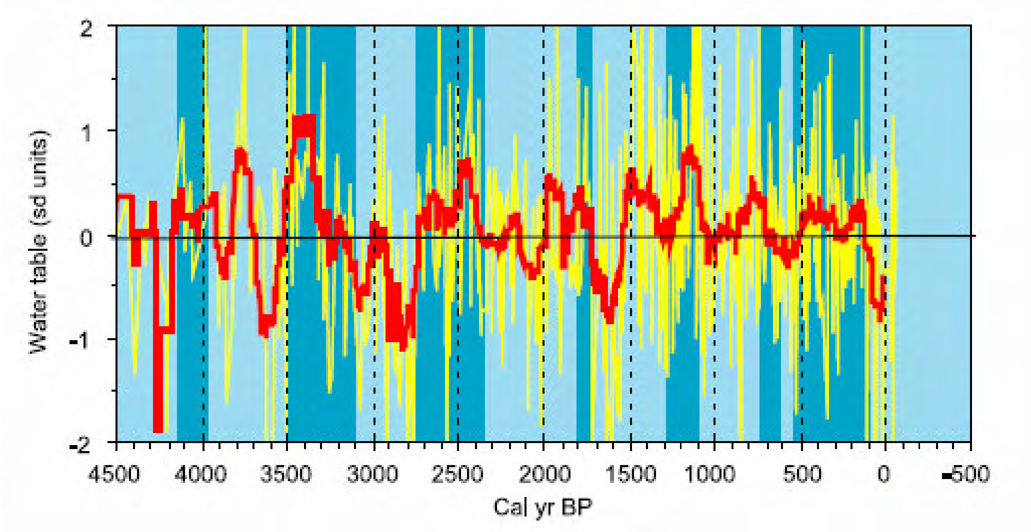


Figure 4.4: Changes in peatland surface wetness over the past 4500 years inferred from 12 records of reconstructed water table variability from northern Britain (Charman et al. 2006). When the peatlands were wet (up on the graph), precipitation was higher and temperature may have been lower. Using multiple cores avoids problems associated with purely local, non-climatic influences. The change at around 2750 years ago is the same period as the Sub-Boreal to Sub-Atlantic transition (see text). This change was identified over 100 years ago but as the diagram shows, there were also other, sometimes equally important changes at other times. The dark grey bands mark periods when lake levels were higher in central Europe, showing that the main phases of wet conditions were similar across the European continent.

stop or at least retard peat growth for much longer periods of time. For example, in some parts of the Arctic, there is evidence that peat growth has slowed down substantially in the last 3000 to 5000 years as a result of regional cooling (Vardy *et al.* 2005). Under natural conditions, peatlands are self-regulated systems that have developed different mechanisms to resist changes in hydrological regime caused by climatic fluctuations. During drought, evaporative loss is reduced due to the formation of a 'skin' of dried surface vegetation. Changes in moisture content result in 'mire breathing' where the surface of the peatland rises and falls depending on the amount of available water, assisting the maintenance of the water table at a high level during drought periods.

Hydrological change is the most frequently recorded response to past long-term climate change but the exact nature of the response depends on the peatland type and local setting. Most climate change is registered as hydrological change in palaeoecological studies on peatlands. The balance between precipitation and evapotranspiration is affected by changes in temperature and precipitation and it is often difficult to distinguish between these two factors. The hydrological response to different climate variables depends primarily on the initial conditions. In cool oceanic areas, peatlands are most likely to be sensitive to shifts in summer precipitation, whereas in more continental areas, temperature is probably an additional significant influence (Charman *et al*. 2004). In high latitudes, snow melt is an important additional influence (Ruuhijarvi 1983). Because hydrology is a key driver of many peatland functions, past hydrological changes would have been accompanied by shifts in biodiversity, carbon accumulation and greenhouse gas exchanges.

Having inputs of surface and ground water, fens often show more resilience to shifts of precipitation and evapotranspiration than bogs, which only have an atmospheric water supply. Less connection to water sources other then precipitation make peatlands more sensitive to paleoclimate fluctuations, as shown by comparison of the Holocene history of the raised bogs, groundwater-fed fen and the peatland with water inflow from adjacent upland in the Central European Russia (Sirin 1999). Among raised bogs of the same region larger peatlands occurring on moraine clay were more resilient to the climate changes during last 3000 years than the smaller bogs lying on the outwash sands (Rauber 2002).

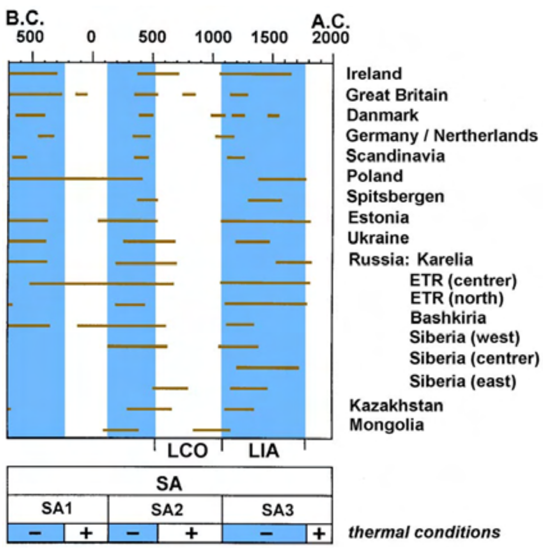


Figure 4.5: Periods of intensive peat accumulation in different regions of Eurasia. SA – Subatlantic (2600 B.P. to present) and some suggested subperiods (labelled here as SA1, SA2, SA3), LCO – Little Climatic Optimum (500–1100 A.D.), LIA – Little Ice Age (1100–1750 A.D.) (After Klimanov and Sirin, 1997).

Palaeoecological records show that fire frequency is increased during periods of warm, dry climate, but much greater changes are brought about as a result of human activity. Although fires occur under natural conditions, there is evidence that fire frequency has been altered by human activity in both prehistoric and historical times. Although peatlands generally have water tables near the surface and are therefore less susceptible to fire than dryland ecosystems, natural fires do occur during dry periods. The relationship between fire, climate and human activity varies between regions and peatland types, although in general peatland fires are more frequent during warm, dry periods. In western Siberia, it seems unlikely that fire has led to large losses of peat at any time during the last 7-8000 years, with fires only affecting the extreme margins of the main peatland expanse (Turunen *et al.* 2001). In this case, it appears that the wetness of the mire has prevented the spread of upland forest fires onto the peatland surface. In northwest Europe, similarly small marginal areas of peatland have been burnt and large increases in fire frequency are only found as a result of human activity (Pitkanen *et al*. 2002). In Kalimantan, Indonesia, the presence of charcoal demonstrates that the forest experienced fires during the whole of the past 30,000 years (Anshari *et al.* 2001). Increases in fire frequency are recorded as a result of human activity during the last 3000 years and especially within the last 1000 years (Anshari *et al*. 2004, Hope *et al.* 2005). Although human activity appears to be typically associated with increased fire frequency on peatlands, this is not always the case. For example, fire is an important part of the ecology of pocosins, which are precipitation-fed shrub bogs of the southeastern United States (e.g. Christensen *et al.* 1981). Fire suppression during the past 100 years is decreasing the natural fire frequency and leading to ecological changes in these systems.

Rates of carbon accumulation have varied in response to past climate change. The nature of the response depends upon the initial climate conditions and the type of peatland. Peatland response depends on the balance between plant productivity and decay rates in the surface peat layers. Rates of peat accumulation in peatlands have varied through the Holocene period. Some of these changes are due to successional change, typically with high accumulation rates in phases of terrestrialisation. However, where there is stability of peatland type through a period of climate change, palaeoecological studies show that the rate of carbon storage changes. In northern Finland, aapa mires show reduced carbon accumulation after 7000 years BP, followed by an increase at around 4500 years BP, thought to be related to the change from a relatively warm, dry mid-Holocene period to a cooler and moister later Holocene (Makila *et al.* 2001). Similar linkages between climate and carbon accumulation have been documented in other regions (e.g. Mauquoy *et al.* 2002, Yu *et al*. 2003).

In southern Finland, the stratigraphy of three raised bogs suggests that carbon exchange and accumulation by the mires have always been sensitive to climatic fluctuations, which have been characteristic of the entire Holocene (Mäkilä and Saarnisto 2005, Figure 4.6).

Prominent changes to higher carbon accumulation rates in the three raised bogs were dated at 6750-6400, 5100-4950, 4100-3850, 2950-2750, 2650-2500 and 800 cal. yr BP up to the present (Mäkilä and Saarnisto 2005). Increased accumulation rates reflect periods with a more positive precipitation-evaporation balance. The lower carbon accumulation rates between the above-mentioned periods are associated with a drier climate. The relationship with climate becomes stronger through the Holocene because autogenic factors relating to a succession of mire types cause significant variability in the early Holocene (Mäkilä 1997, Mäkilä *et al.* 2001, Mäkilä and Moisanen 2007).

Raised bogs in mid-latitude areas show significant changes over time. For example, during the Little Ice Age (approx. AD 1300 to 1800 in this case), carbon accumulation rates in three European mires were lower than former periods because of reduced plant productivity in shorter growing seasons but also perhaps because of a shift to species with high decomposition rates (Mauquoy *et al.* 2002). This last point highlights the inter-relationships between climate, peat accumulation and biodiversity changes and demonstrates the need for a complete systems understanding to be able to predict responses to future change. In Kalimantan, carbon accumulation was lower during the last glacial maximum, presumably due to lower primary productivity because of lower temperatures. Holocene rates were much faster, especially during the early Holocene (Page *et al.* 2004). In West Siberia, the early to mid Holocene was also the most important period for carbon accumulation, with around 55% of the total stored carbon accumulated by 6000 years ago. Particularly rapid lateral expansion of peatlands and consequent increased carbon storage was found between 7000 and 8000 years ago (Turunen *et al.* 2001), perhaps due to a warmer climate during this time.

Lateral spread of peatlands may also be an important control on overall carbon accumulation rates. In southern Finland, the lateral spread of peatlands occurred rapidly with around half of the total present area paludified by 8000 years BP (Mäkilä 1997, Mäkilä *et al.* 2001). In the north, spread was slower (Mäkilä and Moisanen 2007). Local differences in rates of mire expansion and therefore carbon accumulation rates are also affected by topography, which is a key control on the locations to which peatland can spread (e.g. Korhola 1992). For Finnish mires, by the time they had attained their modern extent, they had accumulated over half of their modern carbon store. 55% of the carbon had formed before 4000 cal. yr BP in a southern aapa mire Ruosuo, and 58% of the carbon before 5000 cal. yr BP in a northern fen Luovuoma in Finnish Lapland (Mäkilä 1997, Mäkilä *et al.* 2001, (Mäkilä and Moisanen, 2007).

Peatland response to climate change may not occur smoothly; sudden changes may occur when specific climate and/or ecological thresholds are reached. Palaeoecological research demonstrates that shifts in peatland condition do not necessarily occur smoothly.

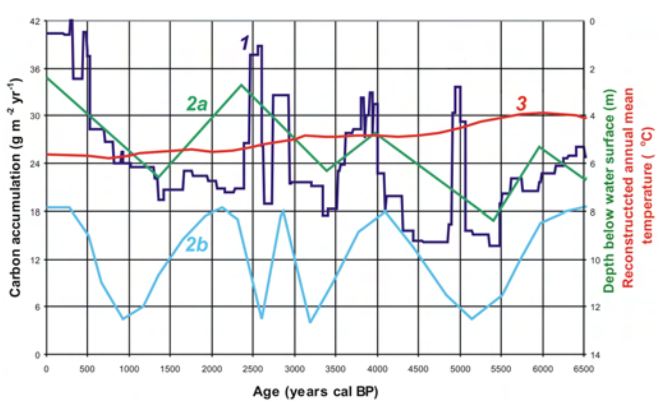


Figure 4.6: Average rate of carbon accumulation in the three raised bogs in southern Finland (Mäkilä and Saarnisto 2005) and lake-level fluctuations in Finland and in Sweden. The 2a line indicates modified Holocene lake-level fluctuations according to Digerfeldt (1988) and 2b line indicates the fluctuations according to Sarmaja-Korjonen (2001). Lake-level positions are expressed only as high or low by Sarmaja-Korjonen (2001). The quantitative annual mean temperature reconstruction based on pollen is also shown (Heikkilä and Seppä 2003).

Transitions between relatively wet and relatively dry conditions can occur over periods of decades rather than requiring centuries to change (e.g. Figure 4). It is not clear whether these shifts are attributable to abrupt climate change or whether they represent crossing of hydrological thresholds as a result of longer term changes in prevailing climate. In either case, it demonstrates that we should not expect future changes to be gradual; sudden shifts in peatland condition are to be expected.

4.5 Peatland feedbacks to climate change

Peatlands are affected by climate changes in many different ways but they also play an important role in modifying climate themselves. These effects are known as 'feedbacks'. Several of these effects are covered in more detail elsewhere in this report so here we simply summarise some of the key points.

Peatlands play a key role in the global carbon cycle, acting both as sinks for carbon dioxide and as sources of methane. Both these processes have had a significant influence on global climate change throughout Earth history. It is evident from the preceding sections that the build up of large volumes of peat represents a vast quantity of carbon. The drawdown of carbon dioxide from the atmosphere to storage in peat has a net cooling effect on the climate. Any factors that either slow down (speed up) carbon sequestration represent a warming (cooling) effect on global climate. The carbon stored in peatlands during previous millennia is the basis of all the coal, oil and gas reserves now being exploited as energy sources. This is therefore a feedback that has operated throughout Earth history. Methane emissions from peatland are a further feedback to climate change. Warmer, wetter conditions enhance methane emissions increasing global temperatures, while cool, dry conditions suppress methane emissions and reduce global temperatures. It is now known that past natural variations in methane concentrations were strongly influenced by changes in peatland extent and condition (see section 7.2 for further detail).

Greenhouse gases show variable atmospheric concentrations throughout the last 15,000 years. Peatlands contribute to these natural variations in atmospheric composition. During the current postglacial period, atmospheric concentrations of carbon dioxide and methane were not stable, even during pre-industrial times. Peatlands and other wetlands contributed to the natural variations in greenhouse gases, increasing methane concentrations during some periods and decreasing carbon dioxide concentrations at other times. For example, the rapid development and expansion of circumarctic peatlands contributed to rising methane levels and a decline in carbon dioxide between 12,000 and 8000 years ago (MacDonald *et al.* 2006, Figure 4.7). These influences are overlain on other factors such as pre-industrial anthropogenic influences and vegetation dynamics and their discrete contributions may be difficult to isolate with any precision.

Peatlands reduce atmospheric warming by reflecting more incoming solar radiation than forested dryland regions. Peatlands are generally more open landscapes than adjacent upland regions. Surface vegetation of mosses, sedges, grasses, low growing shrubs and open water has a much higher albedo (ability to reflect radiation) than closed canopy forest. Treeless peatlands in northern regions and oceanic areas therefore reflect much more incoming solar radiation than surrounding forested areas. On forested peatlands, tree cover tends to be less dense than on mineral soils and there is a therefore a smaller but still significant difference in the albedo between peat and non-peat dominated areas in these regions. Furthermore, open ground in northern regions tends to have much higher albedo during the period of snow cover in winter, an effect particularly noticeable in late spring (Rouse 2000).

Peatlands exert a strong effect on local microclimates such that the temperature regime and relative humidity are significantly different to those in surrounding dryland areas. The high moisture levels in peatlands, the mass of peat with a high thermal inertia and the particular characteristics of the vegetation cover modify local climate regimes. In particular, they produce higher air humidity and lower temperatures in summer. Wind speeds are also typically higher than in surrounding areas. This results in conditions that allow disjunct distributions of species, with some taxa occurring on peatlands far beyond their normal range for surrounding areas (see Chapter 5).

4.6 Recent changes in climate and peatland responses

To document recent changes in both climate and peatland systems, direct observations and measurements can often be used rather than the geological record, although direct observations on peatlands are limited in timescale and scope. The main changes in climate are highlighted in the Summary for Policymakers of the IPCC Fourth Assessment Report (IPCC 2007). The key findings of most relevance to peatlands are summarised here.

Global temperatures have risen by approximately 0.74°C during the last 100 years (years AD 1906-2005). Temperature changes in the last 50 years are very likely explained by anthropogenic greenhouse gas emissions. It is likely that the 1990s and 2000s were the hottest decades for at least the last 600 years. It is not until the 17th century that reliable and regular meteorological measurements were made. Before this we are reliant on 'proxy' records of climate from the geological record, tree rings and indirect documentary sources. The last 150 years or so is the only period for which direct measurements of global surface temperatures are reliable. These show that temperatures have risen by approximately 0.74°C since the early 20th century, with the increases occurring mostly during the first half of the 20th century and since around 1970 (Trenberth *et al*. 2007). These changes can only be explained by invoking both natural climate forcings (solar and volcanic) and the effects of increasing greenhouse gas concentrations in the atmosphere (principally carbon dioxide, CO_2,

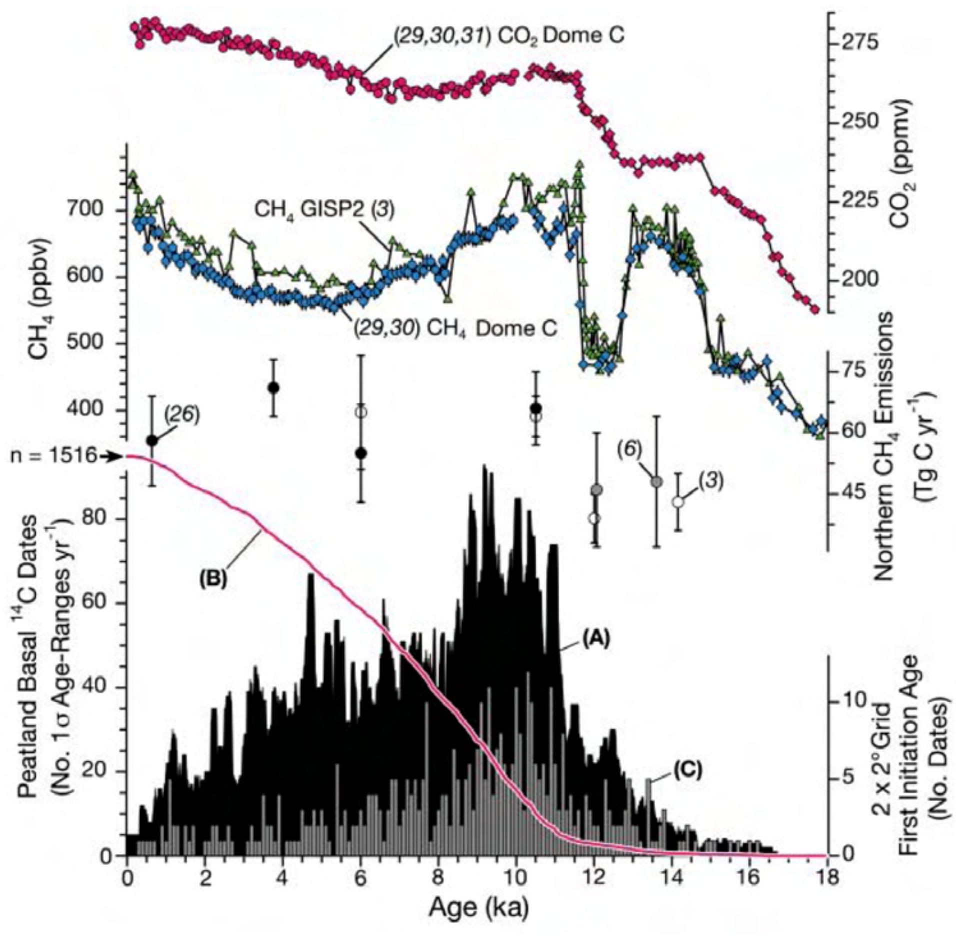


Figure 4.7: The spread of peatlands in the northern high latitudes as indicated by dates on basal peat (bottom), compared to estimates of northern hemisphere methane emissions based on the interpolar CH_4 gradient (lower graph), atmospheric methane concentration from the GISP2 (Greenland) and the Dome C (Antarctica) ice cores, and the atmospheric CO_2 concentration (Dome C ice core) (Source: McDonald et al. 2006).

and methane, CH_4) (Mitchell *et al.* 2001). Although results are still controversial to some extent, a number of studies have shown that it is likely that the 1990s were the warmest decade for at least the last 600 years and probably the last 1000 years (Mann *et al.* 1999, Moberg *et al.* 2005).

Global changes in precipitation over the last 100 years are harder to detect but there is strong evidence to suggest changes in total precipitation, seasonality and extremes in some regions where peatlands are found. Annual precipitation has generally increased over northern hemisphere mid to high latitudes at a rate of 0.5 to 1.0 % per decade during the 20th century. Conversely, precipitation has decreased by about 0.3 % per decade over many sub-tropical land areas (Folland *et al.* 2001). These changes are in accord with predictions for future climate change scenarios for the 21st century (Chapter 8). More recent evaluation shows that within these broad zonal changes, there is strong variability in trends (Trenberth *et al.* 2007). There are no reliable hemispheric or global scale data that reconstruct precipitation changes over longer periods of time. There are some indications that extreme precipitation events are more frequent even where total precipitation is unchanged and there has been an increase in the frequency of heavy precipitation in the mid and high latitudes of the northern hemisphere. Regional changes in precipitation are more complex and suggest changes in seasonality as well as total amounts of precipitation. It is these regional changes that are more important for peatlands than global averages. El Nino Southern Oscillation (ENSO) events have been more intense, persistent and frequent since the mid-1970s, increasing the inter-annual variability of precipitation to some areas (such as Southeast Asia) that have important concentrations of peatlands. There were generally only small increases in severe droughts or severe wetness and much of the variability in these phenomena was controlled by inter-decadal and multi-decadal climate variability rather than centennial scale trends. Seasonal changes in precipitation may be of particular importance in some regions. For example, in the United Kingdom, there has been a decrease in summer precipitation and a smaller increase in winter precipitation over the 20th century.

Global sea levels have risen at an average rate of 1.8 ± 0.5 mm p.a. over the period 1961 to 2003 Regional rates of sea-level rise are moderated by land surface movements which may increase or decrease these global averages. Observations of past sea levels from tide gauges and satellite data suggest that there has been a rise in sea level of 17 cm ± 5 cm during the 20th century Data from before 1900 are rather few but there is high confidence that there was an acceleration of sea-level rise from the 19th to the 20th century (Bindoff *et al.* 2007). Geological data support this conclusion (e.g. Gehrels *et al.* 2002). However, the impacts of any sea-level rise will depend on local factors such as land surface changes principally from isostatic change but also from local variability in ocean circulation, warming and expansion. These local differences are more difficult to predict with any accuracy, although the general directions and magnitude of isostatic change are well-known. For example, there is land uplift in northern Scandinavia and subsidence in southern England.

Recent observed changes show that peatlands have already responded to 20th century climate change. Direct observations of changes in peatlands indicate that recent climate changes may already be having an impact. However, in some cases it is difficult to attribute changes to climate alone because of alterations in atmospheric pollution (especially nitrogen deposition) and management (grazing, fire). The following examples indicate changes that may have already have occurred as a result of 20th century climate change.

The extent and duration of permafrost in northern peatlands has decreased. In northern peatlands a rise in late 20th century temperatures is linked to a reduction in the extent of permafrost. In northern Manitoba, a regional warming of 1.32^{o}C has caused accelerated permafrost thawing (Camill 2005). These patterns are repeated across much of Arctic Canada where the southern limit of permafrost in peatlands has moved north by 39km on average and as much as 200km north in some places (Beilman *et al.* 2001). However, there are indications that changes in permafrost are not exclusively linked to temperature rises. For example, rapid permafrost melting since the late 1950s in Quebec has caused an increase in thermokarst ponds as a result of increased snow precipitation and insulation of the surface rather than a rise in temperature, which did not occur until the late 1990s (Payette *et al.* 2004, Camill 2005). This was accompanied by an increase in peat accumulation rates as a result of renewed succession and terrestrialisation in the areas affected.

Changes observed over shorter timescales also indicate that these northern systems are sensitive even to small changes in climate. For example, in August 2005 the permafrost mounds of the northern fen Luovuoma (Finland) thawed due to abnormally wet weather in the two preceding years. Although there were late snowfalls up to May 2005, the snow cover quickly thawed. In addition, the ensuing July was abnormally warm (eight days in which the temperature was at least 25^{o}C, compared to two for the period 1971-2000). Small changes in precipitation, snow cover and temperature thus cause a step change in the system. Progressively milder winters may already threaten the prolonged existence of frozen palsa mounds because of the thicker snow cover caused by increased precipitation. Several other authors have shown the responsiveness of permafrost to climatic fluctuation. Permafrost has been found to be highly dynamic during short-term climatic fluctuations, for instance in Alaska (Osterkamp *et al.* 1994) and in north-western European Russia (Oberman and Mazhitova 2001).

Changes in plant communities have occurred during the last 50 years that may be related to recent climate change. Many natural peatlands appear timeless and unchanging, but recently it has been shown that even on pristine peatlands, there have been changes in plant communities over the last 50 years recorded by directly by plant ecologists. There are only a few places in the world where direct comparisons of plant inventories over long periods of time are possible. In Sweden, some species disappeared and others colonised one site where comparative data were available from 1954 and 1997 (Gunnarsson 2002). In northern Britain species changes have also been recorded since the 1950s (Chapman 1991). In many cases, it is impossible to separate the effects of successional processes from those 'external' factors such as atmospheric pollution, subtle changes in human management and climate change. However, recent work suggests that the impact of climate change on mid-latitude peatlands may already be one of surface drying and water-table decline (Smith *et al.* 2003, Hendon and Charman 2004).

Strong El Nino events have produced a larger number of severe fires in Southeast Asian peatlands. The smoke from burning forests and peatlands that has become a regular occurrence in Southeast Asia is a severe threat to peatlands in the region as well as to human health and economic growth. The fires are started for forest or scrub clearance and are made much worse by drainage and previous damage making them more susceptible to burning. However, meteorological conditions play an important part in determining the frequency and severity of fires. During ENSO events, Southeast Asia experiences much drier than usual conditions and moisture levels in peatlands are much lower than normal. Thus some of the most severe fires occur during ENSO years. For example in 1997/98, it is estimated that between 0.81-2.57 Gt of carbon was lost from burning peatlands in Indonesia – equivalent to 13-40% of global annual fossil fuel emissions (Page *et al.* 2002).

Changes in the phenology (timing of plant growth stages) such as spore and pollen production have occurred in many ecosystems. It is likely that similar changes have occurred in peatlands. Phenological changes have been recorded for many ecosystems around the world, as evidenced by large-scale compilations of long-term biological records (e.g. Menzel 2006). Phenological records on peatlands are not available over sufficiently long periods but short-term monitoring and experimental studies show that climate exerts a major control on peatland organisms. Monitoring over a 10 year period showed that sporophyte production in *Sphagnum* is positively related to the amount of precipitation the previous summer, suggesting the process is especially sensitive to summer droughts (Sundberg 2002). Experimental studies using artificially altered microclimate show that temperature is an important control on the timing of flowering in higher plants on peatlands (Aerts 2006).

Increasing aridity and associated drought frequency and intensity has led to degradation of peatlands in some steppe and

mountain regions. There is evidence of increased aridity in steppe and mountain regions of Central Asia and some other parts of the world. The last 10 years have been drier than average (especially 2000-2002) and this, combined with overgrazing, has led to the loss of extensive areas of peatland in Mongolia. During the extended droughts, the peatlands become much drier and the growth of dryland grasses is encouraged, changing vegetation to meadows and steppe ecotypes. These effects are particularly noticeable in the Orchon River and Ider valleys and the Darchat inter-montaine basin. Old maps, native populations and existing literature data described these areas as covered with vast mires, and as very wet and impassable during the early 20th century. During the 1950s, botanists described very wet rich fens with peat and tall sedges covering the Orchon River valley. In 2004 and 2005, this same area had only sparse vegetation cover with areas of exposed peat and fungal growth. Instead of being impassable, it is now easy to drive across the surface in an ordinary vehicle (Minayeva *et al.* 2004, 2005).

Drier peat surfaces have experienced erosion during storm rainfall. Increased aridity and consequent drying of peat surfaces makes peatlands more susceptible to erosion because the structure of the peat is weakened, especially where vegetation cover has been reduced or removed altogether. In Mongolia, erosion of dried sloping peatlands was observed in mountain regions during 2004-2005 (Minayeva *et al.* 2004, 2005). Similar situations may exist in other regions of the world, although it is sometimes difficult to dissociate the effect of climate variability from human impacts such as drainage, grazing and burning.

Coastal peatlands have undergone marine transgressions during periods of past sea-level rise and new peatlands have formed in areas where sea level has fallen. In Finland and Sweden new land surfaces are being exposed creating areas for new peatland formation and a succession of peatlands of differing ages at different elevations above current sea level (Merila *et al.* 2006). In subsiding coasts such as southern England, sea-level transgression has occurred at various times in the past and there is a current threat to coastal wetlands only held in check by coastal defences.

In many cases, human activity has exacerbated impacts associated with climate change phenomena. Disentangling the effects of climate change from those of human activity is not always possible, but it is clear that in many cases human actions have increased the vulnerability of peatlands to climate changes during the last 100 years. The impacts of climate change in many of the above examples are much worse where drainage, burning and over-grazing are also involved. In Indonesia, peat fires are always more severe in drained, logged peatlands than in pristine areas. Likewise, peatland damage in Mongolia from increased droughts is exacerbated by over-grazing. Erosion of peat from high intensity rainfall is more likely when vegetation has been reduced or removed by grazing and pollution (Warburton *et al.* 2004).

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5 Peatlands and Biodiversity

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Summary points

- Peatlands exhibit highly characteristic ecological traits and are unique, complex ecosystems. They are of global importance for biodiversity conservation at genetic, species and ecosystem levels.
- Peatlands play a special role in maintaining biodiversity at the genetic level due to habitat isolation and habitat heterogeneity, and at the ecosystem level due to their ability to self-regulate and adapt to different physical conditions.
- Although the species diversity of peatlands may be lower, the proportion of characteristic species in peatlands exceeds that of dryland areas within the same biogeographic zone.
- Peatlands support biodiversity far beyond their borders by regulating the hydrology and mesoclimate in adjacent areas and by providing temporary habitats for "dryland" species.
- Peatlands are often the last remaining natural areas in degraded landscapes. Thus, they mitigate landscape fragmentation and support adaptation by providing habitats for endangered species and those displaced by climate change.
- Peatlands are fragile ecosystems which can be impacted by both direct human activities and those in their catchments, leading to loss of biodiversity as well as associated ecosystem services.
- The unique attributes of peatlands demand special consideration of their biodiversity. They must be approached specifically and separately within all conservation strategies and land use plans.

Introduction

This chapter addresses the peculiarities of peatland biodiversity and the relationship between peatland biodiversity and climate change. The first section addresses basic concepts of biodiversity associated with peatlands, explains what is different in peatlands regarding biodiversity and what the consequence of that difference is for evaluating peatland biodiversity at various scales. It also explains the particular role of peatlands in maintaining biodiversity. The second section gives an overview of how key groups of organisms are represented in peatlands. The final section deals with human impacts on peatland biodiversity. The main conclusion of this chapter is that peatlands and peatland biodiversity need a specific conservation approach.

5.1 Peatland biodiversity: what makes peatlands different?

Different types of ecosystems require different conservation approaches. Lakes differ fundamentally from meadows; forest steppe ecosystems from taiga forests and so on. Peatlands share many attributes with lakes and are considered freshwater ecosystems, but also they share many features of terrestrial ecosystems. Peatlands differ from other ecosystem types in a number of properties. This section reviews how these affect biodiversity at the genetic, phenetic, species and ecosystem level.

5.1.1 Peatlands and the biodiversity concept

Biodiversity can be considered at each level of the organisation of life: from cells, organisms and populations to ecosystems. Peatlands play

a specific role in maintaining biodiversity at all these levels, but especially at those of the organism and ecosystem. The diversity of life can be considered at various organisational (structural and functional) levels: cell, organism, population and ecosystem (community and biome). Different sectors focus on different levels. Process ecologists and economists pay more attention to the diversity of ecosystem functions, whilst evolutionary biologists look in more detail at the diversity of organisms. International conservation programmes and biodiversity related conventions, such as the Convention on Biodiversity (CBD), the Ramsar Convention on Wetlands, and the Convention to Combat Desertification (UN CCD) focus on species, genetic variants, and their habitats.

Biodiversity is a widely used yet very broad concept. The term "biodiversity" represents an evolving idea. In the 20th century, the underlying concept was one of species diversity (see Whittaker 1972), whereas it has now broadened to describe the variety of all forms of life, at all levels from the gene to the species and through to ecosystem scale (for an overview see Gaston 1996, 2004).

Article 2 of the Convention on Biological Diversity gives the following definition:

"Biological diversity" means the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems.

The levels of organisation – cells, organisms, populations, ecosystems and biomes – correspond to the levels of biodiversity – within species, between species, and of ecosystems. Diversity amongst cells, organisms and populations reflects genetic biodiversity. Diversity within species, i.e. amongst individuals and populations of one species, presents both phenetic and genetic biodiversity. Diversity amongst populations, communities and biomes reflects the level of ecosystem biodiversity.

Different levels (species, phenetic, ecosystem) must be defined and utilised in the evaluation of biodiversity. Species diversity reflects relative species richness within certain areas or entities. Phenetic diversity relates to observable similarities (in shape, colour etc) rather than to phylogenetic (evolutionary) relationships. It is part of the intraspecific diversity: the diversity arising or occurring *within* a species (Figure 5.1). Ecosystem diversity reflects diversity that exceeds the level of the species and considers communities formed on different scales. Peatlands possess a high level of autonomy and integrity and consequently constitute outstanding examples of ecosystem biodiversity. Peatlands are complex but clearly organised ecosystems. Their high ecosystem diversity is related to their obvious hierarchical organisation over various scales.

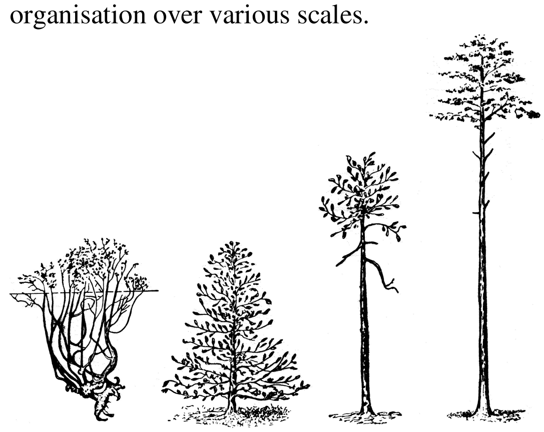


Figure 5.1: A classical example of phenetic diversity in peatlands are the ecological forms of Scots Pine (Pinus sylvestris L.). Trees belonging to the same species show very different growth forms depending on site conditions (Weber 1902, Sukachev 1905, Abolin 1914). Genetic studies have shown that plants taking the form of shrubs and tall trees are genetically identical. From left to right: forma pumila, forma willkommii, forma litwinowii, forma uliginosa (Tyuremnov 1949).

Peatlands have such specific features that standard methods of biodiversity evaluation must be applied with critical awareness. Modern theories of population biology and ecosystem ecology form a well developed theoretical framework for biodiversity evaluation and management, but may not be fully relevant to peatlands. For example, the classical concept of unidirectional energy flow, does not apply to peatlands. The energy from

Table 5.1: Forms of spatial diversity and their application to different organisation and hierarchical levels in peatlands.

Levels of life organisation:→ *Biodiversity hierarchical levels:* ↓	Cell	Organism	Population	Community	Biome
Genetic	α	αβγ	αβγ		
Phenetic	α	αβγ	αβγ	αβγ	
Species				αβγ	Αβγ
Ecosystem				αβγ	Αβγ

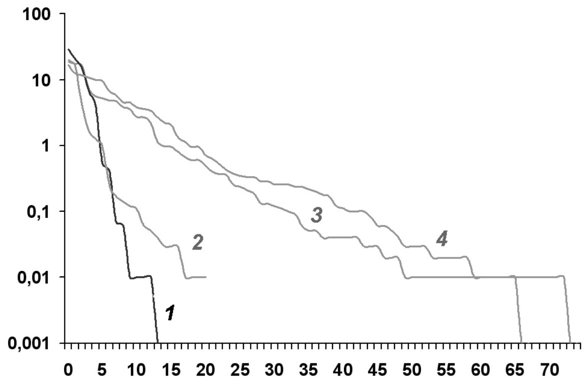


Figure 5.2: Dominance-diversity curves for forested peatland (1) and natural forest types on mineral soil along a gradient of humidity and fertility (2 – 4) in Central European Russia. The type 1 curve with a small number of mainly dominant species is considered to be typical for anthropogenically transformed or polluted communities (Odum 1983). (x-axis – the rank number, y-axis – the rank value based on phytosociological index).

primary production goes only partially to the consumers of higher trophic levels and a significant part is accumulated as peat. As a consequence, the carrying capacity of peatlands is significantly lower than that of other habitats. Therefore, when dealing with peatlands, the applicability of general concepts must always be verified.

Species diversity is the traditional level of biodiversity evaluation, yet is not fully appropriate for peatlands. Traditional methods of biodiversity evaluation are based on species diversity. These include methods such as diversity indexes (Pielou, Simpson, Shannon, etc.) or diversity-dominance analyses (Figure 5.2), yet are hardly applicable in peatlands. The low species richness and high species uniqueness demands other evaluation approaches.

The evaluation of ecosystem-level biodiversity requires consideration of different spatial scales. The ecosystem concept, as developed in classical ecosystem ecology (Hutchinson 1948, Van Dyne 1966, Margalef 1968, Watt 1968, H Odum 1971) is dimensionless. To evaluate ecosystem biodiversity, diversity at different spatial scales has to be considered, from the microtope to the whole biome. Small-scale ecosystem diversity is responsible for diversity of genes, organisms and populations. Because of their very high spatial heterogeneity and system complexity, the ecosystem level of biodiversity is particularly applicable for peatlands.

In peatlands, the concept of alpha, beta and gamma diversity not only concerns species, but also genetic, phenetic and ecosystem diversity. The concept of alpha (α), beta (β) and gamma (γ) diversity, as originally suggested by Whittaker (1975) for species (Figure 5.3), is also applicable to genetic, phenetic and ecosystem diversity (Table 5.1). For example, the elements of a peatland landscape – like hollows and hummocks (microtopes) – are the basic units for peatland diversity at the ecosystem level. In this case alpha diversity is the number of microtope types within an individual peatland, beta diversity is the difference in microtope types between different peatlands, and gamma diversity is the total number of microtope types in all peatlands of the region.

5.1.2 Peatlands as habitats with specific features

Peatland organisms must cope with many inimical conditions. This requires them to adapt their physiology, anatomy, morphology, life cycle and behaviour. The continuous accumulation of peat, the special temperature regime, the high water level and the consequent scarcity of oxygen in the root layer require mire plants to adapt their physiology, anatomy and growth forms. Many peatland plants have aerenchyma of loosely arranged cells with air-filled cavities that allow the exchange of gases between the shoot and the root and increase their buoyancy. Other adaptations to wetness include growth in tussocks, floating mats and rafts, as well as the development of shallow root systems and adventitious roots on stems (Rydin and Jeglum 2006). Paradoxically, vascular plant species growing in peatlands often display xeromorphy (morphological adaptation to dry conditions). This reduces water movement around the roots by restricting evapotranspiration losses and so increases the time available for the oxidation of toxins, and enables plants to root solely in the uppermost peat layers (Joosten and Clarke 2002).

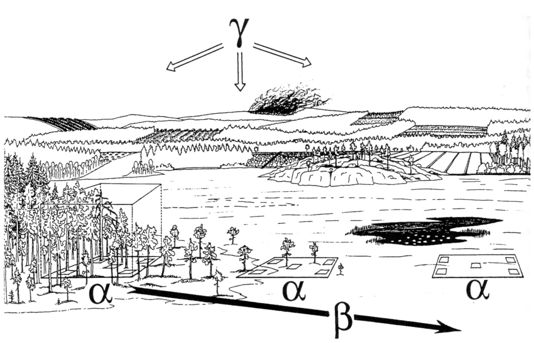


Figure 5.3: The Whittaker (1972) spatial concept of biodiversity (after Vasander et al. 1997). Alpha diversity: the diversity within a particular area or ecosystem, usually expressed by the number of species (species richness) in that ecosystem. Beta diversity: a comparison of diversity between ecosystems, usually measured as the amount of species difference between ecosystems. Gamma diversity: a measure of the overall diversity within a large region and usually measured as the number of species in all ecosystems.

Mire plants generally show adaptations to nutrient shortage, like cation exchange in *Sphagnum*, stunted growth in trees, and parasitism and carnivory. Symbiosis with fungi or bacteria can help to retrieve scarce nutrients (Schwintzer 1983, Saur 1998, Sapp 2004) or even increase effectiveness of photosynthesis (Raghoebarsing 2005). Also the fauna of mires is influenced by the scarcity of nutrients and ions, the acidity of the mire water, the relative coolness, and (in the case of non-forested mires) the strong temperature fluctuations (Joosten and Clarke 2002).

Organisms, forms and species in peatlands depend closely upon one another in terms of food supply, reproductive mechanisms (pollination) and shelter. These connections are often critical for survival, so that loss of one species will lead to the loss of other dependent species. The high demands peatland habitat places on organisms and the resulting low species diversity have led to the co-evolution of strong interactions and dependencies in peatland communities that may lead to the extinction of other species when one species is lost.

Many dependencies in peatlands are based on exclusive partnerships. The butterfly species *Colias palaeno* L., *Arichana melanaria* and *Polyommatus (Vaccininia) optilete* exclusively feed on the peatland dwarf shrubs *Vaccinium uliginosum* and *Oxycoccus palustris* (Otchagov *et al.* 2000). *Coenonympha tullia* is closely connected to *Eriophorum* species. Caterpillars of the latter species also feed on *Andromeda polifolia* and *Vaccinium vitis-idea* (Bink 1992), two more dwarf shrubs found in peatland. The number of species with a direct relationship to the pine tree (*Pinus sylvestris*) is over 800, including 300 fungal species. The peatland form of pine hosts only about 100 species; including 30 fungi, 25 epiphyte lichens, 7 epiphyte bryophytes and 38 phytophagous insects (Masing 1969). Regionally many of these species are strictly connected to this peatland form, like the beetle *Criptocephalus pini* (Maavara 1955) or the great grey shrike (*Lanius excubitor*), which nests in pine exclusively.

Low species diversity leads to competition, which results in adaptation. An example is the differentiation of flowering times and specialised plant-pollinator relationships in case of a shortage of pollinators (Reader 1975). Microtopography and peat soil conditions, particularly as brought about by *Sphagnum*, evoke dependencies in species (Masing 1969). Carnivorous plant species in peatlands have especially limited and unique relationships. *Drosera rotundifolia* has only two fungal consumers and only one insect consumer (*Trichoptilus paludum*), while *Drosera* itself has no preferences in its diet and consumes any protein-based body it can.

Peatlands are characterised by a high level of self-organisation and autonomy. Therefore peatlands constitute explicit examples of ecosystem biodiversity. Peatland ecosystems may develop sophisticated self-regulation mechanisms over time, attaining characteristics similar to those of organisms. As such, peatlands constitute ecosystem diversity that is largely independent from species or genetic diversity. Peatland ecosystems show autonomy at all hierarchical scales. Single hummocks in bogs or sedge fens can persist for thousands of years. Many mire massifs [1] display such coherence that damaging a small part affects the entire system. Single massifs that merge together into a mire complex are hydrologically dependent on this higher-level unit.

Peatlands are island ecosystems in the surrounding landscape. Peatlands are highly isolated in the landscape. Other than peatlands themselves, there are no other "stepping stones" for peatland plant and invertebrate species, as they can hardly use forests and meadows for migration. Peatlands, therefore have all the features of island communities with the associated intra-specific biodiversity and polymorphism.

Peatlands may host mineral islands that are isolated from one another and from adjacent mineral land. Peatlands may host internal mineral islands where ecosystems have developed in long-term isolation from the affinitive dryland ecosystems. Such islands may contain undisturbed ecosystems or remains of historical anthropogenic interference and natural ecosystem regeneration. Peatland islands provide an opportunity to record unique natural successions on abandoned cultural land. They play a significant role in maintaining phenetic and genetic diversity.

5.1.3 Specific features of peatland biodiversity on the species level

Due to very specific and harsh conditions and the necessary adaptations to these, peatlands host a limited number of highly characteristic species. Their species diversity is generally low compared with that of mineral soil ecosystems of the same biogeographic zone. Species diversity is not an appropriate criterion for evaluating peatland biodiversity. The ecological conditions of peatlands (see Chapter 2) are so specific, that they host relatively few species, but the species that occur are often characteristic. In peatlands, dominance-diversity curves (Whittaker 1967, 1970, Figure 5.2) that are usually used for more sophisticated analyses of species diversity show few, mainly dominant species, similar to communities under anthropogenic stress or high-altitude subalpine communities. The proportion of peatland-related species in a region varies with systematic group (mammals, birds, invertebrates, vascular plants, bryophytes, and so on), growth form (trees, herbs, shrubs etc), and trophic level (predators, herbivores and so on).

Within the largest mire system of Europe (Polisto-Lovat in Pskov region, Russia, 90,000 ha), a number of large and small islands host unique undisturbed broad-leaved forests which no longer exist in the surroundings (Maykov 2005). Some of the islands were inhabited by monks and peasants for hundreds of years until they were given up in the middle of the 20th century. High variance of a number of parameters was described for isolated populations of small mammal species in islands in the 3500 ha large raised bog Katin Mokh in Tver oblast (Russia) (Istomin and Vagin 1991).

In Karelia (Russian Federation) the 283 species of vascular plants found in peatlands constitute 17.4% of the total number of 1631 species. Of the 366 Karelian butterfly species, only 31 (8.5%) occur in peatlands, of the 470 bryophyte species 109 species (23.2%) and of 279 bird species, 85 (30.5%) are found in peatlands (Gromtsev *et al* 2003, Kuznetsov 2003).

Although their total species richness is low, peatlands host many characteristic species. For many species, peatlands are the only available habitat, within a biogeographic region and even globally. Many peatland species ('ice-age relicts') show disjunct, azonal distribution patterns and are not found in other habitats.

[1] mire (peatland) massif: the individual peatland within its boundaries

These highly adapted species can only survive if their habitat is conserved. Plant species that can only inhabit peatlands are called 'obligatory helophytes' (Bogdanovskaya-Guenef 1946), animal species 'tyrphobionts' (Peus 1932, Petersen 1954).

> Of the 109 vascular plant species described from the peatlands of the Yamal peninsula (Russian Federation), 40 species only occur in peatlands (Rebristaya 2000). Out of the 288 plant species in the mountain peatlands of West Sayan, 52 occur only in peatlands (Chernova 2006), while 33 out of 277 in the Kuznetsky Alatau (Volkova 2001) are obligatory helophytes.
>
> *Scheuchzeria palustris* is found all over the world and both in modern and palaeo-communities known only from peatlands (Tallis and Birks 1965). Under natural conditions in Eurasia, *Rhynchospora alba* is only known to be found in peatlands (Hulten 1958) while in the Americas it is not only found in peatlands but also in marshes (Small 1933).
>
> In the southern parts of their distribution, a large number of invertebrate species have been reported only from raised bogs (Maavara 1955). This can be explained by the larger temperature extremes, a higher frequency of groundfrost during the growing season, and a lower mean temperature compared to adjacent ecosystems.

Table 5.2: Key differences between typical K- and r-strategy species.

***r*-organisms**	***K*-organisms**
short-lived	long-lived
small size	large size
fast maturation	slow maturation
reproduction at an early age	reproduction at a late age
large number of offspring	small number of offspring
little care for offspring	much care for offspring
variable population size	stable population size

Peatlands host 'climax' communities, which are the products of long-term ecosystem development. The majority of peatland species are highly adapted to the environmental conditions that they have created during a long process of co-evolution (known as K-species). As a rule, K-species are easily threatened by changes in abiotic factors. Typical attributes of these species include high fitness and adaptation to a very narrow range of unfavourable environmental conditions (Table 5.2). Consequently, even small changes in species composition in peatlands may indicate large or long lasting changes in the environment (Gunnarsson et al. 2000, 2002)

From the other side, the prevalence of K-strategists with low adaptation capacity in peatlands implies a large loss of species in the case of dramatic habitat change. All over the world K-strategy species are the first candidates for extinction (Shvarts 2004). Disturbance of peatlands commonly leads to the establishment of extremely species-poor communities as the pool of r-strategy species that could replace the original species under harsh peatland conditions is very small.

Peatlands often support populations of "dryland" species, providing temporary food sources, shelter or breeding ground during parts of their life cycles. Peatlands can also provide permanent habitats for species that have lost their original habitats. Peatlands are generally "closed" communities, but may be colonized by species that have lost their original habitats. Birds of prey, for example, migrate to open peatlands only when the steppe has been totally converted to arable land. Species that invade peatlands have a high adaptive capacity. For example, invasive[2] plant species in peatlands exhibit adaptive mechanisms for the prevailing poverty in nutrients and chemically reducing soil conditions, including insectivory, nitrogen-fixation, and xeromorphy (Minayeva and Cherednichenko 2005).

Peatlands are important temporary habitats for numerous 'dryland' species, providing food, shelter and breeding grounds. This role is increasingly important in landscapes suffering from anthropogenic pressure. Many species living in bogs, including a number of abundant species, can also live outside bogs (Maavara 1955) or can be characterized as generalists (Danks and Rosenberg 1987, Runtz and Peck 1994, Schikora 2002a). These species are, however, integral parts of the bog community

[2] Invasive alien species are those introduced deliberately or unintentionally outside their natural habitats, where they have the ability to establish themselves, invade, out-compete natives and take over the new environments.

and food web (Reynolds 1990), and a number of them depend on the combination of peatland and surrounding biotopes to complete their life cycle (Verberk *et al.* 2006).

5.1.4 Specific features of peatland biodiversity on the population level

Intraspecific diversity, i.e. genetic and phenetic diversity within species, is very high in peatlands, reflecting their complexity and harsh living conditions. Intraspecific diversity is expressed by the variation in traits between organisms of the same species. Genetic diversity within a species may only emerge in the phenotype under different environmental conditions. It may be reflected in such features as variations in seed colour and form and is usually described as 'polymorphism'. Phenotypic variability can also be observed amongst genetically identical organisms. Differences in form and size of leaves, flowering period, duration of fruit ripening and seed germination, for example, do not necessarily indicate genetic differences. In peatlands, where species diversity is generally low, phenetic diversity allows a more effective use of the limited available resources.

> In Central European Russia, 8 species of fish, 8 species of reptiles and amphibians, 220 species of birds, and 17 species of mammals use peatlands as a temporary niche for feeding, hiding and breeding, while their main habitat lies in surrounding areas (Nikolayev 2007).
>
> Valk (1988) mentions insects coming to raised bogs from outside when plants, especially heather, are flowering. Some of these insects, like the fly *Tephritis* sp., stay longer in the bog in order to hibernate.

The surface patterning of many peatlands realizes a high spatial heterogeneity of habitats. Combined with harsh conditions and associated low species diversity, this leads to different niches not being occupied by different species, but by different pheno- and genotypic forms of the same species.

Intraspecific diversity between populations in peatlands often reflects biogeographic differences and develops due to geographical isolation and the island character of habitats. Populations of the same species in different climatic zones exhibit different features. For example, the most widespread peatland species *Sphagnum magellanicum* forms peat both in Tierra del Fuego (southernmost South America) and in Yakutia (northeast Asia), but has different ecological preferences in these different parts of the world. Few studies have been undertaken on the genetic diversity of populations of peatland species.

Genetic and phenetic diversity is also expressed as transspecific diversity. Where environmental conditions are critical, different species may develop similar morphological traits. Transspecific diversity is a typical adaptive mechanism in peatlands. Transspecific diversity is the expression of similar morphological or functional traits by different species (Gregorius *et al.* 2003). Transspecific diversity is typical for peatlands. In extremely wet peat swamp forests, for example, different tree species in the temperate zone, like black alder (*Alnus glutinosa*) and spruce (*Picea abies*) form aerial roots. In raised bogs specific metabolic adaptations compensate for the lack of nitrogen. Insectivore plant genera such as *Drosera*, *Utricularia* and *Sarracenia* use their modified leaves or stems to absorb nitrogen from digested prey. A number of bog species (mostly algae, lichens and mosses) form symbioses with nitrogen-fixating bacteria. Vascular plants like *Alnus glutinosa* in the temperate zone and *Pterocarpus officinalis* in the tropics host N-fixating bacteria in nodules on their roots.

5.1.5 Specific features of peatland biodiversity on the ecosystem level

To define the individual peatland within its boundaries as one entity, the term "mire massif" is used. The shape, size and type of a mire massif are determined by climate, geomorphology, and the origin of the water. Peatland ecosystem diversity depends strongly on environmental factors such as climate, geomorphology and the origin of the water. The "mire massif" is considered an elementary unit in the evaluation of peatland diversity at the *mesotope* level. Different peatland types are distinguished at this level. Polygon and palsa mires only develop under the influence of permafrost and disappear when the permafrost melts. Condensation mires form under very specific climatic conditions on screes and boulders (Schaeftlein 1962, Steiner 2005). Blanket bogs are found exclusively in oceanic or highland areas. The hydrological templates that landscape and climate provide to support peatland formation lie at the root of the hydrogenetic peatland classification (Succow and Joosten 2001).

Peatland massifs are not homogenous, but contain several microtope formations. The best known are the hummock-hollow complexes of raised bogs, ribbed fens and polygon mires. Many peatlands develop surface patterns with regularly ordered vegetation types. A typical continental raised bog consists of a flat and wet central plateau (often with open water bodies), a steep and dry rand (margin slope) and on the gentle slope in between, a ridge-hollow or ridge-pool complex of orderly arranged elongated wet and dry surface elements. A homogeneous area within a peatland massif is called a microtope. Simulation and modelling (Couwenberg and Joosten 2005) has shown that microtopes are a result of natural self-organisation processes including plant intraspecific competition (Kenkel 1988) and more general long-range interactions (Eppinga 2007). That peatland (ecosystem) types are not mere classification constructs, but real, discrete entities, separated by distinct borders.

Individual mires, often of different types, can combine to form mire complexes. Hierarchically, the mire complex is above the level of the individual mire. Individual mires, often of different types, can combine and become a dominant landscape element that expands into the mineral surroundings. The Vasyugan mire complex in West Siberia stretches over 5 million ha and is the largest uninterrupted peat landscape in the world. The Polisto-Lovat Mire System in the Pskov and Novgorod Regions of Russia, the Red Lake Peatlands in Minnesota, USA, the peatlands of the Canadian Hudson Bay Lowlands, the peatswamp forest systems of central Kalimantan on the island of Borneo (Indonesia) and the peatlands of the Peninsula Mitre in Tierra del Fuego, Argentina are other examples of large mire complexes.

Mire zones and regions are at the highest level of the scale hierarchy. At the largest scale, mire zones and regions are defined on the basis of the dominating typical mire type, for example, the raised bog zone or the palsa mire zone. Some mire types are not restricted to one zone and are intrazonal. For example, the flood peat swamp forests of black alder (*Alnus glutinosa*) in the Russian plain may be found from the taiga to the steppe zone and the species composition and stand structure of these forests are similar in different biogeographic zones. The number of mire types in one zone or region reflects gamma diversity.

Peatland ecosystem diversity is displayed at a range of scales and reflected in the hierarchical classifications of peatland ecosystems. Various hierarchical classification systems have been developed (e.g. Galkina 1946, Sjörs 1948, Masing 1972, 1998, Ivanov 1981, Löfroth and Moen 1994, Yurkovskaya 1995, Lindsay 1995, IMCG 1997). The object of all of these is the landscape unit, although in different classifications it is defined with different emphases – e.g. hydrological features, vegetation, or geomorphology. Figure 5.4 presents a generalisation of the classification systems mentioned.

Each spatial hierarchical scale levels has a specific input to ecosystem biodiversity in a global, regional and local context. The mire massif (mesotope) is characterised by a specific richness in species. Also the microtope is associated with a typical species composition (Loopman 1988) or with different forms of the same species, as illustrated by the peatlands of Tierra del Fuego (Patagonia) (Köpke 2005, Baumann 2006). Within each of the hierarchical levels the number of species or phenotypes reflects alpha diversity.

Within the mire massif, one can distinguish various numbers of microtope types. Many sedge fens are homogeneous with only one major microtope type. A raised bog on the other hand may comprise several types of microtope built of different elements (hummocks, pools, ridges etc). The number of microtope types within a peatland massif also reflects alpha diversity.

Differences between mire massifs in species composition, number of ecological forms, but certainly also microrelief elements, reflect beta diversity. The diversity in mire and mire complex types within a region, in microtope elements in a typical mire massif, as well as in nanotopes within these microtopes, all reflect gamma diversity. This way each spatial hierarchical level has its specific input in

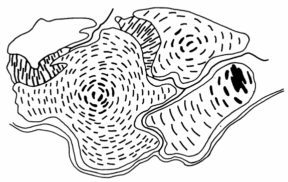
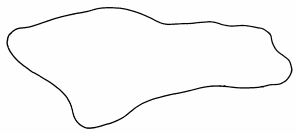
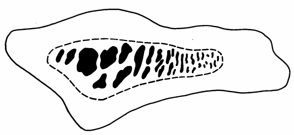
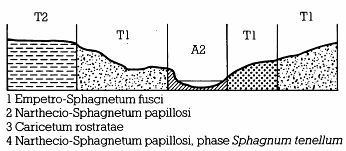
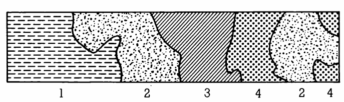
The landscape		Description	Scale (m^2)
	Macrotope	The mire complex (or system; several merged mire massifs)	10^5-10^9
	Mesotope	The mire massif (separate raised bog, fen, etc.)	10^2-10^7
	Microtope	Homogeneous element of landscape heterogeneity within the mire massif (Hummock-hollow complex; ryam, margin; sedge mat; sphagnum mat)	10^2-10^6
	Microform (nanotope)	Hummock, hollow, pool, hillock	10^{-1}-10^1
	Vegetation mosaic	Microcoenosis, tussock etc	10^{-2}-10^{-1}

Figure 5.4: The elements of hierarchical mire classification (After Lindsay et al. 1988).

ecosystem biodiversity at the global, regional and local level.

Some peatland classifications describe peatland massif diversity on a local, regional and global scale. They reflect the dependence of peatland massif types on initial environmental factors, including climate, geomorphology and hydrology, and are based on one or several key attributes. Different types of peatland massifs develop in different climatic, biogeographic and topographic settings depending on key ecological factors including vegetation, geomorphology, genesis, hydrology and biogeography. Generally, it is possible to predict which type of peatland will develop at a particular site. In the forest-steppe zone, for example, infilling of a shallow lake will result in an open sedge fen without clear surface patterning. In the Arctic the same infilling results in a polygon peatland. Some classifications use different attributes for different syntaxonomical ranks. For example, mire massifs can be classified into large groups on the basis of their dominant life form and trophic status (sedge fens, forested swamps, dwarf shrub oligotrophic mires) and subdivided on the basis of geomorphology (valley sedge fens, floating mat sedge fens etc). Further information on peatland ecosystem diversity is given in Kivinen *et al.* (1979), Whigham *et al.* (1993), Succow and Joosten (2001), Steiner (2005), Rydin and Jeglum (2006), and Wieder and Vitt (2006).

Ecosystem biodiversity is particularly apparent in the wide range of peatland types and in their diverse and often spectacular surface patterns. The relevance of intact peatlands for biodiversity thus extends beyond the mere provision of habitat for species and genetic variants. The 7th Conference of Parties of the Convention on Biological Diversity (CBD, Kuala Lumpur, 2004) recognized that the CBD insufficiently addresses the ecosystem-level of wetland biodiversity (CBD VII/4 – 21). As such, a review of the Ramsar classification system was requested, in order to develop a definitive classification system prior to 2010 (CBD VII/4 – 28).

The classification of peatland ecosystems for biodiversity evaluation is scale dependent. The

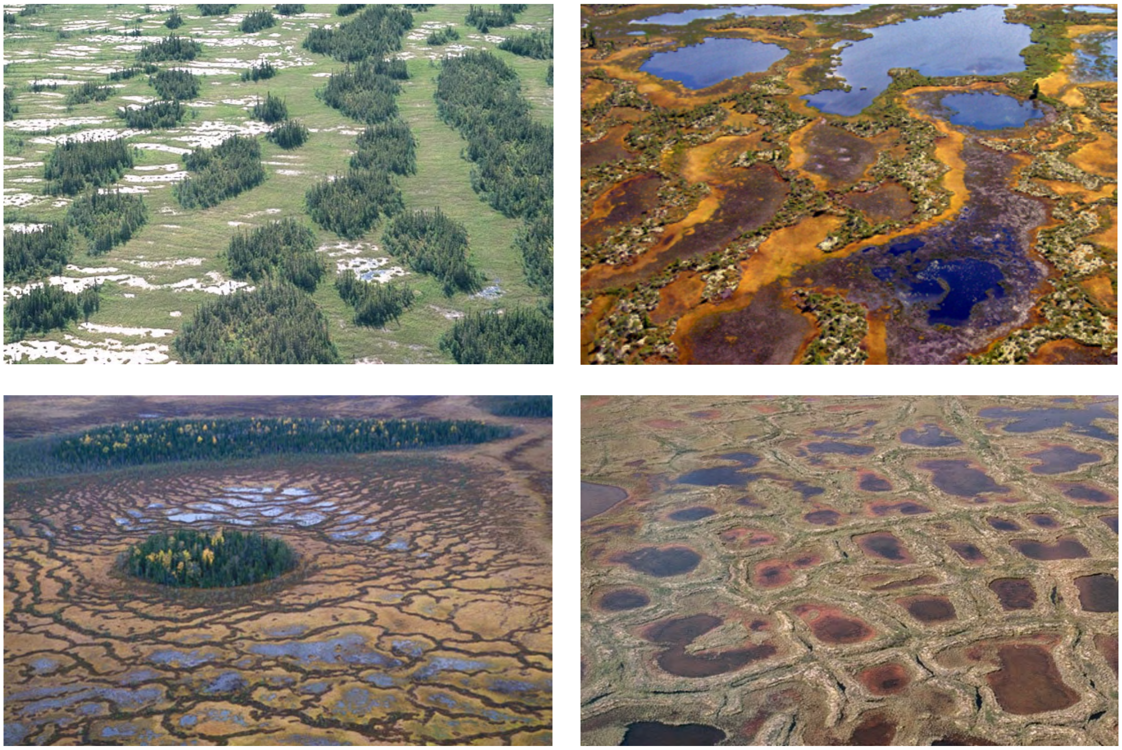


Figure 5.5: Spatial heterogeneity and ecosystem biodiversity are typical characteristics of peatlands.

spatial (and functional) scale of classification should fit the intended purpose. Therefore there are different classification schemes for biodiversity protection, economic use and the hydrological management of peatlands. For global evaluation, zonation is often an adequate parameter. To evaluate the status of populations of individual species and to define the diversity of habitats, we need classifications at the microtope level. For peatland management and conservation purposes, classification at the mire massif level is necessary if problems are to be avoided.

Peatlands are often not recognised and overlooked within different special classifications. Some specific classification systems overlook peatlands. Peatlands need different management than non-peatlands, even if they look surfacially the same. Many conservation-based classifications do not recognise this, however. The Ramsar wetland classification includes two categories that directly refer to peatlands (U – unforested and Xp – forested peatlands). At the same time peatlands are hidden in 20 different other Ramsar wetland types, where they are lumped together with non-peatland wetlands. Similarly, peatlands are classified directly and separately in three categories and 12 types of the EU Natura 2000[3] habitat typology and hidden in four more categories, especially within highland and tundra habitats. The sectorial ecosystem inventories (forestry, agriculture, water management, geological surveys) often do not recognise peatlands as specific ecosystem type (Peatlands of Russia 2001).

Peatlands are often not recognized and overlooked within regions where they are not widespread. Peatlands are particularly overlooked as distinct ecosystems in those regions where they are not dominant. In mountainous areas, valleys are often covered by peatlands, but are seen and managed as grasslands. The same applies to Arctic regions where peatlands are treated like tundra on mineral soil. Little attention is paid to the

[3] Natura 2000 is a network of protected areas aiming to incorporate all of the habitat diversity in Europe established by the so-called European Habitats Directive (Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora). Protected habitats are listed in Annex I of the Directive, see http://ec.europa.eu/environment/nature/nature_conservation/eu_nature_legislation/habitats_directive/index_en.htm

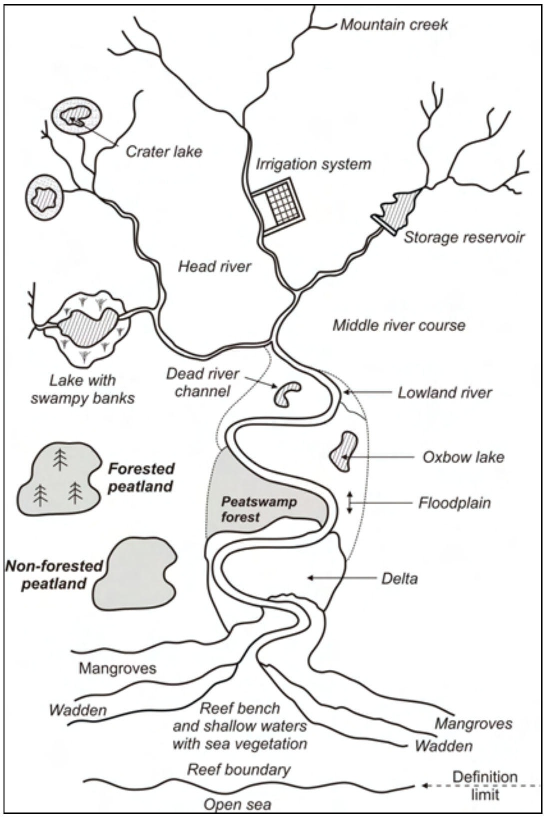


Figure 5.6: Wetland types: Only two Ramsar wetland categories acknowledge peatlands: U – Non-forested peatlands; includes shrub or open bogs, swamps, fens and Xp – Forested peatlands; peatswamp forests. At least five more Ramsar categories may include peatlands: L – Permanent inland deltas, Ts – Seasonal /intermittent freshwater marshes/ pools on inorganic soils; includes sloughs, potholes, seasonally flooded meadows, sedge marshes; Va – Alpine wetlands; includes alpine meadows, temporary waters from snowmelt; Vt – Tundra wetlands; includes tundra pools, temporary waters from snowmelt; W – Shrub-dominated wetlands; shrub swamps, shrub-dominated freshwater marshes, shrub carr, alder thicket on inorganic soils.

vulnerable balance between peat, water and plant cover. The most dramatic examples of disregard are the high altitude peatlands in Central and East Asia. In Mongolia (Minayeva *et al.* 2005), China and Kyrgyzstan, highland sedge fens are not recognized as peatlands by land users and decision makers, or by scientists. Peatlands are used mainly as pastures and are managed without regard for their special hydrological requirements. Within decades these peatlands can degrade to dry deserts.

5.1.6 The specific role of peatlands in biodiversity maintenance

As peatlands are strongly dependent on their surroundings, the conservation of peatlands requires safeguarding a wide range of environmental conditions across large areas. The structure, function and taxonomic composition of peatland ecosystems depend directly on water level and quality, temperature, humidity, relief and other abiotic factors.

Therefore, securing peatlands and their ecosystem functions, including their ability to support biodiversity, demands the maintenance of a wide range of environmental conditions, including climate, across large areas.

Peatlands have a significant impact on biodiversity far beyond their borders by regulating the hydrology and microclimate of adjacent areas. Peatlands play an important role in landscape hydrology. They act as sponges in the landscape, storing water and maintaining water levels in adjacent areas. Like large water bodies, they mitigate droughts and hard frosts, providing cool air in summer and warm air in winter. This is important in regulating regional and local climate for adjacent ecosystems too.

Peat provides thermoisolation and helps to protect permafrost and the underlying soil and bedrock. The presence of peatlands in the Arctic is critical for the maintenance of the current climatic conditions and related biodiversity.

Peatlands in mountains act as water towers, supplying river headwaters with permanent water flow. Mountain peatlands are found at the headwaters of important rivers such as the Yellow and the Yangtze Rivers (Ruoergai peatlands in China), the Yenissey (peatlands of the Darkhat and Ubsunuur basin in Mongolia), the Volga river (peatlands of the Valday hills). River basins support significant biodiversity at all levels, and through them, peatlands have indirect impacts over large distances.

> The Air Hitam Laut River catchment in Sumatra is entirely covered by peatlands. The river runs through Berbak National Park and maintains water levels in peatlands in this protected area. Conversion in the catchment area of peat swamp forest to oil palm plantations is leading to subsidence and the loss of peat. Soon the upper course of the river will no longer flow through the National Park, but will link up with an entirely different river system, posing a direct threat to biodiversity protected in the park (Wösten *et al*. 2005).

Peatlands have a certain flow regulating effect. Although sometimes overestimated, the flow regulating effect of degraded peatlands is much worse than that of living peatlands. This is a good reason to protect the latter, particularly if they feed the headwaters of a river system. The discharge charts (hydrographs) of a drained and of a supposedly pristine bog in Northwest Germany, presented by Uhden (1967), differed in the sense that the discharge peaks from the drained peatland were considerably higher and shorter than those from the "pristine" part (Van der Schaaf 1999) An analysis of the discharge from an Irish raised bog showed that even a single dry summer had an adverse impact on the reservoir characteristics in the next year (Van der Schaaf 2005). This implies that the regulation characteristics of a degraded peatland are far worse than those of an intact one. Similarly, coastal peatlands play a particularly important buffer role, protecting land ecosystems against destruction by floods.

Peatlands mitigate habitat fragmentation or its consequences. For a number of species peatlands provide temporary shelter, food and breeding places, stepping stones for migration or even permanent refugia. Their inaccessibility and peacefulness have made many peatlands the last refuges of species that are not necessarily bound to peatlands, but that have been expelled from intensively-used surroundings. In this manner, the peat swamp forests of Borneo and Sumatra are among the last refuges for orangutan (*Pongo pygmaeus* and *P. abelii*), the Sumatran tiger (*Panthera tigris sumatrae*) and the Malayan tapir (*Tapirus indicus*), in the midst of intensively logged forests on mineral soils.

Similar phenomena are known from Europe and North America. Peatlands are used as temporary habitats by some species, particularly during droughts and frosts. In this way peatlands can mitigate the loss of those species' original habitats.

> The effect of peatlands on forest air temperature and relative humidity extends over a distance of 120 m (Concannon 1995), and snowmelt runoff from damaged peatlands was reduced to 25% by restoration (Shantz and Price 2006). Micrometeorological measurements by Petrone *et al.* (2004) revealed that a restored site lost 13% (2000) and 8% (2001) less water through evapotranspiration than a harvested one.

Peatlands can act as so-called stepping-stones in anthropogenic landscapes, providing migration corridors, thereby supporting gene flow among populations and helping to maintain species diversity. Most peatlands offer unfavourable habitats for amphibians, for example, because they dislike peatland water quality. However, peatlands provide ideal shelter for them during dry summer months. With increasing distance to peatlands, fewer amphibians can reach shelter and species diversity decreases (Figure 5.7).

Peatlands provide adaptation services by securing habitats for azonal, intrazonal, relict and endangered species. With their specific environmental conditions and (with some exceptions) their resilience to climate change, peatlands host numerous azonal and intrazonal species. These include many relic species that have found stable habitat conditions in a changing climate. The phenomenon becomes especially evident when changes such as anthropogenic transformation of landscapes, climate change and related changes in the environment occur.

Peatlands, biodiversity and climate change are linked through very strong mutual feedback relationships. Peatlands are able to immobilise large amounts of carbon and water and rapidly release them under certain conditions. Peatland biodiversity not only depends strongly on climate, it also strongly influences climate. By means of their peat-forming plants, peatlands are able to immobilise large amounts of carbon and water, but they can also release these rapidly under certain conditions (see Chapter 6). Peat-forming plants can grow and form peat in the high Arctic, where peatlands provide insulation for permafrost which in turn maintains the moist and cool air responsible for climatic features of the Arctic region.

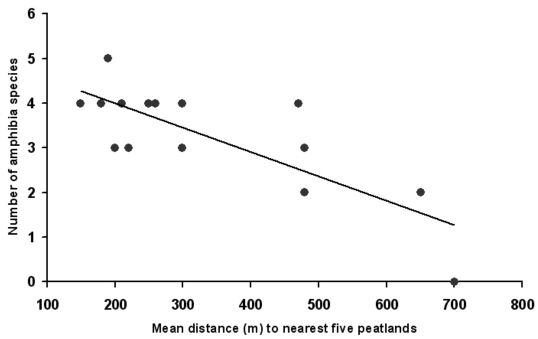


Figure 5.7: With increasing distance to peatlands, fewer amphibians can reach shelter and species diversity decreases. Accessibility to peatland can thus be a controlling factor. The study covered amphibians of Minnesota (USA) (after Lehtinen et al. 1999).

> Peatlands in the southeastern part of the West Siberian Lowland host a number of so-called relic species (Lapshina 2003). Raised bogs host species that were dominant during glacial periods and moderately cold periods of the Pleistocene (*Salix lapponum*, *S. philicifolia*, *Carex vaginata*, *C. media* etc.), whereas fens support relict thermophilic species (*Poa remota*, *Dryopteris cristata*, *Ranunculus lingua*, *Calamagrostis canescens*).

Peatlands are a unique source of information on past biodiversity for both peatlands themselves and for the surrounding areas. Peat deposits preserve the remains of plants and animals living in the peatland, together with pollen and spores of plants from the wider surroundings. These and many other materials and substances preserved in peat provide an archive of biodiversity information from previous epochs. Peat accumulates slowly but steadily, adding layer upon layer. Peat deposits preserve not only the plant and animal remains from the peatland itself, but also pollen and spores of plants from the wider surroundings as well as many other materials and substances (Chapter 4). In this way, peatlands act as an important source of long-term information on ecological, atmospheric and climatic, anthropogenic and other developments. This record of past diversity should be appreciated as an additional value of peatlands.

5.2 The taxonomic biodiversity of peatlands

Peatlands play a very specific role in maintaining the biodiversity of different groups of organisms. Here we highlight some notable facts about taxonomic groups of organisms ranging from microorganisms to the mammals that inhabit peatlands.

5.2.1 Microorganisms and lichens

The biodiversity of microorganisms in peatlands (bacteria, protista, fungi) may be high but has not yet been thoroughly studied. Biodiversity is closely interrelated with the ecological functions of microorganisms that play an important role in peatland biogeochemistry. In spite of their important role in nutrient cycling, peat accumulation and decomposition, and carbon release, peatland fungi, bacteria and protista have not been studied as intensively as other species groups. Cyanobacteria (blue-green algae) and (often unicellular) algae act as autotrophic primary producers in surface water, in wet peat and even inside *Sphagnum* moss cells, as well as on bare (unvegetated) peat surfaces. Some microorganisms synthesise organic materials from inorganic materials not by photosynthesis but by chemosynthesis. Jones (1992) reports food webs based on algal photosynthesis in shallow water in nutrient-rich fens, and food webs based on bacteria feeding on dissolved organic matter in bog pools. Bacteria feeding on inorganic and organic substances (e.g. methane) are more important at the start of the bog pool food web than *Sphagnum* and vascular plants (Van Duinen *et al.* 2006b). Heterotrophic bacteria and fungi decompose cellulose under aerobic and anaerobic conditions using oxygen, nitrate, ferric iron, sulphate or carbon dioxide as electron receptors and producing carbon dioxide, nitrous oxide, molecular nitrogen, ferrous iron, hydrogen sulphide or methane. The balance between the sequestration of carbon dioxide and the release of other greenhouse gases ultimately depends on the micro-organisms and their diversity.

Bacteria are found in all peat strata and their diversity is enhanced by the variety in peatland

Table 5.3: Number of bryophyte species found in peatlands compared with the regional total number of bryophyte species. The symbol '–' signifies no available data.

Country/ region	Moss species			Liverwort species			Source of information
	Peatlands	Region	%	Peatlands	Region	%	
Poland	54	675	8.0	–	250		Jasnowski 1972 / www.plant-talk.org
Estonia	118	525	22.5	35	96	36.5	Kask 1982 / Ingerpuu and Vellak 1998
Lithuania	70	335	20.9	–	–		Strazdaite and Lepinaitite 1986 / Lekavitchus 1986
Ukraine	–	–		50	–		Balashov *et al*. 1982
Russia:							
Murmansk	–	–		93	169	55.0	Konstantinova 1999 / Schljakov and Konstantinova 1982
Karelia	132	442	29.9	30	–		Kuznetsov 2003
Chernozemie	98	–		13	–		Khmeljov 1985
Komi	68	210	32.4	–	–		Shubina and Zheleznova, 2002
West Siberia	181	264	68.6	61	87	70.1	Lapshina 2003
Chukotka	–	–		74	180	41.1	Afonina and Duda 1993

habitats. However, current knowledge on bacterial diversity remains poor. The largest concentrations of bacteria are found near the surface of peatlands, where nitrifying and aerobic bacteria dominate. At greater depths, anaerobic species take over. The taxonomic diversity of bacteria is closely connected with their functional characteristics, which are highly significant for maintenance of peatland ecosystems. Reviews on peatland bacteria can be found in Williams and Crawford (1983) and Wheatly *et al*. (1996).

Protozoa are represented in peatlands by flagellates, amoeboids and ciliates. The best studied group are the Testacea Rhizopoda, which have an important indicator value in palaeoecology. Protozoa are heterotrophic predators of microorganisms and play a significant role in the food web as transmitters of energy. Little is known about their taxonomic diversity with exception of the Testacea Rhizopoda, a group of amoeboids of which the shells are well conserved in peat. As such, they act as excellent indicators of water level and quality. Other protozoa can only be recognised during certain phases of their life cycle, making identification difficult.

Peatlands hold a wide variety of fungi and fungi-like protista. Their diversity is strongly bound to the diversity of substrates. The number of specialized forms and species of fungi is much larger than in other species groups. Fungal species are highly specialised and strongly bound to substrate or partner species. They include saprophytes of trees, herbs, and mosses and their litter, coprotrophs, mycorrhyza forming species, and parasites (Tschastukhin and Nikolayevskaya 1969, Botch and Masing 1979). They show a high seasonal diversity (Salo 1993). Fungi play an important role in peat formation by decomposing litter that is very resistant to other drivers of decomposition (Neofitova 1953).

The diversity of algae and algae-like protista in peatlands has insufficiently been studied but may be rather high. Peatlands contribute significantly to rapid micro-evolution in algae which display a high level of polymorphism in peatlands. Algal diversity is difficult to estimate because few groups have been appropriately studied and new species are regularly discovered. The best-studied groups are Diatomeae, Euglenophyta and Chlorophyta. Amongst the latter, the Desmidiales constitute by far the best studied and hence the most diverse class, with *Cosmarium* as most diverse genus. Rhodophyta are rare in peatlands. Studies report 15 to 300 species of algae in peatlands (Rydin and Jeglum 2006). Peatlands

Table 5.4: Number of peatland typical vascular plant species in relation to the total vascular flora in different regions. The symbol '–' signifies no available data.

Region	Flora			Peatlands	Source
	Total	Peatlands			
	number		%		
Ukraine	4529	300	6.6	0.9	Balashov et al. 1982 / Flora Ukrainskoj RCR. Vol. 1–12. 1936–1965
Poland	2468	309	12.5	0.6	Jasnowski 1972, Mirek 1995
Finland	1240	287	23.1	25.2	Eurola et al. 1984 / Hämet-Ahti et al. 1998
Estonia	1498	376	25.1	6.6	Kask 1982/Eesti NSV floora 1953–1984. Index 1998.
Lithuania	1347	183	13.6	5.3	Strazdaite and Lepinaitite 1986/ Lekavitchus 1986
Belarus	1650	267	16.2	7.9	Bambalov et al. 2005/ Shishkin et al. 1967
Mongolia	2250	404	18.0	1.7	Minaeva et al. 2005 / Gubanov 1996
Russia:					
Karelia	1631	283	17.4	37	Kuznetsov 1989 / Kravchenko et al. 2000
Northwest Russia	1516	357	23.5	28	Botch and Smagin 1993 / Minyayev et al. 1981
Kamchatka	1166	280	24.0	23	Neshatayeva 2006 / Neshatayeva and Neshatayev 2004
Murmansk	1052	252	24.0	18	Ramenskaya 1983
Nerusso-Desnyanskoye Polessie	1243	303	24.4	16	Fedotov 1999 / Kharitontsev 1986
Southeast of West Siberia	1050	344	32.8	35	Lapshina 2003
Kuznetsky Alatau	594	144	24.2	–	Volkova 2001 / Buko 2003
Yamal Peninsula	405	109	26.9	–	Rebristaya 2000 / Rebristaya 1999
Central Chernozyom region	1683	414	24.6	5.8	Khmeljov 1985 / Kamyshev 1978

promote rapid micro-evolutionary processes in algae and many characteristic peatland algae display high levels of polymorphism. Advances in taxonomy have resulted in the identification of new disjunct and endemic species in peatlands (Kukk 1979). Recently,

Ankistrodesmopsis silvae-gabretae (Lederer and Lukavský 1998), a genus and species new to science, was discovered in the mires of the Bohemian Forest (Stanova 2003). Algae are often used as indicators of peatland water characteristics; diatomeae assemblages are especially informative in palaeoecological studies.

The diversity of lichens in peatlands is usually low compared to other ecosystems. The role of peatlands in maintaining lichen biodiversity is unclear. The number of lichen species that occur in peatlands is low (2–10%) compared to the regional non-peatland lichen flora.

Specialized peatland species or adaptations are unknown. Yet, in boreal and temperate regions, peatlands play an important role as refugia for Arctic species (Tolpysheva 1999). There are around 180 lichen species in the peatlands of the former Soviet Union (Trass 1979). Systematic information on lichens in tropical peatswamp forests is lacking. Additional data are needed to draw definite conclusions on the role of peatlands in maintaining lichen species diversity.

5.2.2 Bryophytes and vascular plants

Peatlands provide favourable conditions for mosses and liverworts and contribute considerably to bryophyte species diversity, especially in the regions where peatlands are

common. Due to their wetness and the often low cover of vascular plants, peatlands provide favourable habitats for mosses and liverworts. Consequently, the diversity of these groups tends to be very high. *Sphagnum* mosses are the most important peat-forming plants in ombrotrophic peatlands (bogs), and a small selection of these *Sphagnum* species create the special hydraulic conditions to raise the bog water table above that of the surroundings (Joosten 1993). In regions rich in peatlands, up to 70% of the bryophyte species occur in peatlands (Table 5.3).

The contribution of peatlands to the maintenance of vascular plant species richness varies widely with geographical location. The driving factors are peatland area and degree of "naturalness". The relative species richness of vascular plants depends on biogeographical factors and climate. Glaser (1992) found no significant correlation between vascular plant species richness and length of the vegetative season (base temperature = 5°C.), mean annual snow depth or spatial dimensions of bogs across climatic gradients in eastern North America.

A threshold of 1000 mm of annual precipitation and 1000 freezing degree-days appeared to separate the floristically-rich maritime bogs from impoverished bogs of northern and continental regions.

In regions where few intact peatlands are left (Ukraine, Poland, Lithuania), the fraction of species preferring peatlands is low (5–15%), as peatlands affected by human impact support many non-specific species. In regions with many intact peatlands (West Siberia, Murmansk, Kamchatka, Karelia, Northwest Russia, Finland) typical peatland species make up 20–30% of the total flora (Table 5.3). In alpine, Arctic (Yamal Peninsula) and subarctic (Komi) regions, the total number of species is small and the acreage of peatlands is large. Here, typical peatland species comprise 20–30% of the total flora and peatlands significantly support vascular plant diversity (Figure 5.8).

In Mongolia and the Central Czernozem area of the Russian Federation, a small area of peatland supports many typical vascular plant species due to the high diversity of peatland types present. In the dry regions of Mongolia, peatlands also provide water for many species from other habitat types (Figure 5.8) so that the fraction of species that are typical of other habitats is relatively high.

Highly specialized peatland fungi and their hosts include mycorrhizal species like *Leccinum rotundifoliae* (Sing.) Smith on *Betula nana* and *Lactarius pubescens* (Krombh.) Fr. on *Betula pubescens*; and parasites like *Rhytisma andromedae* Fr. on *Andromeda polifolia*, *Septoria callae* (Lasch.) Sacc. on *Calla palustris*, and *Puccinia calthae* Link, *P. calthicola* Schroet., and *Ramularia calthae* (Cooke) Lindr. on *Caltha palustris*.

With respect to vascular plants, the relative species richness of peatlands is significantly lower than that of bryophytes, algae and fungi. Vascular plants need more time to adapt to the peatland environment and this is highly important for their evolution. In order to tolerate the extreme conditions of peatlands, vascular plants need more complex mechanisms and therefore more evolutionary time to adapt than bryophytes, algae and fungi. Although their species richness (compared to the total regional species list) is significantly lower than that of lower groups of organisms, the evolutionary value of specialisations in vascular plants is therefore very high.

The gentle environmental gradients in peatlands support the development of intraspecific polymorphism in both vascular plants and mosses. Peatlands present a large variety of different ecological growth forms for many species. Small changes in environmental conditions like water level, pH, oxygen content and electrical conductivity may have a strong effect on vascular plants and mosses (Loopman 1988). *Sphagnum* mosses react through shifts in species composition (Früh and Schröter 1904, Overbeck and Happach 1957, Clymo and Hayward 1982, Ilomets and Paap 1982, Hayward and Clymo 1983, Ilomets 1989) or by phenotypic changes in morphology (Beijerinck 1934, Green 1968, Masing 1984, Clymo and Hayward 1982, Hayward and Clymo 1983, Panov 1991). This also applies to vascular plants, which exhibit changes in, for example, the size of roots and shoots, the density of hairs on stem and leaves, and the weight, shape and number of seeds. *Scheuchzeria palustris* can vary its shoot and leaf length by 500%, the number of seeds by

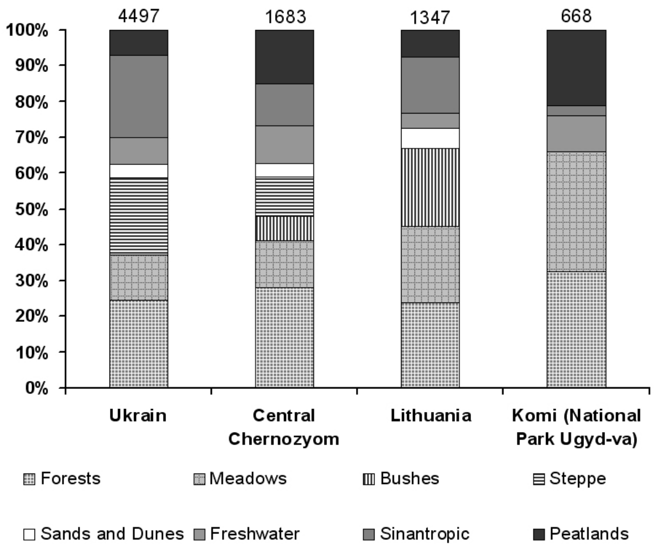


Figure 5.8: The contribution of different ecological groups to the total vascular plant species richness in a region depends on biogeographical factors and climate (data from Khmeljov 1985, Lekavitchus 1986, Prokudin 1987, Balevičienė 1991 and Martynenko and *Degteva 2003).*

300% and its biomass by as much as 1000%. Further adaptations include changes in population structure (juveniles vs. adults), propagation strategy (sexual vs. vegetative reproduction) as well as phenological changes (multiple flowering, changes in growth season). The ecological preferences of *Rhynchospora alba* change with developmental stage and population structure and thus vary with habitat type (Minayeva 1996, 1998). *Pinus sylvestris* exhibits different ecological growth forms, ranging from tree to dwarf tree to shrub, depending on peatland site conditions.

> Aucheninnes Moss, a degraded raised mire in south-west Scotland, provides the country's last refuge for the bog bush cricket *Metrioptera brachyptera* (order Orthoptera), a scarce UK species of wet and sometimes dry heath. Unfortunately, human influence is now bearing down on even this remnant of habitat which will soon be covered by the extension of a rubbish dump.

Species richness in peatland vascular plants is strongly supported by habitat diversity. Diversity in habitats with respect to nutrient content, water level and microclimate leads to increased species richness in peatland ecosystems. Factors that may mitigate the harsh peatland site conditions are the inflow of water rich in oxygen, mineral elements and lime, and disturbance induced by windthrow of trees, the activities of animals, etc. These factors bring more species to peatlands. Only a small shift in water quality can cause a strong increase in species richness.

Some vascular plant and bryophyte species play a key role in peat formation and the maintenance of mire ecosystems. Loss of these species will cause functional changes in peatland ecosystems. Few vascular plant species have the ability to form peat but their input by weight and volume is very significant. In the northern hemisphere, *Eriophorum vaginatum*, *Scheuchzeria palustris*, *Carex rostrata*, *Carex lasiocarpa*, *Carex limosa* and *Carex caespitosa* are irreplaceable in peat-forming ecosystems. The cosmopolitan *Sphagnum magellanicum* is a key peat builder all over the world. The loss of such peat-forming species would have dramatic consequences for peatland ecosystems.

> Percolation of mineral-rich waters can add up to 50 additional vascular plant species to a peatland (Wolejko 2002). Rich fens in the Carpathian Mountains in Eastern Europe are exceptionally valuable habitats that contain a high number of threatened species and community types and contribute significantly to Slovakia's biodiversity (Grootjans *et al*. 2005). The Nature Reserve "Abrod" for example, includes 92 ha of fen grasslands and supports 480 higher plant species, 18% of which appear on the Slovakian Red List (Stanova 2003).

5.2.3 Invertebrates

Invertebrate diversity in peatlands can be very high, as it is supported by the diversity of peatland habitats as well as their changes over time. Invertebrates effectively utilise spatial and temporal changes in peatlands. The diversity of invertebrate species is very high in

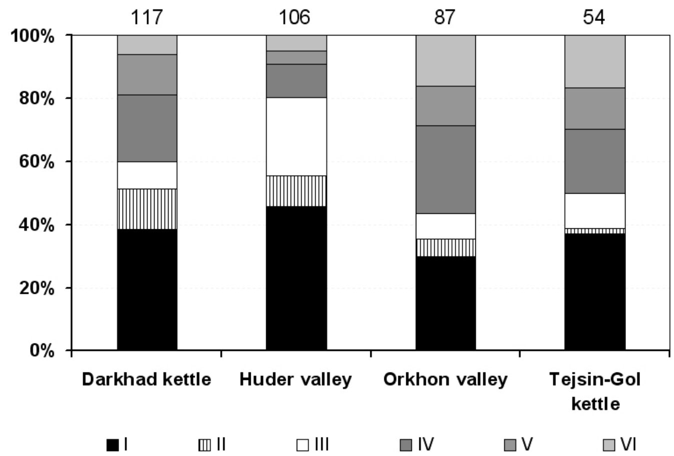


Figure 5.9: Peatland species (I) and species originally typical for other habitats (II – high mountains and gravel; III – meadow and forest; IV – meadow-steppe; V – dry steppe; VI – salt marshes) found in peatlands of Mongolia. The total number of species in peatlands of the different regions is indicated in bold above the graphs. In the dry regions of Mongolia, peatlands provide water and attract many species from other habitat types (from Minayeva et al. 2005).

peatlands, where up to 30% of the total regional invertebrate fauna may be found. In Estonian raised bogs, for example, 800 (Maavara 1955) to 1200 (Valk 1988) insect species have been found, 49 of which occur only in peatlands. The richest taxonomic groups are Coleoptera (244 species), Lepidoptera (250), Diptera (150), Rhynchota (103), and Hymenoptera (70). In the Wagner Nature Area, a boreal spring fen in Central Alberta (Canada), 2181 species of arthropods were found, 1410 of which were Hymenoptera (Finnamore 1994). Based on the number of parasitic wasp species, it is estimated that this fen area is home to about 6000 species of arthropods. A study of 38 Fennoscandinavian peatlands (including raised bogs, nutrient-poor fens, nutrient-rich fens and paludified forests) gave 4020 insect species and 296 other arthropod species (Krogerus 1960).

Besides insects, many other invertebrate species are present in peatlands, including Cladocera and Rotifera (Desrochers and Van Duinen 2006), *Cladocera, Cyclopoida* and sphagnum eaters - *Nematocera* (Smirnov 1961).

> An aquatic invertebrate survey in dolomitic peatlands in the Northwest Province of South Africa produced several new distribution records for South Africa and also 21 new species to science. Of the ostracod (including crustaceans) species found, 30% are new to southern Africa and one species is new to science (Piet-Louis Grundling, contribution).

Microscopic rotifers in *Sphagnum* mats seem to be important in the phosphorus and nitrogen cycles of bog ecosystems (Bledzki and Ellison 1998, 2002). The role of invertebrates in peatlands is very complex, with a large number of species and taxonomic groups at multiple stages in their lifecycles, and with mobile animals using different parts of the landscape (Esselink 2002, Verberk *et al.* 2006).

Invertebrates use habitat diversity effectively in time and space and similar species can occur together using very small but constant niches (Figure 5.10, Manneville *et al.* 1999).

5.2.4 Vertebrates

Water bodies in temperate peatlands, and especially isolated mire pools, are often poor in fish species, but those that are present often demonstrate specialised forms and much polymorphism. On the other hand, many fish species occur in tropical peatlands. Fish are generally rare in temperate peatlands where most of the open water is isolated from water bodies in the surrounding landscape. Where peatland streams and lakes are not isolated, fish diversity increases and peatlands can provide refuge for “outside” species, mitigating the stress of human impact. In Britain, lakes with peat-covered catchments typically have 0–5 fish species drawn from brown trout (*Salmo trutta*), minnow (*Phoxinus phoxinus*), 3-spined stickleback (*Gasterosteus aculeatus*), eel (*Anguilla anguilla*) and occasionally pike (*Esox lucius*) (UKTAG 2004). Fish in peatlands often show specialised forms (polymorphism); in the European part of Russia for example, peatland lakes are mainly occupied by only one fish species, perch (*Perca fluviatilis*) which displays very high morphological differentiation (Nikolayev 2007). Many new fish species have in recent years been discovered in tropical peatswamps (Ng *et al.* 1994), and 20% of Malaysian freshwater fish occur in peatlands (Ahmad *et al.* 2002). The endemic fish species associated with peatlands are often under serious threat. One of examples is *Barbus brevipinnis* (Jubb 1966), endemic to the north-west region of South Africa.

Peatlands can contribute strongly to the biodiversity of amphibians and reptiles of a region. Although these groups are not widespread in peatlands, peatlands play a vital role in the life cycle of many amphibians and reptiles species from surrounding lands. Relatively few amphibians and reptiles are found in peatlands (cf. Figure 5.11), but peatlands may support vital parts of the life cycles of these groups. Numerous publications suggest that amphibians cannot breed in peatlands due to high embryonic mortality connected to the water quality, although some do spawn in lagg fen pools in Scotland. For amphibians using peatlands temporarily for shelter and feeding during summer droughts, accessibility can be a controlling factor (Figure 5.11). There is little food for reptiles in peatlands but many reptiles use peatlands for hibernation because, unlike lakes and small creeks, they do not freeze to the bottom in winter.

A decreasing density because of habitat losses is reported for viviparous lizards (*Lacerta vivipara*) (Moscow region, Russia: Zamolodchikov and Avilova 1989; Middle Volga, Russia: Garanin 1983) and swamp turtles (*Emys orbicularis*) (Belarus: Bakharev 1982). The same is reported for amphibia in West Siberia (Russia) as a consequence of decreasing fen areas (Vartapetov 1980), the Moscow and Kaluga regions in Russia (Leont'eva 1990), and Belarus (Khandogij 1995).

Peatlands play a key role in supporting bird diversity. They host many waterfowl and "dryland" species that depend on peatlands during parts of their life cycles. They provide refuge for species that are driven from other habitats by human activities or environmental change. Peatlands provide feeding, breeding and shelter for numerous bird species, of which many are entirely dependent on them. Increasingly, peatlands harbour "dryland"

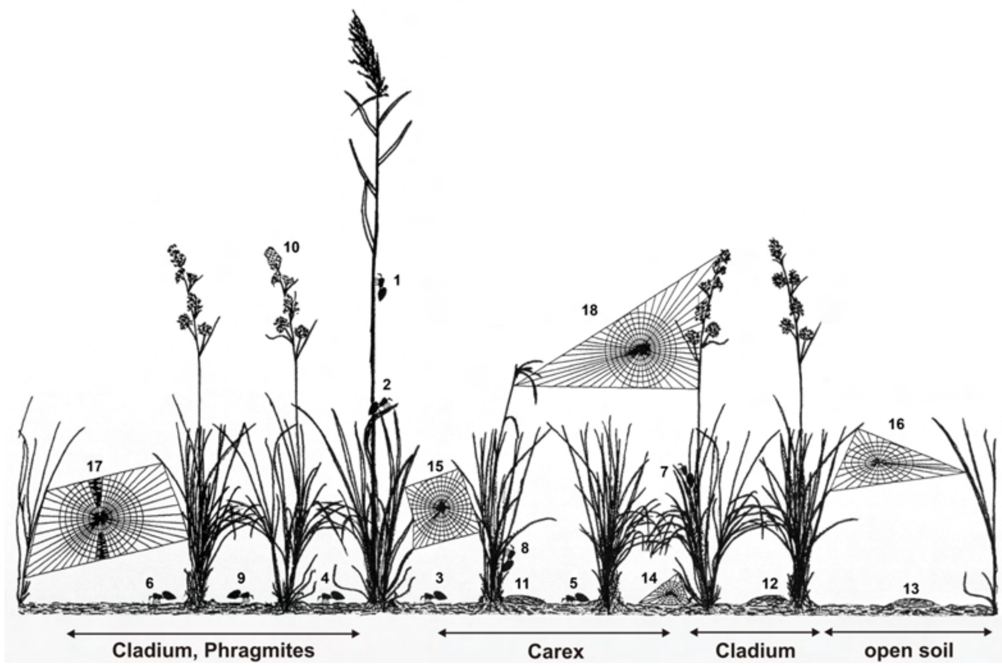


Figure 5.10: Invertebrates use habitat diversity effectively in time and space and similar species can occur together using very small but constant niches. Species and groups. Jumping spiders (Salticidae): 1 – Mithion canestrinii, 2 – Evarcha arcuata, 3 – Sitticus caricis; Wolf spiders (Lycosidae): 4 – Pirata hygrophilus, 5 – Pardosa prativaga; Tube or Sac spiders (Clubionidae, Lycosidae): 6 – Trochosa spinipaplis, 7 – Clubiona stagnatilis, 8 – Clubiona diversa; Crab spiders (Thomisidae): 9 – Oxyptila simplex; Cobweb weavers (Theridiidae): 10 – Theridion pictum; Sheetweb Weavers (Linyphiidae); Dwarf sheet spiders (Hahniidae): 11 – Anhistea elegans, 12 – Maro minutus, 13 – Erigone atra; Orb-weaving spiders (Argiopidae): 14 – Hypsosinga beri, 15 – Singa nitidula, 16 – Tetragnatha extensa, 17 – Argiope bruennichi, 18 – Larinioides cornutus (After Manneville *et al.* 1999)

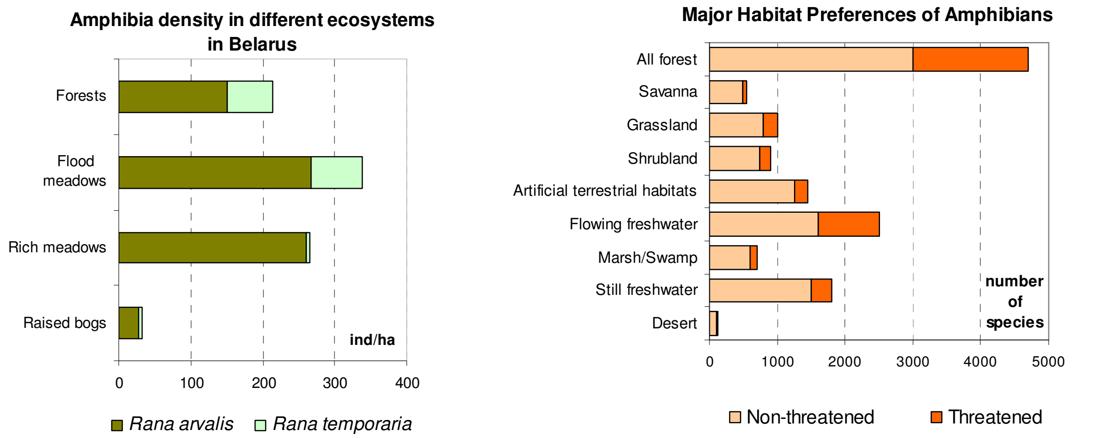


Figure 5.11: Amphibian habitat preferences in Belarus (Pikulnik 1985) and globally (http://www.globalamphibians.org/habitat.htm). Peatlands are not the most common amphibian habitats, but sometimes they play a critical role for their survival.

species that have been driven out of their original habitats by human activities.

Increasing climate and human pressures on drylands make peatlands, including mineral islands within peatlands, the last refuges for an increasing number of rare mammal species.

No mammal species are known that are entirely dependent on peatlands, and high water levels generally prevent them from staying in these habitats for very long. In the tropics, tree-dwelling mammals occur in peatswamp forests, just as in primary forests on mineral soil. Domesticated species such as water buffalo, yak, sheep and reindeer find important grazing grounds in peatlands. Beaver (*Castor* spp.) dams can cause paludification and associated peatland development (Mitchell and Nering 1993, Wright *et al.* 2002) as well as secondary paludification in drained peatlands (Vompersky and Yerofeev 2005). Beaver control management including hunting has addressed this “problem” in the USA and Canada.

With increasing pressure on dryland ecosystems, peatlands are becoming a last safe-haven for an increasing number of rare mammal species. These include, for example, the Sumatran Tiger (*Panthera tigris sumatrae*), Malayan Tapir (*Tapirus indicus*) and Orang

Utan (*Pongo pygmaeus* and *P. abelii*) in Indonesian peatswamp forests (Meijaard 1997).

In the temperate zone populations of some small mammals are increasing on mineral islands within peatlands (Istomin and Vagin, 1991).

Peatlands make a significant contribution to maintaining taxonomic biodiversity. Peatlands harbour species that typically exhibit strong interactions and adaptation to extreme conditions. These common features explain the general characteristics of species diversity in peatlands. Peatlands are extreme habitats that demand a high degree of adaptation. Peatland habitats are formed by well-packed ecological niches maintained by strong and long-term interactions that result in the following general characteristics:

- Peatlands usually contain 15-35% of the total regional number of species
- Of the species occurring in peatlands, 5-25% are characteristic of, or restricted to, peatlands
- Peatland species have developed very strong interconnections in ecological webs
- Peatland species fill the diversity of ecological niches by polymorphism or different lifecycle stages
- Peatlands are resistant to invasions, but in some cases exotic species or forms can adapt to the peatland situation
- By their conservatism, peatlands play a significant role for the survival of many taxa in hard times
- At the same time, due to their tough environment, peatlands are important for the evolution of many taxa.

5.3 Human impacts on peatland biodiversity

In southern Quebec, the list of peatland bird species contrasts increasingly with the regional avifauna from north to south or from undisturbed to managed landscapes, and the peatland avifauna is more similar across regions than to any regional avifauna (Calm *et al.* 2002).

A few bird species depend on peatlands throughout their life cycles, including Black-throated Diver (*Gavia arctica*), Black Grouse (*Lyrurus tetrix*) and Greylag Goose (*Anser anser*) (Nikolayev 2000). Many others depend on peatlands during only parts of their lives, for example for breeding or feeding.

In the forest zone of European Russia such species include Black Stork (*Ciconia nigra*), Greater Spotted Eagle (*Aquila clanga*), Common Crane (*Grus grus*) and Spotted Crake (*Porzana porzana*) in fens; Whimbrel (*Numenius phaeopus*), Golden Plover (*Pluvialis apricaria*), Willow grouse (*Lagopus l rossicus*), Golden Eagle (*Aquila chrysaetos*), Short-toed Eagle (*Circaetus gallicus*), Peregrine Falcon (*Falco peregrinus*), Merlin (*Falco columbarius*), Osprey (*Pandion haliaeetus*), Great Grey Shrike (*Lanius excubitor*), and Capercaillie (*Tetrao urogallus*) in bogs; and Wood Sandpiper (*Tringa glareola*), Greenshank (*Tringa nebularia*) and Curlew (*Numenius arquata*) in both.

In western Europe, peatland pools are important for the roosting of overwintering populations of rare goose species. Ireland and the island of Islay off the west coast of Scotland support an estimated 63% of the world's population of the Greenland White-fronted Goose (*Anser albifrons flavirostris*) (Fox and Francis 2005), whilst the Taiga Bean Goose (*Anser fabalis fabalis*) regularly uses only two sites in Britain, both of which are peatlands (Hearn 2004).

Human activities affect peatland biodiversity in different ways and via various pathways (see Table 3.1). Biodiversity may be totally lost when the peatland entirely disappears as a result of overbuilding, inundation or peat extraction; or it may be modified only very slightly due to hunting, berry-picking or recreation. Changes can be quick and sudden or slow and creeping and even initially invisible.

Human impacts on peatland biodiversity may be evaluated via changes in the three main peatland components that are central for all key peatland functions and processes: water, peat and plants. Anthropogenic changes in hydrology, geochemistry or vegetation may directly and indirectly lead to shifts in peatland biodiversity. Often minor changes in site conditions result in drastic changes in biodiversity. Even slight drainage makes peatlands more vulnerable to peat fires with dramatic impacts to biodiversity.

Peatland biodiversity may be affected by interventions in the water balance of the entire peatland, of part of the peatland, and of the peatland's catchment area or surroundings. Water plays a central role for peatland biodiversity because peat contains about 95% of water by volume. Hence, any drainage leads to loss of soil volume and thus to subsidence. Hydrological and thus ecological conditions on a raised bog's surface are largely determined by the local surface slope and the distance to the internal water divide, often referred to as the flow path length. With increasing flow path length, the surface slope becomes less critical and vice versa (Van der Schaaf 2002, Van der Schaaf and Streefkerk 2002, 2003).

Drainage of the bog margin may result in subsidence, increasing the slope of the bog dome. This then leads to increased runoff and lower water levels that may affect the vegetation in the entire peatland. Drainage of mire margins not only destroys the specific local vegetation, but also facilitates access to people, animals and plants, which may further impact the biodiversity of the rest of the peatland.

Drainage both in and in the surroundings of raised bogs may cause damage to the bog by subsidence. A first and immediate effect of internal bog drainage, usually by shallow open drains, is a drastic shortening of flow paths, loss of water from the upper peat and subsequent subsidence. Because the newly formed drainage base subsides at a speed that is only slightly less than the subsidence speed of the surface itself, the subsidence may continue for a long time.

Human activities in the peatland surroundings raise risks for peatland as well. In South Africa peatlands are in peril in areas where groundwater resources are exploited. Droughts have resulted in huge pressures on already water-stressed catchments and associated mires. The karst peatlands in the western part of South

Africa are affected most. One of these peatlands, Bodibe, is permanently on fire.

> Drainage of the Irpen River valley mires (Ukraine) led to lower groundwater levels in areas 25-30 km away from the river and to dramatic changes in vegetation cover (Kubyshkin 1971). Peatland drainage in the West Bug River basin (Ukraine) has led to greatly increased erosion of adjacent mineral soils and associated loss of habitats (Svedovsky 1974).

Drainage or any form of groundwater extraction in a bog's surroundings causes a lowering of the hydraulic head in the mineral layers under the bog. In Clara Bog, Ireland, this led to a subsidence of 0.6 m in 10 years as a result of compaction of the lower peat (Ten Heggeler *et al*. 2003, 2005). This means that even the dense peat layer at the peat bottom (Van der Schaaf 1999) gave insufficient shielding to the bog.

> In Clara Bog (Ireland), a set of open ditches associated with a bog road caused subsidence up to 5-6 m in about 200 years in a peat profile, that was originally 13 m thick (Van der Schaaf 1999, Connolly *et al*. 2002).

As a result of subsidence, surface slopes of peatlands change, causing changes in flow pattern, flow path length, the position of water divides and catchment size. This may create considerable and sometimes rapid changes in wetness and may have disastrous effects on the vegetation.

> In cutover bogs, populations of the moss *Polytrichum commune* are separated by ditches and cutover areas. Genetic diversity in cutover bogs was lower than in pristine mires (0.729 vs 0.880). In addition, genetic diversity was more structured in the populations from cutover bogs, suggesting that genetic drift strongly affects diversity in these fragmented habitats (Wilson and Provan 2003).
>
> *Scheuchzeria palustris* in Great Britain is known mostly from fossils and is found nowadays only in a few localities. Previously this species was widespread (Godwin 1975).
>
> The type locality of four new endemic fish species identified in Malaysia was destroyed by conversion to agriculture land soon after their discovery (Marcel Silvius pers. comm. 2005).

Water losses and peatland subsidence. The immediate effect of water loss is loss of volume, which becomes manifest as subsidence. In temperate regions, mire drainage can lead to a subsidence of 0.5-1 m in the first ten years (Van der Molen 1975). Subsidence by water losses may continue for more than a century. The rate of subsidence depends on the hydraulic conductivity of the peat, because that determines the speed at which water can flow out. The hydraulic conductivity of peat in tropical peat domes may be three to four orders of magnitude higher than that in temperate bogs (Graafstal 2004). This may explain why tropical peat domes collapse rapidly after they have been drained. Such subsidence processes are virtually irreversible, making restoration illusory.

Changes in peatland ecosystems can affect the biodiversity of surrounding areas. Often peatland drainage leads to lower groundwater levels in adjacent areas. This is especially the case with fens that are in contact with groundwater in the underlying mineral soil. Hydrological changes in bogs tend to have smaller effects as they usually have an almost impervious layer at their bottom and are much more isolated in this respect. Other examples include desertification in mountainous areas of Central Asia, Africa, and South America following the degradation of highland peatlands, and Arctic permafrost melting after vehicles damaged the thin peat layer, leading to feedbacks affecting biodiversity over a much wider area than that covered by peat. Mire growth and associated water level rises may lead to paludification of adjacent areas, as was already noted by Linnaeus (1749).

Loss of peatland habitats, their change and fragmentation, could lead to dramatic changes of species and intraspecific biodiversity. Human-induced changes in peatland habitats are often irreversible and accompanied by loss of natural species diversity. Habitat loss furthermore contributes to fragmentation where surviving populations are no longer able to exchange genes or recolonise an area. Roads and ditches cause fragmentation, as do peat extraction, drainage, overgrazing, fires, and floods. Whereas in theory fragmentation (isolation) may stimulate genetic diversity between populations, diversity within populations will strongly decrease through genetic drift and inbreeding (Young *et al.* 1996).

> From about 2000 plant species in the Kolkheti Lowland (Georgia) 423 are invasive of which 308 occur in the Kolkheti mires and relict swamp forests. Most invasive vascular plant species are Poaceae, Asteraceae, Fabaceae, Brassicaceae, and Apiaceae. This large proportion of invasive flora is caused by landscape transformation (peatland drainage, peat extraction, deforestation, etc) and by increased international trade since the 19th century. The propagules of invasive species were transported from all over the world by ship and later railway and successfully settled in the Kolheti Lowland (Izolda Matchutatze, pers. comm. 2007).

Peatland species are often closely connected to each other. Human induced loss of one species can lead to further impacts on others. Connections between species are often very tight in peatlands. The loss or change in characters of one species can lead to the loss of species dependent upon it, and to shifts in ecological webs, with far reaching consequences. Decreased berry productivity in peatlands in the Tver region of Central European Russia due to overharvesting led to a decrease in Capercaile (*Tetrao urogallus*) populations (Nikolayev 2000). Due to drainage (and also acidification and nutrient enrichment caused by increased deposition of N and S), the occurrence and nutritional quality (balance between N, P, minerals, secondary compounds) of host plants changes. The nutritional quality of the host plant is very important for the caterpillars of those species. This balance is disturbed in Western Europe due to increased N and P availability, which can make plants useless as host plant for characteristic and endangered butterflies. This can result in the loss of such species like *Coenonympha tullia*, *Plebeius optilete*, and *Boloria aquilonaris*.

Human impact promotes the invasion of alien species. Such invasions are increasingly reported in peatlands from different regions of the world. Peatland communities have long been considered resilient to invasions of exotic species but alien species in peatlands are increasing. Most of them have mechanisms for nitrogen fixation (Minayeva and Cherednichenko 2005). Species like *Sarracenia purpurea*, *S. flava* (North America), *Drosera binata* (Australia) and *Drosera capensis* (South Africa) were artificially planted on peatlands in Great Britain and now have settled widely in natural mires (Stace 1997). *Sarracenia purpurea* (North America) was artificially introduced in 1906 in Roscommon (Ireland). Now it is also widely distributed in Switzerland's high mountain peatlands.

Over 300 alien species are reported from the mires of the Kolchis area in Georgia. A well-known example of naturalization in natural and seminatural bogs is *Rhododendron ponticum*. This species prevents regeneration of native species, reduces light, increases evapotranspiration and lowers the water levels, causing severe changes in species composition. It also promotes competition for nutrients with native species (Cross 1975, Shaw 1984, Tyler 2006). In the Cape region of South Africa the black wattle (*Acacia mearnsii*) invades peatlands, causing indigenous, natural vegetation to be shaded out. Generally, invasions by alien species in peatlands are irreversible.

Biodiversity maintenance needs to distinguish clearly between general and natural diversity. After peatland disturbance, general diversity may increase by the establishment of synanthropic and ruderal species, while

Figure 5.12: Endangered butterflies endemic for peatlands. From left to right Coenonympha tullia (feeding on Eriophorum angustifolium, Eriophorum vaginatum, Molinia caerulea, and Carex rostrata), Plebeius optilete (feeding on Andromeda polifolia, Oxycoccus palustris, Vaccinium uliginosum, and Vaccinium vitis-idea) and Boloria aquilonaris (feeding on Andromeda polifolia and Oxycoccus palustris).

natural diversity of peatland species simultaneously decreases. Changes to peatland environments and especially surface destruction remove strong competitors. As a result ruderal, synanthropic and adventive species expand which may lead to an increase in species number. The diversity of typical peatland species usually decreases due to their conservatism. Many publications report an increase in general diversity after peatland drainage for forestry or after peat extraction. Statements like "…closer analysis suggests that, at least in some cases, limited peat extraction can actually increase biodiversity…" (Chapman *et al.* 2003), however, clearly refer to general diversity, not to natural peatland diversity.

The long-term use of peatlands leads to fundamental changes in landscape, ecosystem and habitat diversity, as well in diversity between and within species. Peatland ecosystems that have been transformed in this way can support high and specific biodiversity, but they lose their natural sustainability and require continued human management. Cultural landscapes need sustained human management. Peatlands that were surficially drained and mowed for centuries now display large, specific species diversity, and need permanent mowing to avoid settlement of shrubs and trees and subsequent habitat changes. Peatlands on terraces in the Alps have formed biodiversity specific to today's conditions due to long-term pasturing. The hay-meadows in East-Central Europe (Polessje, Biebrza river valley in Poland, Berezina in Belarus) demand permanent hand mowing for maintenance. In some cases, traditional peatland use is needed to support biodiversity that has been long-established by people, as well as to maintain the sustainability of indigenous and local human communities and their natural resources.

Peatlands are an excellent chronicle of the different anthropogenic impacts on biodiversity, both within these ecosystems and in their surroundings. A wide range of human activities since the first civilisations is responsible for the transformation of ecosystems, as reflected in species and ecosystem diversity. Most dramatic events are recorded in the peatland chronicle. Fossil remains of plants and animals preserved in peat are good indicators of biodiversity changes. The traditional indicators of anthropogenic alteration to natural landscape dynamics are the pollen of cultivated plants and weeds and, in some cases, the decline of tree pollen in favour of herb pollen. Traces of chemical or radioactive pollution in peat can also provide evidence for human activities (forest clearance, mowing, etc) in the vicinity. Multiproxy analyses are required to reconstruct anthropogenic impacts on biodiversity in detail, but peatland palaeoecology contributes significantly to the evidence.

Commercial activities on peatlands lead to both obvious and initially invisible 'stealth' impacts on peatland biodiversity. Peatland biodiversity is influenced by a wide range of economic sectors such as agriculture, forestry, industrial peat extraction, construction (roads, industrial and civil), the oil and gas industries, harvesting of wild natural products, tourism and others. These activities lead to impacts such as direct damage, changes in water levels, contamination, the introduction of invasive species and declines in productivity. Some impacts that have long-term effects on biodiversity do not become apparent for many years, and others cannot be identified due to our incomplete knowledge of ecosystem functions and values.

Peatlands have been used for a long time to harvest biological resources. The maintenance of peatland ecosystems in their natural state is the key condition for the availability of such peatland bioresources. The harvesting of mushrooms, berries and biomass (reeds, sphagnum mosses) in natural peatlands plays a significant role in livelihood strategies in Siberia and large parts of European Russia to date. The role of peatlands in maintaining hunting species is also important.

The Tonga people of the Tembe Tribe have been living next to the Kosi Lake System in South Africa for centuries and use the indigenous plants from the swamp forest for various purposes. In particular, the palm *Raphia australis* has been used for construction. Its leaf has a very long ragis which is light and strong, and therefore is an excellent component for use in building canoes, ladders, roofs and even walls. There is presently less stress on the palm as its use in house construction has decreased due to it being increasingly seen as a sign of poverty. The palm is also protected as one of the area's endemic plant species, prohibiting the felling of any live specimens.

Many indigenous swamp forest plants are also used as medicines and food resources, such as berries from *Syzygium cordatum* (Sliva 2004).

Worldwide, one of the largest causes of losses in natural peatland area, and hence in biodiversity, is agriculture. Agricultural use imposes fundamental alterations to biodiversity, both internally and in neighbouring areas. Peatlands are taken into agricultural use after drainage or partial extraction and are subsequently used as pasture, for haymaking or as cropland. Natural vegetation is replaced by grassland monocultures or, even worse, by crops. The newest agricultural use is biofuel production on drained peatlands (e.g. oil palm cultivation). Such land use shifts can happen very quickly in concentrated areas during times of rapid industrial development. For example, an unpublished land use study of the lowlands of Lancashire (England) showed that 73% of the area of raised bog in 1850 had been converted to agricultural use by 1900. Agriculture converts peatland ecosystems into managed cultural landscapes. Changes in vegetation influence all trophic chains within the peatland, with further effects on neighbouring ecosystems and over even wider areas. Bird species may lose the peatland habitats that they formerly used for feeding, breeding and shelter. In both the temperate zone and the tropics there is often strong agricultural pressure especially on valley peatlands, the alteration of which damages both terrestrial and aquatic biodiversity.

In Central Kalimantan, Indonesia, one million hectares of rain-fed peatland forest was felled and subjected to large-scale drainage in a scientifically unsound attempt to convert it to rice paddy. The area's natural biodiversity was lost forever, along with the many associated goods and ecosystem services that formerly benefited the local population, while rice will not even grow here. Improved access allows small-scale cultivation and animal husbandry, leading to frequent fires that hamper the re-establishment of secondary natural vegetation on unused areas. As the peat soil disappears through oxidation and fire, all that may be left is a vast expanse of barren acid sulphate mineral soil.

Sometimes unique patches representing the last remaining examples in the world of certain types of ecosystem (like the Coastal Peat Swamp Forest in South Africa (Grundling and Grobler 2005)) are also the only available land areas for local populations.

In many regions, the biodiversity of some peatlands has developed under a traditional regime of grazing by cattle. However, when modern pressures result in movements of large numbers of cattle onto previously ungrazed sites, it can have devastating consequences for peatland biodiversity. Peatlands have traditionally been used for cattle husbandry in many regions. The present biodiversity of such peatland ecosystems – whether on the Tibetan Plateau in Asia, in the mountain regions of South America and South Africa or on terraces and wet slopes in the European Alps – is the product of centuries of grazing. A sudden change in stocking rates is highly likely to disturb the delicate ecological balance of such peatlands. However, modern overstocking and overgrazing of pastures on mineral soils against a backdrop of increasing climate aridity means that large numbers of cattle are now being moved onto new peatland sites. Being more vulnerable to overgrazing than minerals soils, peat soils and their vegetation cover are rapidly degraded and so lose much of their biodiversity.

Forestry has one of the largest impacts on peatland biodiversity. Biodiversity is influenced by logging in peat forests, by forest drainage aimed to enhance tree production and for establishing new plantations, by digging canals for timber transportation, and by other related activities. Forestry has the most widespread anthropogenic impact on peatlands. Forests with peat layers cover large areas of the temperate zone and the tropics. Very often forest management hardly distinguishes between forest stands on mineral and peaty soils. However, forest on peat requires special management, not only from a technical point of view (e.g. for harvesting) but also because of the fragility of peatland ecosystems. Forestry on peatlands not only involves the felling of any native trees, but also drainage to improve productivity or for planting, digging of canals for transport etc., as well as the introduction of exotic/alien tree species, often in monoculture. All these activities increase the general anthropogenic pressure on the peatland and increase the probability of catastrophic events like fire. They also involve the loss of habitats for birds, mammals, fish, insects, plants, fungi and microbes that were part of the native ecosystem but which cannot function under the new environmental conditions or form associations with the introduced tree species. Moreover, the species being cultivated for their timber often fail. In the Flow Country of northern Scotland, large areas of treeless peatland were commercially afforested between 1979 and 1987 but this activity became uneconomic when the supporting fiscal incentives were withdrawn in 1988 (Lindsay *et al.* 1988). Much effort has since been invested in attempting to restore some of the area's natural values.

> The swamp forests on the flat coastal plain of Maputaland form 75% of the swamp forests of South Africa, making them very valuable for biodiversity conservation (Lubbe 1997). The Coastal Peat Swamp Forest in the Kosi Lake System in South Africa is highly threatened by slash and burn agriculture. The peat soils of the swamp forests provide the only suitable habitat for cultivating bananas (*Musa)* and other crops such as Taro (*Colocasia esculenta*), sweet potato (*Ipomoea batatas*), and manioc or as it is locally known umDumbula (*Casava edulis).* Peat soils of swamp forests are favoured above other peat soils such as those dominated by *Typha capensis* and *Phragmites australis,* because their soils are typically sloping and can be more easily drained. The need for more food and therefore more crop cultivation is continually escalating and intensifying (Sliva 2004).

Almost immediately, the story began again on a much grander scale and with much greater implications for peatland biodiversity, with the expansion onto peatswamp forests in the tropics of vast timber estates feeding enormous paper pulp mills (Whitten *et al.* 2001). From the other side some countries have especially high part of poludified forests (Lavoie *et al*. 2005).

Logging in forested peatlands affects the species composition of the tree stand. Partial or total removal of the trees can lead to changes in water level, insolation, light regime and microclimate, with further effects on biodiversity. The process of tree harvesting, especially using heavy machinery, causes additional damage to biodiversity. Forests on peaty soils have often been harvested for timber. Peatswamp forests in the tropics are a principal source of high-quality wood. Logging affects tree species composition especially when selective felling is applied. Total or partial removal of trees reduces interception and increases the effective precipitation reaching the ground so that the water level may rise. The removal of trees also changes the insolation, light regime and microclimate. All these factors affect biodiversity. Impacts may vary depending on the natural characteristics of the site and the forestry methods applied. Clearcutting of peat forest usually leads to fundamental ecological changes with major losses of biodiversity. The use of modern mechanised forestry techniques can destroy ground vegetation, seriously alter peat soils and disturb animal populations. Timber harvesting replaces oligotrophic peat pine forests (in Europe) or black spruce forests with dwarf shrubs (in America), brown and *Sphagnum* mosses with communities including *Calla, Caltha, Typha, Scirpus*, and *Phragmites*. Even if forest regeneration begins afterwards, it can take a long time for the original vegetation to be restored.

Drainage for forestry has a wide range of repercussions on biodiversity for both peatlands and the adjacent areas. If successful, this activity replaces peatlands with productive forests whose biodiversity is totally different from the initial conditions. Forest drainage is intended to increase timber production by improving the water regime. After ditching, additional silvicultural measures are used to enhance tree growth and to achieve the desired tree stand composition and quality. Planting is applied on treeless drained peatlands after clearfelling. Successful forest drainage and related silvicultural measures replace peatland vegetation with productive forest stands that are more typical for mineral soil sites. At the species level there will be shifts in species composition, but the number of species is likely to increase overall (Korepanov 2000). Nevertheless, this biodiversity will be different from that associated with the natural condition of the habitat. Specialised and rare species may be lost, and drainage increases the accessibility of the internal parts of mire massif to visitors, who may bring in alien species. On the other hand, deterioration of ditches and beaver damming can lead to secondary paludification, and in some cases, typical peatland species composition can be restored in 15-30 years (Yefremov 1972, Grabovik 1998).

Tropical peatswamp forests are ditched so that harvested timber can be floated out to the nearest river. The resulting drainage changes the ecology of the peatland and paves the way for the penetration of various anthropogenic impacts to its internal reaches. This has both direct and indirect impacts on biodiversity. The vast tropical peat swamp forests of Southeast Asia have traditionally been used for forest logging. Dug channels, which naturally fill with water, provide the easiest route for access and for transporting out the harvested timber. The small hand-dug channels that were made in previous decades generally had little impact on the ecosystem, but modern techniques provide possibilities for the construction of large channels that penetrate further into the peatland and so extend the reach of a range of human impacts. Escalation of the intensity of both legal and illegal logging is promoted by policy initiatives which increase populations above the carrying capacity of the forest for traditional livelihoods and at the same time reduces the area of forest available through the allocation of large tracts to commercial enterprises. Thus, the selective felling of valuable and rare tree species is expanding, and because the water regime has been altered by the channels, the same species do not always replace the extracted trees. Moreover, peat fires occur more frequently and people begin to plough felled areas for agriculture. Thus, these peatland ecosystems are gradually losing their biodiversity value (Rieley *et al.* 1994, 1997).

The global area of peat extraction is not large, but peat extraction leads to total destruction of peatland biodiversity and often affects the biodiversity of the surroundings. Globally, peat extraction has not led to large losses of peatland area. Peat is extracted for different purposes using a variety of methods. The traditional hand cutting practiced by crofters in the west and north of Britain and Ireland can be managed in a relatively sustainable way, especially if the 'top spit' (uppermost layer of the acrotelm) is replaced after some of the underlying peat has been removed. Extraction using machinery is, in general, a much more destructive activity. When practiced at a commercial scale, this eradicates entire peatlands along with their habitats and species, together with other goods and services. Moreover, by altering groundwater levels and microclimates, peat extraction can affect habitats on adjacent land. In parts of the world where commercial peat extraction was a very dominant feature in the landscape (formerly Northern Germany, Ireland and the Netherlands; now Canada and Central European Russia), peat mining activities can lead to serious loss of peatland and biodiversity at a regional level.

Occasional fire has been one of the development mechanisms for the buttongrass moorlands of Tasmania and the New Zealand pakihi. However, an increase in fire frequency and intensity will have conservation implications for these peatlands, both in terms of species and in peat accumulation rates. In the mountains of mainland Australia, fire is shifting the balance from *Sphagnum* peatlands towards sedge and tussock grasslands. Fires associated with the El Nino event in 1997-98 burnt 10,000 km² of tropical peatlands in Kalimantan and Sumatra. Next to ecological impacts, more frequent and more intensive fires have implications for carbon feedback mechanisms (Whinam and Hope 2005).

The long-term impact of peat extraction on biodiversity very much depends on landscape planning and the after-use options for destroyed areas. From a biodiversity point of view, it is preferable to avoid peat extraction but sometimes there is an overriding socio-economic justification for this activity. Moreover, as it may be driven from several economic sectors – e.g. horticulture, agriculture, energy, chemistry and so on – it is not always easy to pinpoint and influence demand. Slightly humified *Sphagnum* peat is still irreplaceable as a growing medium in professional horticulture, and in some regions peat is the only available or the most cost-effective fuel for heating purposes. In order to minimise detrimental impacts on biodiversity, it is necessary first to divert peat extraction away from the areas that are most valuable for biodiversity and to plan works to avoid landscape and habitat fragmentation. Secondly, areas from which peat has been excavated must be restored in such a manner that the maximum positive effects for biodiversity are achieved.

The restoration of extracted peatlands has various impacts on biodiversity and needs careful planning to achieve eventual restoration and to avoid losses and significant changes. Over the last 20 years, significant advances have been made in the development and introduction of peatland restoration techniques as integral components of the peat extraction process. Rewetting and further recovery of ground vegetation protects the land from erosion, peat fires and carbon emissions, and leads to positive changes in local hydrology. However, the restoration of peatland habitats is rarely effective in bringing back their original species and genetic diversity because fragmentation and a lack of habitat corridors prevent remote populations from recolonising the restored area. As a result, the genetic diversity of founder populations is low and the homogeneity of the restored habitats will lead to further loss of genetic diversity, making populations less resistant to future impacts. In some cases, rewetting of peatlands has resulted in water level rise areas adjacent to their boundaries, with negative consequences for biodiversity in neighbouring ecosystems. Thus, the restoration of extracted peatlands has a differential impact on biodiversity and needs careful planning to ensure that the aim of peatland restoration is ultimately achieved, as well as to avoid losses and significant changes in neighbouring ecosystems (Wheeler and Shaw 1995, Wheeler *et al.* 1995, Pfadenhauer and Grotjans 1999, Bakker *et al.* 2000, Bragg 2007, Panov 2007, Van Duinen 2007).

Fire caused by lightning storms is a significant ecological factor for the development and biodiversity of several peatland types. However, peat fires originating from human activities could have dramatic impacts on peatland ecology and their natural biodiversity. Fires started by lightning storms arising during drought are natural and significant ecological factors for the development and biodiversity of many peatland types. However, human activity seldom discriminates between peatland types and may lead to modern fires in areas where natural fires occurred only under a previous (paleoclimatic) weather regime, or areas that have never been burned before. Such fires can kill almost all natural vegetation and initiate unusual successions, with dramatic changes in biodiversity extending not only across the peatland but also across the area as a whole.

Many water reservoirs now cover peatlands that occupied lower-lying positions in landscape. Inundation leads to the disappearance of peatland types, the formation of new ecosystems and shifts in biodiversity. Land flooding by dam construction also has a long-term indirect impact on peatlands by shifting land use and pressure to peatland areas. The construction of dams to form reservoirs has several consequences for peatland biodiversity. This activity most often eradicates valley peatlands, which are valuable because they support characteristic vegetation and species, provide habitat for waterfowl, and are used as migration corridors by birds and other animals. On the other hand, the filling of reservoirs causes the water table to rise around the new shoreline, where ecosystems and biodiversity also change as a consequence. If the reservoir water level does not fluctuate widely, this may lead to paludification of new areas and, eventually, to the formation of new lacustrine peatlands. Flooded peat can become intermittently or perennially buoyant so that other new ecosystems are developed on the resulting floating peat islands, which appear some years (typically 10 – 25) after inundation (Van Duzer 2004) and may cover up to 20% of the flooded area. In the Arctic, floating palsas (with ice cores) are especially stable and can float for decades (Preis 1979). Thus the construction of large dams can lead to the replacement of valuable valley and lowland peatland types with a new type of ecosystem – the floating fen. Very often the land use from flooded lands shifts to remaining peatlands, causing indirect impacts on peatland ecosystems.

Industrial and civil construction lead to total transformation of the peatland areas, losses of significant peatland biodiversity and the transformation of biodiversity of adjacent areas and dependent species, including migrating birds. Peatlands are traditionally regarded as areas with very low land values, because no account is taken of the ecosystem services that they provide, including their biodiversity capacity. Many peatlands have been destroyed by industrial and civil construction, especially in highly populated areas. Peatlands are often the last unused areas close to population centres, and so become the obvious locations for vast new constructions such as airports. Fens and swamps occupying flat, moist lowlands that have previously been unsuitable for building are the peatland types that are most frequently altered in this way. This type of land transformation results in loss of most of the peatland's biodiversity and alters that of adjacent areas and dependent species such as migrating birds. The new requirement for low-carbon energy sources in Europe has created a need for the erection of wind turbines to service the main centres of population, preferably without causing too much visual inconvenience in those areas. As a result, concentrations of wind turbines (wind farms) are now beginning to compete with peatlands for the gently-sloping parts of remote upland areas. The construction of a wind farm on peat requires access by heavy machinery and thus the installation of roads which inevitably sink into the peat and require drainage, together with the extraction of peat to provide firm standings for the bases of turbine towers some 100 metres high. The fraction of the peatland habitat that is lost directly is fairly small, but the combined effects of road-building, peat extraction and the associated drainage threatens the hydrological integrity of much more extensive areas, and this in turn will alter the character of the biota and thus affect biodiversity. These are also areas that are used by (often rare) bird species, which not only lose habitat but are also prone to injury from collision with the moving turbine blades.

> The Lesotho Highland Water Project flooded fertile valleys and thereby reduced grazing lands and increased pressure on alpine areas. The grazing impact on mires increased particularly in communal alpine areas. Species such as *Isolepis fluitans* are heavily grazed and while they have a high resilience to grazing, the main problem is the secondary impact of trampling by grazing animals. Peat is more resilient to this form of erosion than the mineral soils originating from the underlying basalt. Gully erosion occurring upstream of mires in mineral soils is especially significant in causing erosion in the more resilient mires as well (Grundling and Lerotholi 2006).

In peatland areas, roads and other linear constructions like oil and gas pipelines affect biodiversity through landscape fragmentation and changes to the water regime along their routes. The construction of roads and other linear structures such as oil and gas pipelines on peatlands causes a range of impacts on biodiversity. The linear form causes the fragmentation of landscapes and habitats which affects, for example, amphibian and reptile populations. Linear constructions can significantly alter the hydrology of the peatland itself and of adjacent areas, by, for example, causing ponding of water upslope and unnatural water deficit downslope, which in turn leads to vegetation changes. Further consequences for biodiversity may arise depending on the peatland type. One example is the death of trees as a result of raising the water level upslope of a road, leading to dramatic plagues of phytofagous insects that attack adjacent forest stands. This may then be followed by changes in bird diversity and other consequences.

Air pollution and water contamination could change the geochemical regime of a peatland with consequent impacts on biodiversity. Peatlands are altered by air pollution from industrial and energy sources as well as by water contamination. Addition of nitrogen leads to subtle changes in dynamics of species and changes in species composition. A number of studies have shown that N deposition at low rates initially leads to increased growth in *Sphagnum*, but higher doses, or lower doses over a longer time period, will reduce *Sphagnum* growth (Gunnarsson and Rydin 2000). High inputs of both P and N over a long period are probably the reason that *Molinia caerulea* and *Betula pubescens* have invaded bog vegetation in the Netherlands (Tomassen *et al.* 2003, 2004). In raised bogs, nitrogen deposition leads to a higher sensitivity of the dominant peatmoss vegetation to hydrological changes (Limpens 2003). It may also give rise to an increasing share of vascular plants in the vegetation, which may partially compensate the normal evaporation reduction in a *Sphagnum* cover during dry summer periods (Kim and Verma 1996), thus increasing water losses in dry periods. Pollution by metal or toxic compounds can have dramatic effects on peatland ecology and its related biodiversity. In severe cases, such as pollution by saline water or oil, peatland vegetation can be killed or physically destroyed. Surface pollution from roads and waste water from livestock farms can also have serious effects on peatland biodiversity, although the ability of peatland soil and vegetation to cleanse water is now widely utilised in this context. Human impact is mostly caused by drainage, with pollution in second place. The effect of water pollution is generally limited to fens, because they depend at least partly on the inflow of water from elsewhere, whereas bogs solely depend on rainwater. Any discharge of nutrient-rich water into a river with valley fens downstream has a comparable effect. Air pollution may in some cases affect bogs, especially nitrogen influx (Lamers *et al.* 2000, Gunnarsson 2000). Examples are found in northwestern Estonia, where some bogs show fen-like vegetation, caused by the emission of calcium into the atmosphere from a power plant that uses locally mined oil shale.

Peatlands are often the last remaining natural areas in degraded landscapes and a refuge for species from surrounding areas.

Peatland biodiversity suffers as a result of a wide range of human activities. Peatland loss is typical in regions where they are both common and rare. Loss of peatlands means loss of ecosystems and their diversity, goods and services, as well as the loss of habitats and species including their forms. Losses are caused by changes in water level (drainage or flooding), peat extraction, conversion to arable and industrial land, contamination, fires and other direct impacts. Losses of peatlands due to human impact take place both in regions where they are common and in those where they are rare.

The famous Yaselda river valley fens in Belarus have not only suffered from drainage, but are also threatened by water pollution and eutrophication caused by fish farming (Belokurov *et al.* 1998) with subsequent losses of valuable species.

The rate of human-induced pressure on peatland biodiversity depends on natural conditions and land use activities in the region. However, one of the common causes of peatland loss everywhere is the under-estimation of their value for biodiversity combined with their vulnerability. Common causes of peatland losses are under-estimation of the value of these ecosystems for biodiversity conservation and human well-being, under-estimation of their vulnerability and sensitivity, and under-estimation of the consequences of human-induced impacts. These common causes are illustrated below for four typical modern situations. In all four situations, human impact is reflected in the loss of habitats, changes in species composition (including invasion by alien species), landscape fragmentation and resulting habitat isolation.

Situation 1: Peatlands are a dominant ecosystem type in the region. Being abundant, they limit socio-economic development and people spontaneously change and destroy them. In areas where peatlands are extensive such as West Siberia, they have a key and mainly negative impact on economic development. Road and other construction works, oil and gas exploitation, agriculture and forestry all need more investment than in other regions. Only those people living in rural areas profit from natural peatland resources, while others develop negative emotional and practical attitudes to peatlands. Socio-economic structures are imported from elsewhere and do not attach value to the goods and services provided by peatland ecosystems. This obstructs the implementation of wise use principles (Plusnin 2001a, 2001b, 2006).

Tropical peatlands are widely distributed but they are concentrated in Southeast Asia. As in West Siberia, the natural values of peatlands are under-estimated, and instead of drawing benefits from them, economic development can lead to the destruction of peatlands and their biodiversity. In Finland too, a significant proportion of the original peatland has been destroyed or severely impacted. Even peatlands in protected areas are partly drained and this has led to a loss of ecosystem services, including carbon accumulation.

Situation 2: Peatlands are not rare in the region. Peatland use often has a long history and can result in serious losses through transformation of these ecosystems. In many regions, peatlands were once common ecosystems. Some of the peatlands have been transformed whilst others remain in a pristine state. Land use has a long history in the region and people have traditionally benefited from using peatlands and their natural resources. Peatlands are integrated into land use schemes and are valued for the goods and services that they provide. At the very least, they are not regarded negatively. Although there are forms of land use (like peat extraction) that clearly have a negative effect on peatlands, other uses like collecting berries and plants are managed at a sustainable level. The benefits of peatlands are more obvious to people in locations where a large fraction of the population uses them (Plusnin 2001b, 2006).

Situation 3: Peatlands are the last available productive ecosystems in the area. Their active use is just beginning, and they are destroyed when some of their basic values became saleable. In many regions, peatlands exist but are not common. Peatlands do not cover a large area in Mongolia, but neither are they very rare in that country. As more and more pastures on mineral soil are overused and degraded (leading to erosion and desertification), pressure on peatlands increases. Peatlands are not recognised as vulnerable and different from grasslands on mineral soil. Additional functions like groundwater recharge, regulation of atmospheric moisture and water retention are not acknowledged, and as a result these functions are often lost through the use of peatlands as pasture in order to make short-term gains. Although they do benefit from peatlands, the population does not recognise them for their specific values. A similar situation applies to peatland used for extraction; the value of energy peat rises when alternative sources of energy are unavailable.

Situation 4: Peatlands are rare and valuable for the conservation of rare species and for tourism and education. Peatlands are very rare in some regions and/or countries, such as Slovakia and the steppe zone of European Russia, and they have very high biodiversity value for such regions. Many of these regionally rare peatlands are under protection, but by no means all of them. One of the reasons is that the general public is often unaware of their value. Even ecologists do not pay special attention to their biodiversity.

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6 Peatlands and Carbon

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Summary points

- Peatland ecosystems (including peat and vegetation) contain disproportionally more organic carbon than other terrestrial ecosystems. In the (sub)polar zone, peatlands contain on average 3.5 times more carbon per ha than ecosystems on mineral soil; in the boreal zone 7 times more carbon; and in the humid tropics as much as 10 times the amount of carbon.
- While covering only 3% of the world's land area, peatlands contain 550 Gigatons (Gt) of carbon in their peat. This is equivalent to 30% of all soil carbon, 75% of all atmospheric carbon, as much carbon as all terrestrial biomass, and twice the carbon stock of all forest biomass of the world.
- This makes peatlands the top long-term carbon store in the terrestrial biosphere and (next to oceanic deposits) the Earth's second most important store.
- Peatlands store carbon in different parts of their ecosystem (biomass, litter, peat layer, mineral subsoil layer, pore water), with each pool having its own dynamics and turn-over. The peat layer is a main long-term store of carbon. Peatlands have accumulated and stored this carbon over thousands of years.
- Almost all coal and lignite and part of the oil and natural gas originated from peat deposits of previous geological periods.
- Permanent waterlogging and consequent restricted aerobic decay is the prerequisite for sequestration and long-term storage of carbon in peatlands.
- Peat sequestration depends on the balance between production and decay. Therefore natural peatlands may shift between being carbon sinks and sources on seasonal and inter-annual time scales, and show variability in carbon accumulation rates during the Holocene. The long-term natural balance is generally positive.
- Carbon may be lost from peatlands through emission of gases (CO_2 and CH_4), efflux of dissolved organic and inorganic carbon, and wind and water erosion of particulate carbon.
- The delicate balance between production and decay causes peatlands to easily become carbon sources following human interventions. Drainage for agriculture, forestry and other purposes increases aerobic decay and changes peatlands from sinks and stores of carbon to (often vigorous) sources. Peat extraction and use transfer carbon to the atmosphere even more quickly.
- Peat oxidation from degraded peatlands leads to an annual CO_2-emission of over 3 Gt, being equivalent to 20% of the total net 2003 GHG emissions of the Annex 1 Parties to the UNFCCC. Peat fires in Southeast Asia (primarily Indonesia) are responsible for half of these global peatland emissions.
- Peatland restoration is an effective way to maintain the carbon storage of peatlands and to re-install carbon sequestration.

6.1 Peatlands and carbon stock

Peatlands are the most space-effective carbon (C) stocks of all terrestrial ecosystems. In the (sub)polar zone, peatlands contain on average at least 3.5 times, in the boreal zone 7 times and in the tropical zone 10 times more carbon per ha than all other ecosystems. Peatlands contain disproportionally more organic carbon than other terrestrial ecosystems (Figure 6.1). In the (sub)polar zone, peatlands (>30 cm peat) contain about 360 t C ha^{-1} (Alexeyev and

Birdsey 1998, corrected to exclude peats <30cm based on Vompersky *et al.* 1996) compared to ecosystems on mineral soil's 92-128 t C ha^{-1} (Alexeyev and Birdsey 1998, the soil carbon estimate [57-89 t C ha^{-1}] includes peat soils with <100 cm peat).

In the boreal zone peatlands contain 1120 t C ha^{-1}, versus non-peatland ecosystems' 289 t C ha^{-1} (IPCC 2001, the latter estimate likely also to include peatland forests). Alexeyev and Birdsey (1998) estimate a C-content of 158 (136-172) t C ha^{-1} in boreal areas of the former Soviet Union. Their soil carbon estimate of 92 (57-105) t C ha^{-1} also includes peat soils.

In the tropical zone, the C-content of rainforests is estimated as between 243 t C ha^{-1} (Dixon *et al.* 1994) and 316 t C ha^{-1} (IPCC 2001). This figure likely includes some peat swamp forest. With a dry bulk density of 0.1 g cm^{-3} (Sorensen 1993), a mean organic C content of 57% (Page *et al.* 2002, Shimada *et al.* 2001) and an estimated mean depth of 5 m (cf. Sorensen 1993), the C-content of peat swamp forest peat is 2850 t C ha^{-1} (cf. Immirzi *et al.* 1992, Diemont *et al.* 1997). Including 124 (Dixon 1993) to 194 (IPCC 2001) t C ha^{-1} of biomass, the total average C-content of tropical peat swamp forest amounts to 3166 t C ha^{-1}.

In comparison to other ecosystems, peatlands have an extra carbon pool: the peat layer. Ecosystems store carbon in various pools, each with their own dynamics and turn-over. The **biomass** pool consists of the living vegetation (leaves, stems, trunks, branches, roots). The **litter** pool consists of dead trees, dead roots, fallen wood, dead fallen leaves and twigs. The **mineral soil** pool consists of the dead organic matter (humus) in the mineral subsoil. Compared to these pools that they share with

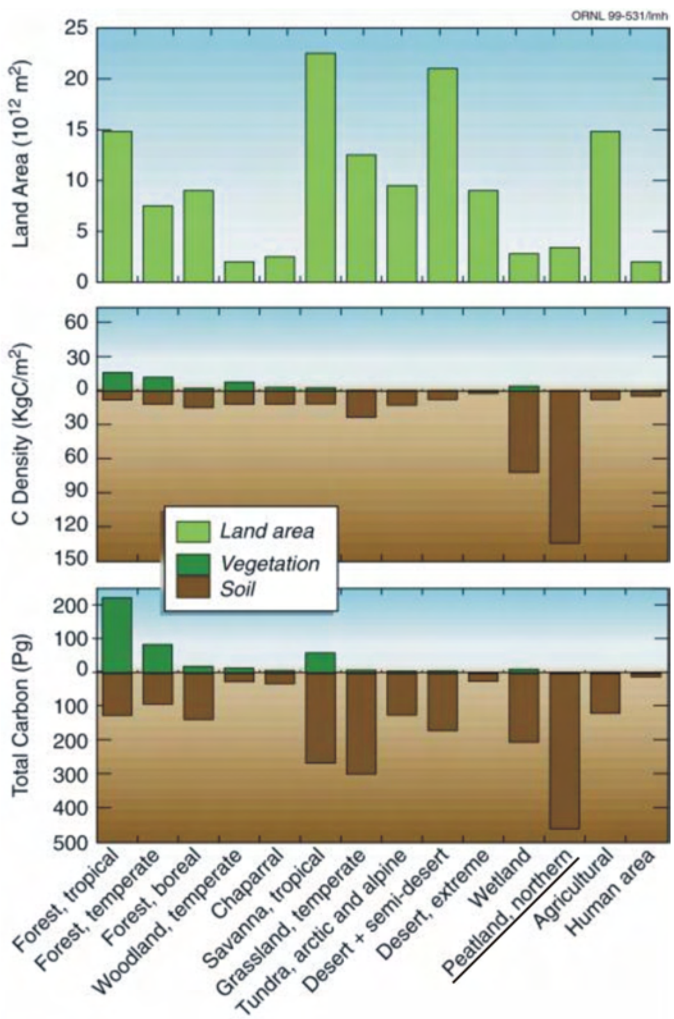

Figure 6.1: Land Area, Carbon density, and Total Carbon Pool of the major terrestrial biomes (Source: http://csite.esd.ornl.gov/faqs.html).

other terrestrial ecosystems, peatlands have an extra carbon pool: the **peat** layer.

The huge carbon stock of peatland ecosystems is attributable to the often thick layers of peat. Peat largely consists of organic material with a carbon content of over 50%. Peat is a highly concentrated stockpile of carbon because it consists by definition of more than 30% (dry mass) of dead organic material (Joosten and Clarke 2002), that contains 48–63% of carbon (Heathwaite and Göttlich 1993). The peatlands of the world hold a carbon pool in their peat of an average 1375 t C ha^{-1} (550Gt / 400 10^6 ha, see below, cf. Gorham 1991, Botch *et al.* 1995, Vompersky *et al*. 1996, Lappalainen 1996, Sheng *et al*. 2004). This huge peat stock (that other ecosystems do not possess) causes peatlands to have total carbon pools that greatly exceed those of other terrestrial ecosystems. Only the Giant Conifer Forest in the Pacific West of North America reached in its pre-anthropogenic past (and over a very small area) a total carbon stock per ha that equalled half of that of the average peatland of the world (Table 6.1).

While covering only 3% of the world's land area, peatlands contain 550Gt of carbon in their peat. The peatlands of **Canada** (≥ 40 cm of peat) are estimated to contain 147 Gt of carbon in their peat (Tarnocai 2006). For the peatlands (≥ 30 cm of peat) of **Russia,** Vompersky *et al.* (1996) give a figure of 101 Gt of peat carbon and an additional 13 Gt for peatlands with < 30 cm of peat. Efremov *et al.* (1998) estimate the total carbon store of the peat deposits of Russia is more than 118 Gt. In a detailed analysis, Sheng *et al.* (2004) arrived at an estimate of a total peat carbon pool of 70 Gt, against 40–55 Gt in previous estimates for the peatlands with > 50 cm peat of the **West-Siberian lowlands**. If this divergence is systematic, the quoted estimates of Vompersky et al. 1996 for all of Russia would have to be increased to 176 Gt and those of Efremov *et al.* to 161 Gt. Stolbovoi (2002) gives a figure for the Russian peat carbon pool of 156 Gt C in the upper 0–2.0 m layer. Botch *et al.* (1995) calculate a carbon stock of 215 Gt in the peatlands of the **Former Soviet Union** (including Russia and the Newly Independent States). For the boreal and subarctic zones,

Table 6.1: Average carbon stocks of selected natural (pre-anthropogenic) ecosystems (in t C ha^{-1}) (after www.esd.ornl.gov/projects/qen/carbon3.html) compared to that of the average peatland of the world. Italics = also includes some peatland; n.a. = non applicable.

Ecosystem type	**Vegetation**	**Litter**	**Soils**	**Peat**	**Total**
Peatland	25[1]	0	50[2]	1375	1450
Giant Conifer Forest	350	256	120	n.a.	726
Warm Temperate Forest	190	36	145	n.a.	371
Cool Temperate Forest	160	25	140	?	325
Tropical Rain Forest	210	10	100	?	320
Main Taiga	82	15	219	?	320
Southern Taiga	140	15	135	n.a.	290
Tropical Montane Forest	130	15	130	?	275
Moist Steppe	10	0	250	n.a.	260
Forest Steppe	10	11	220	n.a.	241
Lowland Tundra	10	0	210	?	220
Forest-Tundra	11	20	166	?	197
Open Boreal Woodland	50	15	129	?	194
Mediterranean Forest	100	8	80	n.a.	188
Mediterranean Scrub	40	5	60	n.a.	105
Temperate Scrub	45	5	45	n.a.	95
Tropical Savanna	35	0	55	n.a.	90
Dry Steppe	6	0	70	n.a.	76
Temperate Semi-Desert	4	0	56	n.a.	60
Montane/Dry Tundra	5	0	50	n.a.	55
Tropical Grassland	12	0	42	n.a.	54
Desert	1	0	0	n.a.	1

[1)] Global average from solely moss-covered peatlands to tropical rain forest swamps with high trees, cf. Gorham 1991; [2)] Estimate based on Turunen *et al.* 1999, Moore and Turunen 2004.

Gorham (1991) arrives at a peat carbon store estimate of 461 Gt, whereas Turunen *et al.* (2002) estimate 270-370 Gt.

Gajewski *et al.* (2001) estimate the C store in **Northern Hemisphere Sphagnum peatlands** to be 455 Gt. The **tropical peatlands** may contain 100 Gt or more of peat carbon (H. Faure, unpublished calculations, www.esd.ornl.gov/projects/qen/Lena.html). For Southeast Asia, the latest data point at a peatland carbon stock of at least 42 Gt (Parish and Canadell 2007). Immirzi *et al.* (1992) give for the total global peat carbon stock a value of 329–525 Gt. Estimates of global peat carbon stocks generally suffer from a lack of adequate inventories in large parts of the world, especially with respect to the depth and dry bulk densities of global peat deposits (Turunen *et al.* 2002).

The carbon content of global peat is equivalent to 30% of all global soil carbon, 75% of all atmospheric carbon, equal to all terrestrial biomass, and twice the carbon stock in the forest biomass of the world. This makes peatlands the top long-term carbon stock in the terrestrial biosphere. Carter and Scholes (2000) estimate the global **soil** carbon stock for the top one metre to be 1,567 Gt. The soil carbon stock is estimated to be 1,502 Gt at 0-1 m depth, 491 Gt between 1–2 m depth, and 351 Gt at 2-3 m depth by Jobbágy and Jackson (2000). The **atmosphere** contained (in 1990) 750 Gt of carbon, mainly as CO_2 and CH_4 (Houghton *et al.* 1990). The global **terrestrial plant biomass** carbon stock is estimated to be 654 Gt (IPCC 2001). Kauppi (2003) estimates the **tree biomass** of the world's forests to contain 300 Gt of carbon, whereas the Millenium Ecosystem Assessment estimates the total **forest biomass** in the world to hold 335–365 Gt of carbon (Shvidenko *et al.* 2005).

Peatlands have produced and stored this peat over thousands of years. The peatlands existing today largely originated at the end of the Late-Glacial and in the first part of the Holocene and have continued to accumulate since then (Halsey *et al.* 1998, Campbell *et al.* 2000, MacDonald *et al.* 2006). Peatlands have in the past 15,000 years withdrawn enormous amounts of carbon dioxide from the atmosphere and stored it in their peat deposits. Some scientists consider carbon sequestration in peatlands during interglacials as a major cause of decreasing atmospheric CO_2 concentrations and as an important trigger for the onset of glaciations (Franzén 1994, Franzén *et al.* 1996, Yu *et al.* 2003, cf. Rodhe and Malmer 1997, Franzén 1997).

Peatlands store an enormous amount of carbon

Coal and lignite and part of the "mineral" oil and natural gas originate from peat from previous geological periods. Most fossil fuels (all coal and lignite, and some oil and natural gas) originate from peat deposits of previous epochs. Much Carboniferous coal has accumulated in environments analogous to the modern peat swamp forests of Southeast Asia (Moore 1987, 1989, Cobb and Cecil 1993, Greb *et al.* 2006), whereas much Permian coal originated under cool-temperate and even permafrost conditions (Greb *et al.* 2006). About 15% of the world's petroleum originates from former peatlands in deltaic and lacustrine environments (Demaison 1993, Taylor *et al.* 1998). Lignite and coal are formed when peat is physically and chemically altered in a process called "coalification". Burial squeezes water out of the peat, while heat and time causes the hydrocarbon compounds to break down and change. The gaseous products (e.g. methane (Kopp *et al.* 2000)) are expelled. During the successive stages of coalification (from plant debris, via peat, lignite, sub-bituminous coal, bituminous coal, anthracite coal, to eventually graphite, Taylor *et al*. 1998), the other elements gradually disappear, the carbon fraction increases, and the mass of the deposit is reduced (Dukes 2003, Figure 6.2).

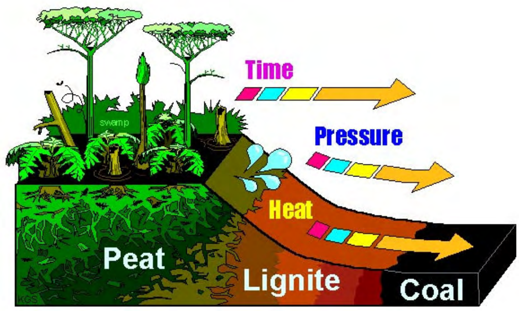

Figure 6.2: The development of coal from peat (www.uky.edu/KGS/coal/coalform.htm).

The slow rate of renewal of peat implies that it should be treated as a non-renewable resource. Peat has been forming at least since the Late-Devonian (385 to 359 million years ago, (Greb *et al.* 2006)) and it is still being formed today. Part of the present-day peat is at this moment changing into lignite and will change into new coal in future. Similar to lignite and coal, peat is renewable. Coal and lignite are, however, *called* "non-renewable" because their slow rate of renewal makes their renewability *irrelevant* for humankind. The volume of old coal currently being burnt is many orders of magnitude larger than the volume of new coal currently being formed. Peat has been classified as a "slowly renewable biofuel" because its rate of renewal is much faster than that of lignite and coal, but much slower than that of living plants (cf. Table 6.2). From a climate change point of view, such classification is misleading, since – to be carbon neutral – renewable resources must replenish as quickly as they are consumed. Global peat losses exceed the new formation of peat by a factor of 20 (see below), so the use of peat contributes as equally to the greenhouse effect as other fossil resources. Therefore it is more appropriate to treat peat – similar to lignite and coal – as a non-renewable resource.

"Observations at the Aitape coast (New Guinea) indicate that in this area, peatlands are rapidly and regularly covered by marine clastic sediments resulting from at least 4 m subsidence in the last 970-1100 years" (www.dpiwe.tas.gov.au/inter.nsf/ WebPages/UTAR-52X8LP?open).

"Holocene to modern peat is also widespread along the Guyana and Suriname (Guiana) coastal plain adjacent to and southeast of the Orinoco Delta. Studies of the Orinoco Delta and Guiana coastal plain would provide valuable insight into environmental conditions conducive to widespread peat, and ultimately coal, development" (Warne *et al.* 2001).

From a climatic point of view peat is clearly a 'fossil fuel', not a 'biofuel'. Combustion of peat releases carbon from a long-term store. Without exploitation the peat carbon would remain in this store more or less indefinitely. Here lies the fundamental difference between 'biomass' fuels and 'fossil' fuels (like peat and coal).

By burning biomass fuels (like wood and straw), organic material is oxidized that anyhow would have been oxidized by decay after the plant's death. In the case of biomass combustion, humans consume the energy, whereas in the case of natural decay, microbes consume the energy provided by oxidation. In both cases the same amount of CO_2 ends up in

Table 6.2: Age and turn-over time of selected types of fuel. Within parentheses: maximum age (after Joosten 2004). The distinction between peat, lignites, and coals is made on the basis of carbon content (Asplund 1996).

Fuel type	Age	Turn-over time
	Years	
Reed, straw	0.5 – 3	$10^{-1} – 10^{0}$
Willow coppice	1 – 5	$10^{0} – 10^{1}$
(Living) wood	5 – 100 (- 5 10^{3})	$10^{1} – 10^{2}$ (- 10^{4})
Peat	100 – 120 10^{3} (-10 10^{6})	$10^{2} – 10^{5}$ (- 10^{7})
Lignite	0,1 – 50 10^{6}	$10^{5} – 10^{8}$
Coal	20 – 325 10^{6}	$10^{7} – 10^{8}$
Oil shale	65 – 500 10^{6}	$10^{8} – 10^{9}$

the atmosphere, only the pathways are different.

Fossil fuels, on the contrary, would – without exploitation – remain in the long-term store and not end up in the atmosphere as CO_2. By burning peat, organic material that otherwise would have remained stored for thousands and thousands of years is oxidized. This applies whether the peat is 10 or 1,000 or 100,000 years old. It is not *age* that determines whether something is 'fossil' or 'biomass', but the *natural destiny* of the material. Similar to coal, lignite or oil, the natural destiny of peat carbon is to remain stored.

6.2 Carbon accumulation in peatlands

As the rate of carbon sequestration in natural peatlands is larger than the total rate of carbon losses, their carbon stock continues to increase. In all terrestrial ecosystems, plants convert atmospheric CO_2 into plant biomass that after death rapidly decays under the influence of oxygen. In peatlands the dead plant material is subject to aerobic decay only for a limited time, because it soon arrives in a permanently water-logged, oxygen-poor environment, where the rate of decay is orders of magnitude lower (Ingram 1978, Ivanov 1981, Clymo 1984). When the aerobic layer is thin, a large proportion of dead plant material is conserved. When the layer is thick (only temporarily), more material is decomposed with less remaining as peat. When the aerobic layer is too thick, no peat accumulates at all (Belyea and Malmer 2004). The permanently anaerobic layer, the so-called catotelm, is the true site of peat accumulation. Approximately 5–15% of the net produced biomass is sequestered in the catotelm in the long term (Clymo 1984, Moore 1987, Gorham 1991, Warner *et al.* 1993, Francez and Vasander 1995).

Also in the catotelm, slow decomposition takes place. As the catotelm becomes thicker, total carbon losses increase, because there is more peat to decay (Clymo 1984, Hilbert *et al.* 2000). On the other hand, as the easily degradable substances are decomposed first, the rate of decay slows down with increasing age of the peat (Tolonen *et al.* 1992, Figure 6.3). Because of continuous decay, the peat store would, without continuous addition of new organic material from above, diminish, slowly but inevitably. Active peat formation in living peatlands is therefore a prerequisite for the long-term maintenance of the peat carbon store.

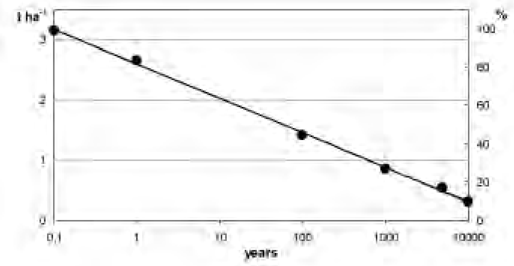

Figure 6.3: Remaining part of net primary production in time (after Gaudig and Joosten 2002). Note the logarithmic scale of the x-axis.

Peat accumulation shows a strong local and regional variation. Peat accumulation rates are dependent on climatic, hydrologic and hydrochemical conditions. In general peat accumulation rates increase from nutrient rich to nutrient poor, from polar to equatorial, and from continental to oceanic conditions (Turunen and Tolonen 1996, Turunen *et al.* 2002, Prager *et al*. 2006).

The rate of peat accumulation is expressed in many different ways, all with their own values. The "REcent Rate of Carbon Accumulation" (RERCA) refers to the fresh peat that is annually added to the peatland system. Depending on the mire type and the geographical location, RERCA generally ranges from 10 to 450 g C m^{-2} yr^{-1} in boreal and temperate regions (Joosten 1995, Tolonen and Turunen 1996, Ohlson and Okland 1998, Camill *et al.* 2001, Mueller *et al*. 2003, Turunen *et al.* 2004). The RERCA, however, does not adequately express the amount of peat that is accumulating; it neglects the peat losses from the deeper layers that are simultaneously taking place.

The **"Actual true net Rate of Carbon Accumulation" (ARCA)** integrates these gains and losses. ARCA can be determined by measuring the total (gaseous, dissolved and particular) carbon fluxes in and out of a peatland (cf. Waddington and Roulet 1996; Carroll and Crill 1997, Worrall *et al*. 2003b, Roulet *et al.* 2007, Table 6.3). Because of this complexity and its momentary character, ARCA is often approached via peat accumulation models (Clymo 1984, Clymo *et al.* 1998, Frolking *et al*. 2001, Yu *et al.* 2001).

The ARCA for boreal and subarctic peatlands has been estimated as 21 g C m^{-2} yr^{-1} (Clymo *et al.* 1998), or 2/3 of LORCA (Tolonen and Turunen 1996).

The most common measure is the **"LOng-term apparent Rate of Carbon Accumulation" (LORCA)** (Figure 6.4). LORCA arrives at a sort of long-term mean accumulation rate by dividing the total carbon mass in a column of peat by the total number of years the column represents. LORCA values in the subarctic, boreal and temperate zone are generally in the order of magnitude of 10–40 g C m^{-2} yr^{-1} (Clymo *et al*. 1998, Turunen *et al.* 2002, 2004, Figure 6.4), but may reach values of 100–200 g C m^{-2} yr^{-1} in temperate and tropical swamp forest peatlands (Prager *et al.* 2006, Sorensen 1993, Neuzil 1997, Page *et al.* 2004). LORCA provides insight into the balance between long-term input and decay but is misleading because of the ongoing decay in the catotelm.

Peat accumulation rates expressed in mm/yr are – similar to LORCA – calculated by dividing the total thickness of a column of peat through the total number of years represented in the column. Height increase is typically 0.5–1.0 mm yr^{-1} (Gorham 1991, Couwenberg *et al.* 2001, Lavoie *et al.* 2005). As peat largely consists of water, height increase is only a very crude way of expressing peat accumulation rates.

The present-day rate of C sequestration in the pristine peatlands of the world is less than 100 Mt C y^{-1}. Botch *et al.* (1995) present a total rate of carbon accumulation in the peatlands of the former Soviet Union of 52 Mt C yr^{-1}. Turunen *et al.* (2002) provide a figure of 66 Mt C yr^{-1} for the Boreal and Subarctic zones in which the majority of the world's peatlands are situated. Over a large part of the permafrost peatlands, where peat accumulation is anyhow slow, net accumulation has stopped because of natural processes and recent climate change (Vitt and Halsey 1994, Oechel *et al.* 1993, 1995). Similarly in the tropics, where accumulation rates per ha may be higher (Page *et al*. 2004), a substantial area of the undrained pristine peatland no longer accumulates peat (Sieffermann *et al.* 1988). In the temperate zone pristine peatlands have become rare. Worldwide, the remaining area of pristine peatland (>3 million km^2, see chapter 2) will therefore presently sequester less than 100 Mt C y^{-1}.

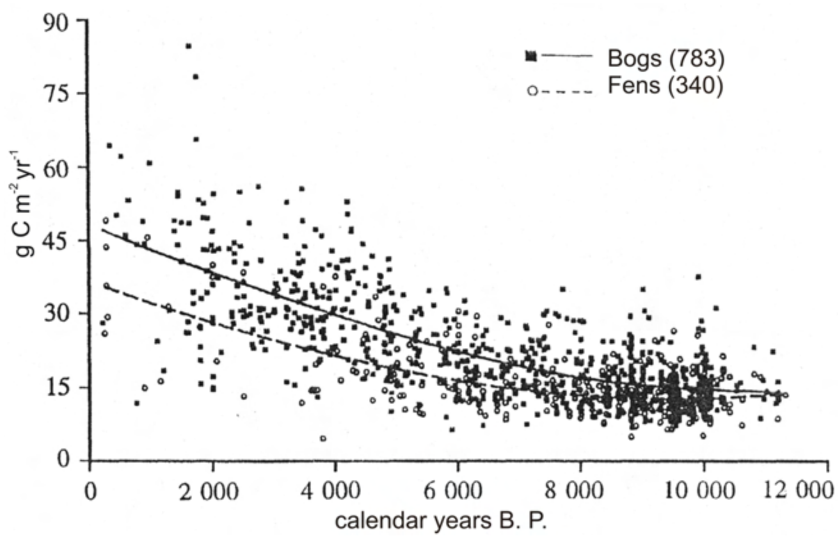

Figure 6.4: Long-term apparent rate of Carbon accumulation LORCA peat accumulation rates from Finland (Clymo et al. 1998). Note how the rates in younger peatlands are larger because LORCA approaches RERCA.

6.3 Carbon losses from peatlands

Carbon losses from peatlands take place in the form of C-gases and as dissolved and particulate material. Gaseous carbon flux largely takes place in the form of carbon dioxide and methane. CO_2 exchange is determined by the balance of carbon fixation by photosynthesis and carbon released through plant respiration and the mineralization of peat carbon. The latter is strongly controlled by the water table and temperature (Charman 2002). Peat fires may lead to enormous emissions of carbon gases. Methane production by bacteria under anaerobic conditions is controlled by the temperature (Dise *et al.* 1993) and water table (Bubier *et al.* 1993).

Peat accumulation and population growth

A comparison with population growth may be helpful to explain the different ways of expressing peat accumulation.

The "recent rate of C accumulation" (RERCA) can be compared to the birth rate in a human population. The birth rate does not give information on net population growth, because the latter is also influenced by mortality and emigration/immigration. Similarly the RERCA gives no adequate information on peat accumulation because it neglects carbon losses by decay and other emissions.

Actual population growth, as a function of all population gains and losses, can be compared to the "actual net rate of C accumulation" (ARCA) that integrates all carbon gains and losses.

LORCA is similar to determining long-term population growth by taking the sum of all individuals in a population and dividing that sum by the age of the oldest individual. In a population with high infant mortality (cf. the enormous losses of organic matter in a peatland in the first years, Figure 6.3) the inclusion of the many newborns gives an overly positive view of population growth.

Loss of **Dissolved Organic Carbon (DOC)** from peatlands is well-studied (Urban *et al.* 1989, Sallantaus 1992, 1995, Dosskey and Bertsch 1994, Sallantaus and Kaipainen 1996), also because of the impact of associated water colour problems on the water supply industry (Hope *et al.* 1997a, Freeman *et al.* 2001, Neal *et al.* 2005, Worrall *et al.* 2004a, 2004b, Evans *et al.* 2005c). Export from temperate peatlands ranges between 10 and 500 kg DOC ha^{-1} yr^{-1} (e.g. Dillon and Molot 1997). The aerobic zone of drained peat soils is a significant source of DOC (Kalbitz and Mutscher 1993, Chow *et al.* 2006). A portion of the DOC is transported downstream and some is oxidized and lost to the atmosphere as CO_2 (Billet *et al.* 2004, Dawson et al. 2004). Part also precipitates in the mineral subsoil under the peatland (Turunen *et al*. 1999).

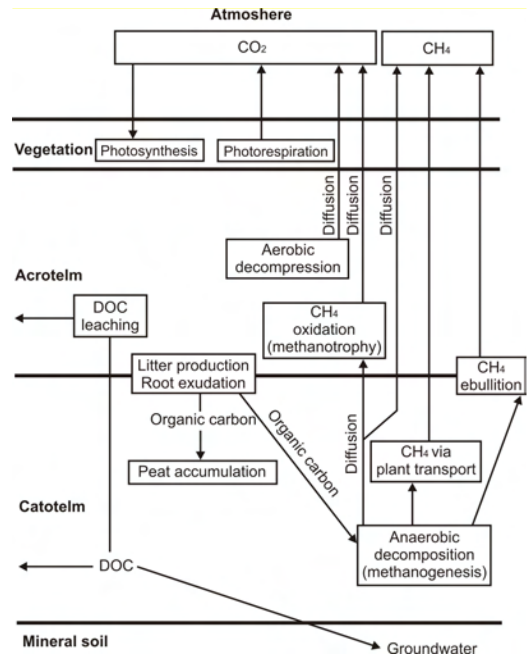

Figure 6.5: Components of the peat carbon cycle (from Faubert 2004)

Dissolved Inorganic Carbon (**DIC**) is the least studied component of the carbon flux and is a relatively small component of the overall flux (Worrall *et al.* 2003b). Modelling suggests that DIC production is largely controlled by temperature (Worrall *et al*. 2003b).

Fluxes of **Particulate Organic Carbon** (**POC**) are largely caused by physical erosion of the peat surface and controlled by vegetation cover (Evans *et al.* 2005a, Holden *et al.* 2006). POC release from UK upland peatlands ranges from 1 kg ha^{-1} yr^{-1} in intact (Hope *et al.* 1997b) to 100 kg ha^{-1} yr^{-1} in heavily eroding peatlands (Evans *et al.* 2006). In severely eroding peatlands, fluvial POC losses may be the largest single component of carbon mass budgets (Holden *et al.* 2006). POC may be buried in anoxic conditions in lakes or reservoirs, but may also be rapidly oxidised in the fluvial system (Pawson *et al.* 2006).

Table 6.3 presents the complete carbon budget of a small upland blanket peat catchment from the North Pennines (UK). The largest single component of the budget is the fixation of carbon.

Peat sequestration thus depends on the delicate balance between production and decay and other losses of organic material. Thus, natural peatlands may shift between being carbon sinks and sources on seasonal and inter-annual time scales and show variability in carbon accumulation rates during the Holocene. The long-term natural balance is positive. As only a small proportion of the peatland biomass enters the anaerobic zone, peat sequestration is a matter of a delicate imbalance of production and decay. Many peatlands may be close to the tipping point between carbon sources and carbon sinks (cf. Holden *et al.* 2006). High-resolution peat records reveal changes in peat carbon accumulation rates during the Holocene on millennial and century scales related to climate change. Peatland carbon sequestration rates may be highly sensitive even to minor climatic fluctuations (Yu *et al.* 2003) and show considerable year-to-year variability (Roulet *et al.* 2007) including short-term negative rates (Alm *et al*. 1999).

Table 6.3: Carbon balance for a small blanket peatland, Trout Beck catchment in the Northern Pennines (UK) (after Worrall et al. 2003b). The catchment has been significantly affected by gully erosion, and parts are affected by land drainage.

Flux	**Aerial Flux**	**Range**
	gC m^{-2} yr^{-1}	
Rainfall DIC	1.1	
Rainfall DOC	3.1	
CO_2	55	40 to 70
CH_4	-7.1	-1.5 to -11.3
DOC	-9.4	-9.4 to -15
POC	-19.9	-2.7 to -31.7
Dissolved CO_2	-3.8	-2 to -3.8
DIC	-5.9	-4.1 to - 5.9
Weathering DIC	1.8	0 to 1.8
Total	14.9	13.8 ± 15.6

6.4 Human impact on peatland carbon

The delicate balance causes peatlands to easily become carbon emission sources following human interventions, especially drainage. Lowering of the water table in peatlands stimulates decomposition rates. The oxygen allows aerobic decomposition to take place, which occurs fifty times faster than anaerobic decomposition (Clymo 1983). CO_2 emissions from drained peatlands generally increase with increasing drainage depth and warmer climates (Figure 6.6).

Peatland agriculture, especially when associated with drainage, leads to substantial losses of peat through mineralization and erosion. "Peat is a wasting asset – it can be drained and farmed only at the cost of its inevitable destruction" (Waltham 2000). Under **grassland**, drained bogs and fens in the boreal and temperate zones lose approximately 2.5 and 3.5 tons of C ha^{-1} yr^{-1} respectively (Joosten and Clarke 2002, Schipper and McLeod 2002). The highest mineralization rate is observed with a water table depth of 80–90 cm. At deeper water levels, drought inhibits peat mineralization again (Mundel 1976, Wild and Pfadenhauer 1997).

Under **arable farming** associated with tillage, peat mineralization is accelerated compared to grassland due to more intensive aeration (Joosten and Clarke 2002). When the soils are left bare, arable farming may lead to additional losses of particular carbon through water and wind erosion (Holden *et al.* 2006). Also irrigation encourages erosion (Evans 2005b).

Livestock production and overgrazing in undrained peatlands can also lead to erosion and consequent carbon losses (Harrod *et al.* 2000, Huang and O'Connell 2000, McHugh *et al.* 2002, Evans *et al.* 2005b), especially in many upland peat areas (Meakins and Duckett 1993, Schwabe 1995, Backshall *et al.* 2001, Joosten in press). Overgrazing leaves bare organic surfaces that are susceptible to erosion by water and wind. Poorly drained peats on flat or gentle slopes are particularly vulnerable (Evans 1997), as animal hooves cut through the vegetation into the underlying peat (Evans 2005a). In Ireland large increases in organic - rich sediments in lakes have been attributed to increasing numbers of sheep (Holden *et al.* 2006).

Many upland peatlands in Britain are managed as grouse moors that require **rotational burning** to ensure heather regeneration. Garnett *et al.* (2000) found that this burning reduces peat accumulation. Mismanaged burning can remove all surface vegetation, making the underlying peat susceptible to erosion (Radley

1965, Mallik *et al.* 1984, Rhodes and Stevenson 1997, Glaves and Haycock 2005, Holden *et al.* 2006) and – in the case of deep water levels – vulnerable to unintentional peat fires (Watson and Miller 1976, Maltby *et al.* 1990).

Biomass fuels cultivated on drained peatland lead to higher CO_2 emissions than fossil fuels. To reduce anthropogenic CO_2 emissions, fossil fuels are increasingly substituted by biomass fuels. As a consequence, the demand for arable land has grown, and with it the pressure on marginal lands, including peatlands. Cultivation of biomass crops on peat soils is usually associated with drainage. Drainage leads to oxidation of the peat and subsequent release of CO_2 to the atmosphere. In many cases CO_2 emissions from degraded peat soils exceed the amount of CO_2 offset by the substitution of fossil fuels. The use of biomass fuels cultivated on peat soils then leads to a net-increase in CO_2 emissions compared to the use of fossil fuels (Table 6.4, Couwenberg 2007).

An innovative, carbon-saving alternative to drainage-based peatland agri- and silviculture is 'paludiculture': the sustainable production of biomass on wet peatlands. Paludiculture is the cultivation of biomass on wet and rewetted peatlands. Ideally the peatlands should be so wet that steady (long-term) peat accumulation is maintained or re-installed. Paludiculture uses only that part of net primary production (NPP) that is not necessary for peat formation (which is ca. 80-90% of NPP). In the temperate, subtropical and tropical zones of the world, i.e. those zones where high production is possible, most peatlands naturally support vegetation of which the belowground parts (rootlets, roots, and rhizomes) produce peat, while the aboveground parts can be harvested without harming the peat sequestering capability. Pilot projects in Europe with a (large) positive effect on the peatland carbon balance include the cultivation of reed (*Phragmites*), cattail (*Typha*), sedges (*Carex*), alder (*Alnus*), reed canary grass (*Phalaris*) and peatmoss (*Sphagnum*) on rewetted degraded peatlands (Wichtmann and Joosten 2007).

When peatland is drained for forestry, various processes with contrasting effects occur simultaneously. The integrated effects differ considerably in different areas and over different time-scales (Crill et al. 2000, Joosten 2000). After drainage, increased aeration of the peat results in faster peat mineralization (cf. Moore and Dalva 1993, Silvola *et al.* 1996) and a decrease in the **peat carbon store**. In the boreal zone this aeration may be accompanied by a lowering of the peat pH and temperature (Laine *et al.* 1995, Minkkinen *et al.* 1999), which may again reduce the rate of peat mineralization. After drainage, forest vegetation (trees and shrubs etc) takes the place of the original, lower and more open, mire vegetation. The increased interception and transpiration add substantially to the lowering of the water table, often even more than drainage (Pyatt *et al.* 1992, Shotbolt *et al.* 1998). The peatland **biomass carbon store** (both above and below ground) increases quickly (Laiho and Finér 1996, Laiho and Laine 1997, Sharitz and Gresham 1998). This store eventually reaches a new equilibrium that is much higher than that of the pristine peatland. Before this stage is reached however, the wood is normally harvested and the biomass store is once again substantially reduced.

Peatland drainage for forestry also leads to changes in the **litter carbon store**. The "moist litter" in the upper layer of a pristine peatland is generally considered part of the peat, as it

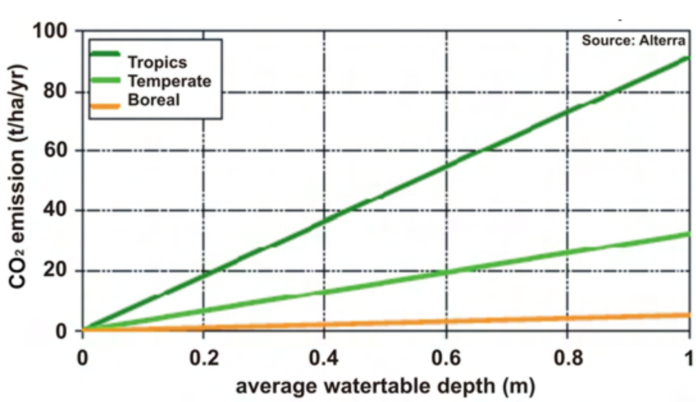

Figure 6.6: Peatland CO_2 emissions as a function of drainage depths and climate (Hooijer et al. 2006).

gradually passes into the catotelm peat. The litter in a drained forest (consisting of remains of conifer needles, branches, rootlets, forest mosses etc) is of different quality (Berg *et al.* 1993, Laiho and Laine 1996, Couteaux *et al.* 1998, Laiho *et al*. 2004) and can be considered a separate component. The accumulation of litter leads to an increase in the litter carbon store, also in the uppermost soil layer (Cannell and Dewar 1995, Domisch *et al.* 1998, Minkkinen and Laine 1998). The forest litter, enriched with lignin, is rather resistant to decay (e.g. Melillo *et al.* 1982, Meentemeyer 1984), but as it accumulates largely under aerobic conditions, the litter carbon store eventually reaches equilibrium and net accumulation stops. Depending on the peatland type and the cutting regime of the forest, it might take centuries before this equilibrium is reached. Peatland drainage for forestry therefore leads to:

- a steady decrease in the peat carbon store,
- a rapid initial increase in the biomass store, the harvesting of which leads to a typical saw-tooth curve of the carbon biomass store (Figure 6.7), and
- a slow initial increase in the peatland litter store, which eventually, after some centuries, reaches an equilibrium.

The **peatland carbon store**, being the combined effect of these processes, therefore varies strongly in time and space. In boreal and Atlantic peatlands, the increase in above- and below-ground biomass (Sharitz and Gresham 1998, Laiho *et al.* 2003) and litter stocks (Laiho and Finér 1996, Laiho and Laine 1997, Finér and Laine 1998) may strongly exceed the losses from the peat carbon store (Minkkinen *et al.* 1999) in the first period after drainage (Crill *et al*. 2000, Hargreaves *et al.* 2003). As the biomass and litter stores tend towards an equilibrium but the peat carbon losses continue, cumulative carbon losses from peat oxidation prevail over the long term (Cannell *et al.* 1993; Laine and Minkkinen 1996, Minkkinen and Laine 1998, Minkkinen 1999) (see Figure 6.7).

In temperate fens, drainage for forestry leads to large ecosystem carbon losses through increased peat mineralization (Janiesch *et al.* 1991, Kazda 1995, Siemens 1996, Münchmeyer 2000, Schäfer and Joosten 2005, cf. von Arnold *et al.* 2005, Minkkinen *et al.* 2007). Only in exceptional cases, under very shallow drainage, peat accumulation may increase because of the strongly enhanced production of lignin rich biomass (Schäfer and Joosten 2005, Prager *et al*. 2006).

In subtropical and tropical peatlands, forestry leads to rapid carbon losses through drainage. In these areas even the mere harvesting of wood (without drainage) may lead to peat carbon losses as it decreases organic matter inputs and increases radiation and consequent peat decomposition (Brady 1997).

Peat extraction rapidly removes carbon from the peatland carbon store and furthermore leads to substantial losses of carbon from the extraction site by stimulating decomposition and erosion. Extraction of peat for fuel, horticulture, landscaping and other purposes rapidly removes carbon from the peatland, leading to a loss of 50 kg C m^{-3} of extracted peat (Hillebrand 1993, Rodhe and Svensson 1995), or 20–35 tons of carbon per ha/yr in modern peat fields (Cleary *et al.* 2005). Peat

Table 6.4: Energy yield and emission factor of typical biomass fuel crops on peat soil, compared to fossil fuels (after Couwenberg 2007).

	Fuel	Net yield [GJ ha^{-1} yr^{-1}]	Emission factor [t CO_2/TJ]
Biomass fuels	Palm oil (SE Asia)	-	600
	Maize, net energy (Germany)	165	240
	Maize, biogas (Germany)	45	880
	Miscanthus, net energy (Germany)	213	115
	Miscanthus, hydrogen (Germany)	4	625
	Sugar cane, ethanol (Brazil)	140	570
	Sugar cane, net energy (Florida)	155	350
	Coniferous wood, net energy (Scandinavia)	15	225
Fossil fuels	Peat	-	106
	Coal (anthracite)	-	98
	Fuel oil	-	73
	Natural gas	-	52

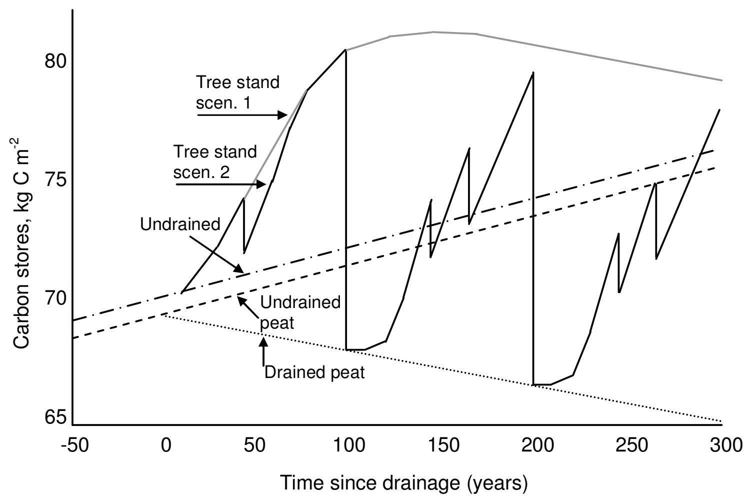

Figure 6.7: Dynamics of the carbon stores of an oligotrophic tall sedge pine fen site during the first 300 years after drainage. Tree stand scenario 1: Total carbon store of an untreated drained tree stand. Tree stand scenario 2: Total carbon store of a drained production forest. Tree stand stores are shown as the difference between the total (continuous line) and peat store lines (dashed line). (From Laine and Minkkinen 1996).

extraction also leads to substantial carbon losses through vegetation removal during site preparation, drainage of the extraction site and its surroundings, the peat collection process (e.g. milling which increases aeration and oxidation of the upper peat layer) and storage (in stockpiles) (Sundh *et al.* 2000, Crill *et al.* 2000, Waddington *et al*. 2002, Cleary *et al*. 2005). In addition, the bare dark and lightweight soils are easily warmed up and susceptible to wind and water erosion (Holden *et al.* 2006)

Both peat fuel combustion and the use of nonfuel peat in horticulture, landscaping, and gardening lead to immediate or rapid release of peat carbon as CO_2 to the atmosphere. After extraction, the extracted peat is immediately (fuel peat) or within some years (horticultural peat) completely mineralized through oxidation. Life-cycle analysis showed that the final decomposition of peat products makes up 71% of the total atmospheric carbon release of nonfuel peat extraction in Canada (Clearly *et al*. 2005). Land use change (removal of vegetation etc), the transport of peat to the market, and extraction and processing activities comprise 15%, 10%, and 4% respectively. Peat used in horticulture, landscaping, greenhouse cultivation and for other agricultural purposes, quickly decomposes in a well-aerated environment. The vast majority of such peat is mixed with other substances such as lime, fertilizer and soil, which increase peat decomposition rates (Murayama *et al.* 1990). Most nonfuel peat extraction results in CO_2 emissions within some years. This also accounts for peat used for bedding, filter and absorbent material, chemistry, balneology, medicine and body care (Joosten and Clarke 2002). An exception is peat used for long-lasting products like building and insulation material and peat textiles, but their volumes are very small (Joosten and Clarke 2002).

Abandoned peat extraction sites that are not rewetted remain important sources of carbon emissions. Many peatlands previously used for peat extraction and agriculture, especially in Eastern Europe, are now abandoned and have an unclear status. Often the peat surface remains without vegetation for many years after extraction has stopped. The dry conditions resulting from intensive drainage causes rapid peat decomposition, frequent fires, and large carbon emissions. On abandoned agricultural sites peat decomposition is additionally stimulated by the high nitrogen content from fertilisation and inputs from agricultural crops.

Intensive recreational use of peatlands may lead to peatland erosion. Peatland erosion due to human traffic on footpaths is, for example, a widespread problem in England and Wales

(Bayfield 1987, Grieve *et al.* 1995). Similar effects are observed as a result of alpine and cross-country skiing in several countries.

Peat fires following anthropogenic peatland drainage are globally important, with a current estimated annual CO_2 emission of 1.5 Gt. Whereas peatland fires in many regions of the world have played an important role in natural peatland dynamics (Brown 1990, Kangas 1990, Paijmans 1990, Kuhry 1994, Frost 1995, Zoltai *et al.* 1998), human activities have severely increased their frequency, intensity and extent. Page *et al*. (2002) estimate that the 1997 fire season led to an emission to the atmosphere of between 0.81 and 2.57 Gt of carbon from peatland fires in Indonesia. CO_2 emissions due to peatland fires in Indonesia over 1997-2006 are estimated to be between a lower estimate of 1.4 Gt yr^{-1} to possibly as much as 4.3 Gt yr^{-1} (Hooijer *et al.* 2006).

***Currently 65 million ha of the global peatland resource is degraded, largely as a result of drainage. Peat oxidation from this area (i.e. from about 0.5% of the Earth's land surface) is responsible for annual CO_2 emissions of over 3 Gt*.** Total CO_2 emissions from oxidizing peat may currently amount to over 3 Gt. This sum results from 635 Mt CO_2 from 12 Mio ha of deforested and drained peatlands in Southeast Asia (Hooijer *et al.* 2006), an additional 1,400 Mt from peatland fires in Southeast Asia (Hooijer *et al.* 2006), 900 Mt from 30 million ha of peatlands drained for/by agriculture outside SE Asia (especially in the temperate and (sub)tropical zones, cf. Joosten and Clarke 2002) with an average emission of 30 t $ha^{-1}yr^{-1}$ (Figure 6.6), 150 Mt from 5 million ha of peatlands degraded by urban and infrastructure development (Joosten and Clarke 2002) with an average emission of 30 t $ha^{-1}yr^{-1}$, 60 Mt by peat extraction (cf. Joosten and Clarke 2002), and over 100 Mt from peatlands drained for forestry (incl. 12 million ha in the Boreal zone (Paavilainen and Päivänen 1995) with an estimated average emission of 1 t $ha^{-1}yr^{-1}$ and 3.5 million ha in the temperate to tropical zones with an average emission of t $ha^{-1}yr^{-1}$ (Schäfer and Joosten 2005).

The current CO_2 emissions from degraded peatlands of 3 Gt yr^{-1} are equivalent to over 10% of the total global anthropogenic CO_2-emissions in 1990 or 20% of the total net 2003 GHG emissions of the Annex 1 Parties to the UNFCCC. The total global anthropogenic CO_2 emissions in 1990 amounted to 29.8 Gt (Olivier et al. 1996). The total net 2003 GHG emissions of the Annex 1 Parties to the UNFCCC amounted to 15.7 Gt CO_2-equivalents (Climate Change Secretariat UNFCCC 2005).

Both the world's peatland carbon store and the current carbon dioxide emissions from degraded peatlands are so substantial that peatlands deserve a prominent positon in global carbon policies.

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7 Peatlands and Greenhouse Gases

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Summary points

- Natural peatlands play a complex role with respect to climate by affecting atmospheric burdens of CO_2, CH_4 and N_2O in different ways.
- Since the last Ice Age peatlands have played an important role in global GHG balances. By storing enormous amounts of atmospheric CO_2 they have had an increasing cooling effect, in the same way as in former geological eras, when they formed coal, lignite and other fossil fuels.
- GHG fluxes in peatlands have a spatial (zonal, ecosystem, site and intersite) and temporal (interannual, seasonal, diurnal) variability which needs to be considered in assessment and management.
- Small changes in ecohydrology can lead to big changes in GHG emissions due to its influence on peatland biogeochemistry.
- In assessing the role of peatlands in global warming the different time frame and radiative forcing of continuous and simultaneous CH_4 emission and CO_2 sequestration should be carefully evaluated to avoid global warming potentials that are not fully applicable.
- Anthropogenic related disturbances (especially drainage and fires) have led to massive increases in net emissions of GHG from peatlands. These are comparable to global industrial emissions.
- Peatland drainage leads to increased CO_2 emissions, a rise of N_2O release in nutrient rich peatlands and commonly to reduced CH_4 efflux.

7.1 GHG related to peatlands

Peatlands are responsible for all three main greenhouse gases – carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). All three of the main greenhouse gases (GHG) – carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are related to peatlands, which act as a valuable key source and sink. Together with other GHGs, including the most important, water vapour, they absorb infrared radiation emitted from the Earth and thus decrease the Earth's radiation (that is, its energy transfer to space). Peatlands remove CO_2 from the atmosphere via photosynthesis and the carbon not held in biomass or stored in accumulating peat is returned back to the atmosphere as CO_2. Anaerobic conditions typical for peaty soils are highly favourable for the production of methane (Clymo 1983) and nitrous oxide (Hemond 1983).

Burning peatlands, Indonesia

The global warming potential methodology is not directly applicable in helping to understand peatlands' net role in radiative forcing and climate change. The competing impacts of different GHG emissions/uptake on the radiative forcing of the climate are usually compared and integrated in the widely adopted global warming potential (GWP) methodology (e.g. Lashof and Ahuja 1990, Ramaswamy *et al.* 2001). This can be used to relate the radiative forcing of a pulse emission of CH_4 or N_2O over a specified time horizon, with a pulse emission of CO_2. An emission of CH_4 or N_2O can then be converted into a CO_2-equivalent emission by multiplying by the GWP value. Using this approach, emissions from any source are treated as perturbations to an otherwise constant atmosphere. However, it may be argued that the assumption about a non-changing background is very unrealistic (e.g. Smith and Wigley 2000, Lashof 2000). This is especially true with regard to peatlands, which both emit and take up GHGs over their millennia history.

Table 7.1: The atmospheric lifetimes and the IPCC (1996) accepted global warming potentials over different time horizons of GHG associated with peatlands.

Species	Atmospheric lifetime (years)	Global warming potential (mass basis) time horizon, years		
		20	100	500
CO_2	variable	1	1	1
CH_4	12±3	56	21	6.5
N_2O	120	280	310	170

The global warming potential methodology is limited to assess peatland's fluxes of GHG by treating a single year's fluxes as isolated pulse emissions. The intended application of the GWP methodology is to assess the relative climate impacts of anthropogenic emissions of greenhouse gases (Albritton *et al.* 1995). The role of the GWP methodology in the Kyoto Protocol process is to provide a mechanism for 'trading' among gases in a multi-gas 'basket' approach (Fuglestvedt *et al.* 2003). The ease and transparency of the GWP methodology (two features that are important for its usefulness as a policy tool), along with its IPCC imprimatur, have led to its widespread application. In the field of biogeochemistry, it has become common to apply the GWP methodology to compare climate impacts of ecosystem-atmosphere fluxes of greenhouse gases, treating a single year's fluxes as isolated pulse emissions.

7.2 Net peatland impact on GHG radiative forcing of the climate

Historically, peatlands could play an important role in the control of atmospheric GHGs, especially carbon dioxide and methane levels. The concentrations of carbon dioxide and methane were not stable in the past. Variations are largely due to changes in the global hydrological cycle, with the development and expansion of peatlands contributing either as a mediator or as a positive feedback for the atmospheric change (Prinn 1994, Chappellaz *et al.* 1997). This can be assumed for the whole Quaternary period and for its Holocene epoch in particular. Although the exact contributions of wetlands to these more recent GHG variations are still under investigation, the observed change in methane values during the latter half of the Holocene (i.e. within the last ca. 5000 years) has been attributed to increasingly arid conditions in the tropics and accelerated peat development in the north (Blunier *et al.* 1995). It appears that regional changes in precipitation and temperature patterns over the past few millennia may have been sufficiently important to trigger some significant readjustments to the land carbon reservoir (Korhola *et al.* 1996, Ciais 1999). The increased concentrations of methane in the atmosphere in the early Holocene were related to the expansion of tropical peatlands (Chappellaz *et al.* 1993, Blunier *et al.* 1995, Severinghaus and Brook 1999), and later, supported by interpolar methane gradient data, to the widespread peatland establishment in West Siberia Lowland (Smith *et al.* 2004).

Peatlands play a dual role in greenhouse gas radiative forcing of climate, affecting the atmospheric burdens of carbon dioxide, methane and nitrous oxide. The role of peatlands as global GHG sinks and sources has often been mentioned, but both positive (e.g. Armentano and Menges 1986, Gorham 1991, Oechel *et al.* 1993) and negative feedbacks (Hobbie 1996, Laine *et al.* 1996, Myneni *et al.* 1997) of GHG emissions following utilization and/or global warming have been suggested. Peatlands could have both cooling and warming impacts on the climate system through their influence on atmospheric burdens of CO_2 and CH_4. Carbon sequestration in peat lowers the atmospheric CO_2 burden, and thus causes a negative radiative forcing of climate (i.e. cooling); methane emissions from peatlands increase the atmospheric CH_4 burden, and thus cause a positive radiative forcing (warming). A positive input could also be made by N_2O. To evaluate the net result of a peatland's competing impacts on climate radiative forcing (cooling and warming), the effects of both CO_2 removal as well as CH_4 and N_2O emissions have to be quantified on a comparable basis (see Frolking *et al.* 2006).

> Using the standard GWP methodology assumptions of a constant value for lifetime/adjustment time and for radiative efficiency (i.e. under the assumption of small perturbations), the GWP value for methane is a decreasing function of the time horizon chosen. This is due to the overall slower atmospheric adjustment of CO_2 compared to CH_4. For any pulse emission of CH_4 or N_2O, there is a set of CO_2–equivalent pulse emissions; these values are tabulated for 20-year, 100-year and 500-year time horizons (Ramaswamy *et al.* 2001). The 100-year time horizon has been adopted in the Kyoto Protocol (UNFCCC/CP/1997/7/Add.1 /Decision 2/CP.3) (e.g. Lashof, 2000). However, the choice of time horizon is often dictated by the specific impact under consideration (Rodhe 1990; Albritton *et al.* 1995). Some components of the climate system, like troposphere temperature, may respond quickly, and so a short time horizon might be more appropriate. Other components, such as ice sheet dynamics, may respond more slowly, and might be better assessed by using a long time horizon (Albritton *et al.* 1995).

Peatlands could be assessed as sources or sinks of GHGs, depending on the different time horizon under consideration – 20, 100 or 500 years. There are several examples of using GWP methodology to assess the climate impact of wetlands based on the annual exchange of CO_2 and CH_4 at the wetland surface (see Frolking *et al*. 2006). Whiting and Chanton (2001) classified seven wetland sites (sub-tropical to boreal) where they had concurrently measured CO_2 and CH_4 fluxes. Without considering a time horizon, all wetlands were found to be a net greenhouse gas sink. For a 20-year time horizon, all seven sites were classified as net greenhouse gas sources; for a 500-year time horizon, all seven sites were classified as net greenhouse gas sinks; and for a 100-year time horizon, the boreal sites were classified as sources, and the temperate and sub-tropical sites as sinks. Similar GWP results were found for Canadian peatlands (Roulet 2000), for natural and managed peatlands in Finland, if emissions from the storage and combustion of harvested peat are excluded (Crill *et al*. 2000), and for a site in western Siberia (Friborg *et al.* 2003). Thus, the application of different time horizons refers to different time scales over which annual pulse emissions can be assessed; it is not an assessment of a continuous greenhouse gas source/sink lasting for 20, 100, or 500 years.

The net radiative forcing impact of a peatland could change direction depending on how long it exists. The model of CH_4 and CO_2 pools in the atmosphere shows that the net radiative forcing impact of a northern peatland could change from warming to cooling over the history of its life. Frolking *et al.* (2006) used modelled atmospheric CH_4 and CO_2 pools to quantify the dynamics of the net radiative forcing impact of a peatland that continuously emits CH_4 and sequesters C over years to millennia time horizons. Taking the observed ratios of CH_4 emission to C-sequestration (roughly 0.1–2 mol mol^{-1}), the radiative forcing impact of a northern peatland begins at peatland formation as a net warming that peaks after about 50 years. The impact remains one of diminishing net warming for the next several hundred to several thousand years, depending on the rate of C sequestration, and thereafter is (or will be) an ever-increasing net cooling impact. In all cases, taking various changes in CH_4 and/or CO_2 emissions, the impact of a change in CH_4 emissions dominates the radiative forcing impact in the first few decades, and then the impact of the change in CO_2 emissions slowly exerts its influence.

Specific conclusions about peatland impact on radiative forcing that do not emerge from a GWP analysis could be made in order to assess the impact of sustained greenhouse gas emissions on radiative forcing. The GWP methodology puts time-integrated radiative impacts of CH_4 and CO_2 pulses into common units (CO_2-equivalent emissions), providing a mechanism for evaluating trade-offs between the climate impacts of different gases. It does not assess the impact of sustained or variable greenhouse gas emissions on radiative forcing and the climate system at any given time. The analysis made by Frolking *et al.* (2006) which assessed sustained GHG emission led to several conclusions about impact of northern peatlands:

– relatively constant methane emissions maintain the atmospheric methane perturbation burden and the associated perturbation to radiative forcing at relatively constant levels;

– relatively constant C-sequestration causes an increasingly negative (or cooling) perturbation to radiative forcing;
– the current radiative forcing impact of a peatland is determined primarily by a trade-off between the total C sequestered since the peatland's formation and the recent (decades) methane fluxes.

For many northern peatlands that would be characterised as net greenhouse gas emitters in a 20-year or 100-year GWP analysis, the current radiative forcing perturbation due to past and present methane emissions and C sequestration is negative (i.e. cooling). This is a direct consequence of their persistence as a C sink over millennia. If peatland CH_4 and CO_2 fluxes change, the atmosphere and radiative forcing will respond rapidly to changes in CH_4 fluxes, and more slowly to changes in CO_2 fluxes. If the methane flux stabilizes at a new value, the atmospheric burden and radiative forcing due to methane will also stabilize within a few decades.

The current climate impact of peatlands is likely to be a net cooling if they are considered a stable sink of atmospheric CO_2 over a millennia time horizon. Two factors influence a GHG's accumulated radiative forcing for a chosen time horizon: its radiative efficiency per molecule or unit mass, and its lifetime in the atmosphere (Albritton *et al*. 1995). CH_4 has a higher radiative efficiency per unit mass than CO_2, and for equal mass pulse emissions, CH_4 will initially generate a stronger instantaneous radiative forcing than CO_2. However, because CH_4 has a shorter atmospheric lifetime than CO_2, for all the time after about 65 years following equal mass pulse emissions, the remaining CO_2 in the atmosphere will generate a stronger instantaneous radiative forcing than the remaining CH_4. After 4000 years of constant fluxes, only 0.3% of the total emitted methane is still in the atmosphere, while ~20% of the CO_2 sequestered as peat has not been restored to the atmosphere from the other components of the carbon cycle (Frolking *et al*. 2006).

The net peatland impact on GHG radiative forcing of the climate depends on the peatlands' natural characteristics. In the case of a peatland that emits CH_4 and takes up CO_2 (sequesters C), its overall instantaneous impact on the atmosphere must eventually be dominated by C-sequestration and will be a net cooling. However, peatlands have a wide range of GHG emission rates depending on their origin: some of them are accumulating carbon in peat and do not emit methane, others with high methane emission rates are characterized by low peat growth, while lots are in between. As applied to Finnish peatlands with an estimated area-weighted mean age of 4200 years (Turunen *et al.* 2002) the current radiative forcing impact of a peatland of that age has been an approximately constant source of methane and sink for carbon will be a net cooling if the mole-ratio of CH_4 emission to C sequestration is less than 0.75, and a net warming if the ratio is greater than 0.75 (Frolking *et al.* 2006). At the same time the existing data show that peatlands with flux ratios of both less and greater than 0.75 may be found (Laine *et al*. 1996, Alm *et al*. 1997, Minkkinen *et al*. 1999, 2002).

The methods applied to assess the net role of peatlands and their utilization in understanding global warming should carefully evaluate the competition between the quick, strong warming from CH_4 emissions and the slow cooling from CO_2 uptake. Peatland greenhouse gas fluxes will inevitably involve competition between quick, strong warming from CH_4 emissions and slow cooling from CO_2 uptake. The methods used to evaluate this competition can obscure or highlight the dynamics. These dynamics are important for our understanding of past changes, and for the assessment of possible future paths for emissions and uptake from peatlands. If the methane fluxes from northern peatlands (or another source) changes significantly and rapidly, the atmospheric methane burden and associated radiative forcing will respond within decades, possibly stabilizing at a new level.

7.3 Ecological and environmental control of GHG emission from peatlands

7.3.1 General

Patterns and controls of GHG emissions from peatlands may vary depending upon the spatial and temporal scale being examined. The factors affecting these emissions are thought to be hierarchically related according to their respective scales of importance. Emissions of GHGs related to peatlands are influenced by a wide range of biological, physical and chemical processes that are interrelated in a hierarchical fashion. Given that these processes are tightly coupled, relationships between GHG emissions and controlling factors should be found when comparisons are made at the appropriate scales (Klinger *et al.* 1994). Some of these processes may affect the magnitude of GHG fluxes, while others may affect the spatial and temporal distribution. Peatland ecology can strongly control regional GHG emissions by influencing net primary productivity, species composition, community structure, peat characteristics, and landscape hydrology. Site–to-site variations in mean GHG fluxes may be closely related to the mean water-table level and for a specific site, for a period without water-table changes, GHG fluxes will tend to follow soil temperature fluctuations.

Peatland hydrology (sources and quality of water, water flow direction and rate, depth to the water table, etc.) is the single most important condition influencing peatland ecology and biogeochemistry, as well as the level of CO_2, CH_4 and N_2O flux. The quantity and quality (chemistry) of water coming to the peatland via precipitation, groundwater discharge, upland inflow, flooding, or other sources is the most important condition influencing peatland ecology, development, functions and processes. Water chemistry has a large influence on the plants that can occur in a peatland and therefore on the character of peat that accumulates. The hydrological origin of a peatland defines the key ecological factors – depth to the water table and its fluctuations in time, and the direction and rate of water movement in surface and deep peat layers. Water exchange in peat is the main driving factor of mass and energy exchange in peat deposits. There is a strong link between temperature and water regime in peat deposits. Water delivers various dissolved substances and suspended particles both upward and downward. This could support GHG production and movement (e.g. Sirin *et al.* 1998a). GHGs may even be released from a peatland horizontally with the lateral outflow (Sirin et al. 1998b), while a significant amount of organic matter may leave the peatland dissolved in water (Kortelainen and Saukkonen 1994, Sallantaus 1992), later supporting GHG production in adjacent aquatic systems like streams, ponds and drainage ditches.

Atmospheric CO_2 fixed to mire plant biomass through photosynthesis, is the primary source of carbon GHGs (CO_2 and CH_4) emissions from peatlands. Thus, the net primary productivity of peatland vegetation potentially controls CO_2 and CH_4 fluxes. Part of the carbon photosynthesized by plants is returned to the atmosphere as CO_2 in the maintenance and growth respiration of above- and below-ground parts of plants and their associated heterotrophic microbial communities. In the aerobic surface peat layer about 80–95% of the litter is decomposed by aerobic bacteria and released as CO_2 (Reader and Stewart 1972, Clymo 1984, Bartsch and Moore 1985). The remaining C is transformed into plant structures and finally deposited as peat. In the underlying water-saturated anaerobic peat layers, a large portion of the available organic carbon is used to form CH_4 as the end product, later released to the atmosphere as itself, or being oxidized by methanotrophic bacteria in the upper aerobic peat layers, and diffusing upwards as CO_2 (e.g. Sundh *et al.* 1994). Thus, being a primary source of organic carbon in peatlands, net primary productivity (total C fixed by plants minus carbon used in respiration) is a potentially controlling factor of CO_2 uptake and release and CH_4 release.

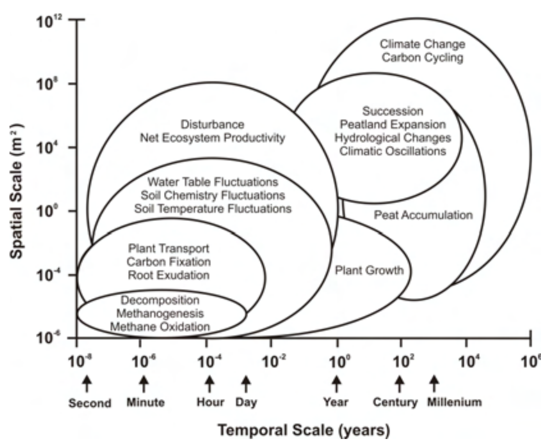

Figure 7.1: The hierarchical relations of processes proposed to affect methane emissions and the spatial and temporal scales at which these processes predominate (Klinger et al. 1994).

The water table determines the oxic-anoxic ratio of the peat profile and thus the preference for aerobic or anaerobic biogeochemical processes influencing the rate and ratio between GHGs emitted from a peatland. The position of the water table determines the oxic-anoxic ratio of the peat profile that defines the preference for aerobic or anaerobic biogeochemical processes. It is the key abiotic factor that influences the type of microbial respiration – aerobic versus anaerobic - and finally the rate of peat decomposition. The aerobic metabolism is more efficient and tends to favour the rapid production of CO_2. The water table influences the ratio between CO_2 and CH_4, the two main GHGs emitted from peatlands. Up to 90% of the CH_4 produced in the anaerobic peat zone may be oxidized above the water table in peat (e.g. Fechner and Hemond 1992), but in wet sites or during wet periods, it could directly release into the atmosphere. The aerobic conditions in peat can stimulate the nitrification of peat matrix nitrogen and potentially support further N_2O production.

Temperature could widely influence GHG fluxes in peatlands. CO_2 and CH_4 production and CH_4 oxidation are temperature dependent. Surface temperature affects GHG release from a peatland to the atmosphere. Temperature directly affects decomposition through its influence on microbial activity. CO_2 and CH_4 production and CH_4 oxidation are all temperature dependent. Rising temperatures could stimulate both processes to a different extent. Temperature affects the solubility of GHGs in peat and thus determines the mechanism of their upward movement. Higher surface peat temperatures lead to higher CO_2 respiration and CH_4 emission supporting diffusion between the soil and atmosphere. Soil temperature is the best predictive environmental variable for the seasonal dynamics of in situ CO_2 and CH_4 emission. Temperature convection in northern peatlands could support water exchange in deep peat layers with potential effects on GHG production and release (Sirin and Sirin 2003).

Substrate including peat matrix, dissolved substances and suspended particles in peat pore water, serve as the energy source for GHG production. The quality of substrate determines its suitability to support or inhibit GHG production in peatlands. The substrate composition of peat is highly variable and this is dependent on the original peat-forming plant communities. Generally, peat substrate should include peat matrix, dissolved substances and suspended particles in peat pore water. This material serves as the energy source for the micro-organisms, so differences in the substrate quality result in differences in peat decomposition rates, and finally in the resulting GHG production. Differences in CO_2, CH_4 and N_2O production are not directly due to differences in peat nutrient levels, and are mainly determined by the availability of suitable material. When peat becomes depleted of high-quality substrate, GHG production falls.

Net ecosystem production is a master variable, integrating many factors that control CH_4 emission in vegetated peatlands. Peatlands with high net ecosystem productivity could increase CH_4 fluxes because of enhanced transport via plants (Chanton and Dacey 1991) and/or enhanced methanogenesis through root senescence, decay, or exudation (Whiting and Chanton 1992). The idea that CH_4 emissions are directly related to net primary production via substrate availability and plant transport were shown in field studies in the Florida Everglades (Whiting *et al*. 1991), subarctic Canada (Whiting and Chanton 1992), and Arctic Alaska (Morrisey and Livingston 1992). From simultaneous measurements of CO_2 and CH_4 exchange in wetlands extending from subarctic peatlands to subtropical marshes, Whiting and Chanton (1993) found a positive correlation between CH_4 emission and net ecosystem production. They suggested that net ecosystem production is a master variable, integrating many factors that control CH_4 emission in vegetated wetlands. According to this study, about 3 per cent of the daily net ecosystem production is emitted back to the atmosphere as CH_4. Net primary production may also be indirectly related to the ability of certain plants to transport CH_4 through their stems and leaves by providing metabolic energy for transpiration or for oxygen transport to the roots (Klinger *et al*. 1994). The relationship derived between primary production and methane emission provides an important tool for refining global scale source estimates (Whiting and Chanton 1993).

7.3.2 Carbon dioxide

CO_2 emission from a peatland includes autotrophic respiration, regulated by photosynthesis and temperature, and heterotrophic respiration controlled largely by soil temperature. CO_2 emission from a peatland is formed by autotrophic and heterotrophic respiration, which comprises a significant part of the CO_2 uptake in photosynthesis during intensive growth (in northern peatlands around 1/3 – Bubier *et al.* 1998). The rate of autotrophic respiration is regulated by photosynthesis and temperature while heterotrophic respiration is controlled largely by soil temperature (Chapman and Thurlow 1998). Total CO_2 release from peat includes aerobic and anaerobic decomposition, root respiration and respiration of soil fauna. Root-associated respiration follows the phenology of the vegetation and may account for 10-45% of the total soil CO_2 release (Silvola *et al.* 1996b), mainly originating from the turnover of fine root litter and root exudates.

7.3.3 Methane

The flux of CH_4 from a peatland is a function of the rates of CH_4 production and consumption in the profile and the transport mechanisms to the atmosphere, such as diffusion, ebullition, or plant-mediated movement. The methane flux from a peatland is dependent not only on the production rate of methane through anaerobic degradation of organic matter but also on the transport pathways and consumption of methane in oxic parts of the system. Methane formation is restricted to the anoxic part of the profile below the actual water-table position. Methane in the saturated part of the profile occurs either as a dissolved species or as bubbles. It can be transported to the atmosphere by: 1) molecular diffusion through the soil pore space and, if present, the snow pack or water standing above the peatland surface; 2) transport by ebullition to the atmospheric interface at the water table; and 3) transport through aerenchymous tissues in plants from the rooting zone directly to the atmosphere. A variable fraction of the methane produced is oxidised by methanotrophic bacteria in the oxic zone above the water table, and either in the rhizosphere or inside vascular plants.

CH_4 production depends on the amount of high-quality organic material that reaches the anoxic zone. This means that plant primary productivity and depth to water table are the two most important factors controlling this process. CH_4-producing organisms grow anaerobically beneath the water table, and their main zone of activity shifts up and down with the water table. Their most common substrates are H_2 + CO_2 (to form CH_4+H_2O) and acetate (to form CH_4 + CO_2). The primary control on CH_4 production is the amount of high-quality organic material (fresh litter and root exudation) that reaches the anoxic zone. This means that plant primary productivity, vegetation type and depth to water table are the most important factors influencing the process. A minerotrophic *Carex rostrata* peatland site had higher rates of CH_4 production than nutrient-poor Sphagnum-dominated sites, probably owing to the higher supply of easily degradable litter and root exudates (Bergman *et al.* 1998). Within a bog, *Sphagnum majus* peat produces 1.5 times more CH_4 than *S. fuscum* peat. Where the water table is closer to the surface, the upper anoxic zone will contain greater amounts of fresh, resource-rich material. Secondary controls on methane production are alternative electron acceptors, which could inhibit this process, temperature, and pH. Occurrence of competing electron acceptors like nitrate (NO_3^-), ferric iron (Fe^{3+}), or sulphate (SO_4^{2-}) will lead to decreased CH_4 production.

Depth to water table is the key factor controlling the balance between CH_4 production and consumption and finally the

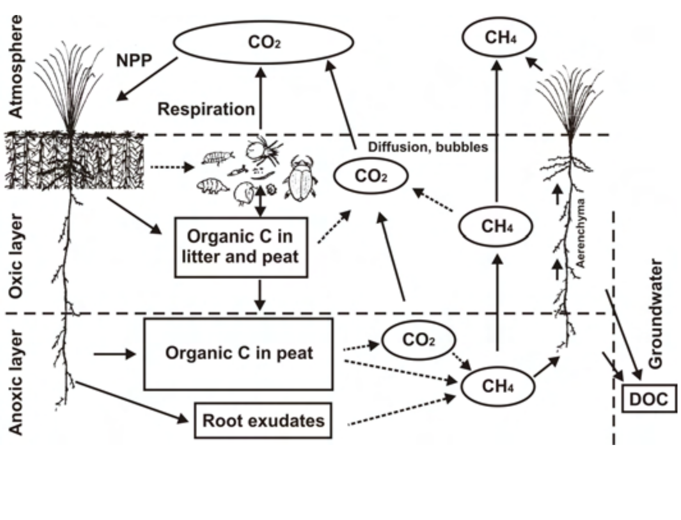

Figure 7.2: Simplified description of carbon flow and peat formation in a peatland with an oxic upper part and an anoxic layer beneath. Encircled symbols represent gases and dashed arrows show microbial processes. NPP is the net primary production (i.e. the difference between photosynthesis and the plants' respiration). DOC is dissolved organic carbon leaching out from both the oxic and anoxic layers of the peatland via the groundwater (After Rydin and Jeglum 2006).

ratio of CH_4 and CO_2 emitted from a peatland. The most active zone of CH_4 production in a peat layer is located just below the water table. The methane production potential in peatlands has been found to peak approximately 10 cm below the average water table (Sundh *et al.* 1994).

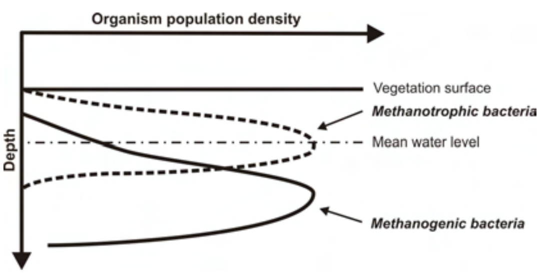

Figure 7.3: A generalized depth profile describing distribution of the methanogenic and methanotrophic communities in relation to the mean water table in a peatland (after Granberg et al. 1997).

A large fraction of the methane transported by diffusion through the oxic part of the peat profile is oxidised by methanogenic bacteria. This portion reached up to 80% in a swamp forest (Happel and Chanton 1993) and 90% in a *Sphagnum* bog (Fechner and Hemond 1992). Oxidation capacity is also suggested to be *maximal around the mean water table (Sundh et al.* 1994). The position of the actual water table determines both processes of CH_4 production and consumption, multiplying its effect and defining the rate of CH_4 emission. On a spatial level, the highest emissions of CH_4 will be from peatland surfaces close to the water table. Wet periods with high water levels also provide better conditions for methane release to the atmosphere.

Temperature can influence methane production and consumption as both processes are temperature dependant. Methane production increases exponentially with increasing soil temperature (Svensson 1984, Westermann 1993, Bergman *et al*., 1998). The optimum temperature observed in the laboratory for methane production is 25-30°C (Dunfield *et al.* 1993) and production occurs down to 2°C provided there is no substrate limitation (Bergman *et al.* 1998). Like production, the consumption rate is also determined by soil temperature. Consumption of methane occurs at temperatures between 0 and 35°C, with optimum consumption at 20-25°C (Dunfield *et al*. 1993). The decrease in CH_4 oxidation at low temperatures might be due to the decrease in substrate availability as an effect of reduced numbers of methanogens (Saarnio *et al.* 1997).

Specific peatland vegetation could provide a direct route for methane release to the atmosphere, bypassing oxidation, with a final effect on high emission rates. A substantial amount of the CH_4 emitted from peatlands passes through vascular plants (e.g. Sebacher *et al.* 1985, Schimel 1995, Thomas *et al.* 1996), bypassing attacks from the methanotrophs (e.g. Saarnio *et al*. 1997, Nilsson *et al.* 2001). In an adaptive response to submerged soils, vascular plants have developed porous tissues (aerenchyma), which both facilitate O_2 transport

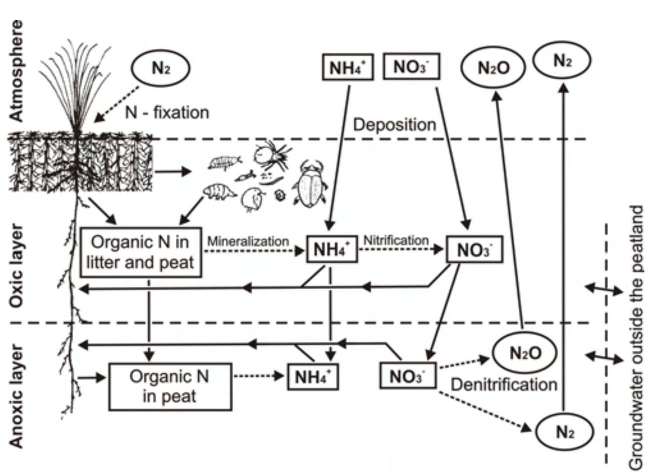

Figure 7.4: Simplified scheme of the nitrogen cycle in peatlands. Encircled symbols represent gases; dashed arrows represent microbial processes. The largest pool in the peatland is the organic nitrogen in peat, which is unavailable to the plants. In the oxic zone, plant uptake includes the ecologically important assistance of mycorrhizal mutualism. Some microbial nitrogen fixation occurs in the anoxic zone, based on N_2 gas transported down through plant aerenchyma. The bidirectional arrows to the right indicate the exchange with groundwater outside the peatland, that is, leaching and inflow of inorganic components and nitrogen in dissolved organic matter (after Rydin and Jeglum 2006).

to the roots (Armstrong 1991) and allow dissolved or trapped gases in the sediment to pass to the atmosphere. Transport through the vascular plants is usually the dominant emission pathway when peatland is covered by appropriate vegetation (e.g. Chanton and Dacey 1991, Chanton and Whiting 1995, Thomas *et al*. 1996). Such peatland species as *Phragmites sp., Typha spp., Scheuzeria palustris* and others could significantly enhance CH_4 release to the atmosphere (e.g. Grosse *et al.* 1996, Shannon *et al*. 1996). Molecular diffusion is the most important transport mechanism in most sedges (one of the dominating vascular plant groups in peatlands). Peatland sites with a high cover of aerenchymatous plants are characterized by high emission rates. Transport via plants could make the CH_4 cycle relatively independent of the long-term C cycle. Peatlands in their fen stages act as sedge-mediated CH_4 pumps, converting atmospheric CO_2 to CH_4 (Korhola *et al*. 1996).

7.3.4 Nitrogen oxide

Environmental conditions of undisturbed peatlands are rather favourable for N_2O production but in most cases are severely limited by low nitrate concentrations. The emission of nitrous oxide and other nitrogen oxide gases (NO and NO_2) from soils is a result of the cycling of N. Where N cycling is rapid, through nitrification and denitrification, and the microbial cycle is "leaky", significant emissions of these gases are likely to occur (Davidson 1991, Moore 1994). The environmental conditions within an undisturbed peatland (i.e. anaerobic and relatively acidic, Hemond 1983), are considered highly favourable for N_2O production through denitrification, although generally low nitrate concentrations in peatlands severely limit the extent to which the process can proceed (Clymo 1984).

Limited by low nitrate concentrations, N_2O production in peatlands can be raised by external sources or by higher nitrification of the organic-N within the peat matrix. The lack of suitable material for N_2O production in peatlands can be compensated for by external sources or by stimulating mineralisation (and nitrification) of some of the organic-N within the peat matrix (Williams and Wheatley 1988). The aerobic processes of nitrification are a potential nitrous oxide source (Bremmer and Blackmer 1978). Water samples taken along a gradient from bog to extreme rich fen (Vitt *et al*. 1995) showed decreasing NH_4^+ and weakly decreasing NO_3^-. This may mean that the vegetation in the rich fen is consuming the supply of mineralized N faster than in the bogs. In cases where organic-N is available from peat matrix, extension of aerobic layer in both depth and time could support N_2O production.

7.4 GHG flux rate in natural peatlands

Peatlands emit large amounts of CO_2 to the atmosphere even though, in general, they are a net sink. (This is clearly shown by the occurrence of peat accumulation). However, different peatlands in different geographical conditions and over specific time periods (season, year or longer) could act both as a sink and a source of CO_2. Soil respiration measurements, which include the C released by decomposition of organic matter as well as the respiration of plant roots and heterotrophic organisms, give average figures for annual CO_2 emissions between 50 and 400 g C m^2 a^{-1}, depending on the climate and peatland type (Raich and Schlesinger 1992, Moore 1996, Silvola *et al.* 1996a). Micro-topographical differences within sites (e.g. Moore, 1989, Waddington and Roulet, 1996) and differing climatic conditions between years (Silvola *et al.* 1996a) further increase the variation in CO_2 fluxes from peatlands. Root respiration may account for 10-40% of soil respiration in peatlands, the major part of which is probably derived from decomposing root exudates, not from the maintenance respiration of roots (Silvola *et al*. 1996b). The variation of CO_2 flux in peatlands could be very high.

Peatlands are one of the main sources of atmospheric methane. Peatlands together with other wetlands are the major biogenic source of atmospheric methane, contributing about 20% of the total input of 552 Tg CH_4 yr^1 (IPCC, 1994). Many peatlands emit methane, and northern peatlands only are currently contributing ~3 to 5% of total global methane emissions (Prather *et al*. 2001, Milakoff Fletcher *et al.* 2004). Wetlands in high latitudes have been identified as one of the main sources of CH_4 emission (Cicerone and Oremland,

GHG flux measurements in peat

Different methods can be applied to measure GHG fluxes in peatlands (Figure 7.5), providing data at scales ranging from <1m² (chambers) to several hundred m² and km² (micro-meteorological towers and aircraft platforms).

The most common method involves placing a chamber (of different size, form and material) on the soil surface and monitoring the exchange between the soil/vegetation and the atmosphere for a limited length of time (from minutes to hours). The change in concentration of the gas inside the chamber shows the gas exchange from the surface (e.g. Silvola *et al*. 1985, Crill *et al.* 1988). The chamber method is the best choice for providing instant CO_2, CH_4 and N_2O flux for small well-defined surface areas (microsites), for conditions when fluxes are low, and when the direct environmental response to the fluxes are of interest. Chamber measurements give gas exchange values under specific conditions of peat moisture, temperature and so on. To expand such data in time, different model approaches were developed, ranging from simple regression-based to physiologically based models (e.g. Silvola and Hanski 1979, Granberg *et al.* 1997, Alm *et al.* 1997, 1999c, Saarnio *et al*. 1997, Kettunen 2000, Tuittila *et al*. 2003). Advances in this technique have made the sampling from chambers automatic, thereby allowing continuous measurement series of fluxes (e.g. Bubier *et al.* 2003).

Micrometeorological flux measurement techniques (gradient, eddy correlation and other methods), allow continuous measurements at the level of the whole mire site (e.g. Hypponen and Walden 1996, Alm *et al*. 1999c, Aurela *et al*. 1998, 2004), the size of which (footprint) starts from dozen of meters in diameter and depends on the tower height. Within the commonly used eddy correlation (= eddy covariance) method, flux calculations are based on the principle of turbulent exchange in the lower atmospheric boundary layer, where fast response instruments are applied to measure fluctuations in vertical wind exchange and gas concentrations (e.g. Moncrieff *et al*. 1997). Nowadays this method is widely used for CO_2 flux measurements but still too costly for measurements of gases with low concentrations or where fluxes are small, as for CH_4 or N_2O.

In specific conditions, for example during wintertime, special approaches like snow gradient methods can be employed (Sommerfed *et al.* 1993, Alm *et al*. 1999b, Saarnio *et al*. 2003). Generally a combination of different methods provides better estimates of GHG fluxes in peatlands.

1988, Fung *et al*. 1991). Estimates of the contribution from high latitude peatlands, at 50°–70°N, have converged around 17-35 Tg CH_4 yr^1 (Aselmann and Crutzen 1989, Fung *et al*. 1991, Taylor *et al*. 1991, Bartlett and Harris 1993, Reeburg *et al*. 1994, Roulet *et al*. 1994). A survey published in 1991 estimated that Swedish wetlands emit 2.2 Tg CH_4 yr^1, which would account for about 70% of the total CH_4 emission from Sweden (Svensson *et al*. 1991). Annual CH_4 emissions from boreal peatlands have varied between 0 and 70 g CH_4 m^{-2} a^{-1} (Crill *et al.* 1992), with mean fluxes for Finnish undisturbed bogs and fens being 8 and 19 g CH_4 m^{-2} a^{-1} respectively (Nykanen *et al.* 1998). Usually these comprise less than 10% of the annual net C flux from peat to the atmosphere (Alm *et al*. 1997).

Natural peatlands make relatively small contributions to N_2O emissions to the atmosphere. Even though relatively few data are available on the flux of N_2O from undisturbed peatland, studies are similar in that they show low emissions. For example, in the Hudson Bay lowland the annual flux was between -2.1 to 18.5 mg N_2O m^{-2} (Schiller and Hastie 1994). Goodroad and Keeney (1984) observed annual fluxes of 0.02 to 0.08 g N_20 m^{-2} from undrained marshes; Urban *et al.* (1988) reported fluxes of < 0.2 to 0.6 μg N_2O m^{-2} h^{-1} from Minnesota and western Ontario ombrotrophic peatlands; while Yavitt and Fahey (1993) measured fluxes of 14 μg N_2O m^{-2} h^{-1} from a peaty soil in a New England forest. Even if nitrogen concentrations in peats are fairly high (generally 0.8-2.5% of dry matter) N_2O emissions have been found to be negligible (Martikainen *et al*. 1993). N_2O emissions from all Finnish undrained peatlands are estimated to be only 0.2 Gg (Crill *et al*. 2000). Laboratory estimations of the annual flux of nitrous oxide based upon a daily flux of 0.11 mg N_2O m^2 d^1 assumed to be constant year round, and an area of intact sub-arctic/boreal peatland of 3.3×10^{12} m^2 (Gorham, 1991), yields an annual flux of 0.133 Tg yr^{-1} (Freeman *et al*. 1993). This represents a relatively small contribution to global N_2O emissions of 12.4 Tg N_2O yr^{-1} (Davidson 1991).

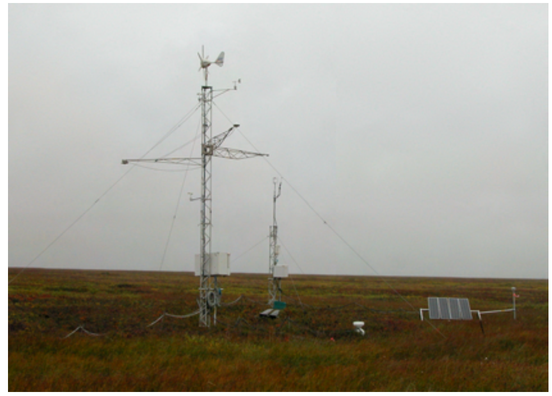

Figure 7.5: GHG flux measurements.
a) Gas sampling for greenhouse gas flux determination by the closed chamber method in clear felled burned peatland at Ex-Megarice area, Central Kalimantan. Photo: Jyrki Jauhiainen.

b) Installations for micrometeorological (eddy covariance) flux measurements in tundra peatlands (Indigirka lowlands, East Siberia). Photo: Andrey Sirin.

Uncertainties about estimates of GHG emissions from peatlands are very large because of spatial variability depending on their natural origin, geographical location and weather conditions. Temporal and spatial variations of GHG emissions from peatlands can vary by up to 100-1000 times depending on the natural origin of the site, geographical location and weather conditions. Spatial differences in GHG fluxes in peatlands can be seen on geographical, typological and site levels. Neighbouring peatlands or even micro-sites could simultaneously be a source and a sink of GHGs. On a raised bog in summer, hollows were actively emitting CH_4 while closely adjacent elevated sites with pine dwarf-shrub vegetation were absorbing CH_4 (Chistotin *et al*. 2006). Thus, it is extremely hard to make general spatial estimates of GHG fluxes from peatlands considering their ecosystem, site and micro-site diversity. Use of a combination of in situ measurements with remote sensing technologies is the only way to extrapolate GHG flux observation data for spatially relevant territories.

Local uncertainties such as hollows, pools, streams could play a valuable and sometimes key role in GHG emissions from peatlands. Local uncertainties could provide specific conditions for GHG production and release in peatlands. Thus, their contribution to the GHG flux from a peatland could be relatively much higher than their surrounding area. Hollows, pools and streams support the release of GHGs partly delivered by lateral flow from adjacent peat layers and partly produced in situ. For example, ditches in drained peatlands are a cause of increased CH_4 emissions and this partly offsets reductions in CH_4 emissions due to the drainage of peat soils.

GHG fluxes in peatlands demonstrate high temporal variability and the annual flux rate could change between years with different weather conditions. To estimate average GHG emissions, diurnal and seasonal fluctuations should be considered. High temporal variability in GHG flux is observed in peatlands. Three different time scales can be identified: annual, seasonal and diurnal. Seasonal changes in GHG flux are related to the seasonal changes of peatland ecosystems and could be very large, varying from absorption to high emission rates. Usually the emission peaks when the above-ground biomass in peatlands is at a maximum. A large proportion of GHGs, especially methane, could release over short time episodes (e.g. for northern peatlands, this takes place during the spring thaw period). The variation on an annual scale may, to a large extent, be determined by differences in inter-annual and seasonal weather conditions. Most GHGs related to peatlands demonstrate diurnal variability, which in turn, is dependent on the weather conditions (mostly relating to temperature changes and precipitation). The most promising approach to estimate annual GHG flux in peatlands is to use correlations between environmental parameters and measured emissions to reconstruct flux patterns over longer periods (Granberg *et al.* 1997).

Non-growing season emissions could make valuable contributions to GHG fluxes from northern peatlands. A considerable amount of CO_2 and CH_4 could be released through the snow pack during winter. Very high emission rates of CH_4 may take place after the snowmelt in spring. Winter efflux was found to be an important component of the annual C balance; carbon losses during winter may constitute 10-30% of the growing season net carbon gain in the boreal zone (Zimov *et al.* 1993, Alm *et al.* 1999c). During the long boreal winter, methane release alone is significant and consists of 5-33% of the annual total (Dise 1992, Alm *et al*. 1999b). Under Finnish seasonal weather conditions about 80% of the emissions of CO_2 and CH_4 occur during the growing season (Alm *et al*. 1999c), but a considerable part (20%) of the C fixed in the ecosystem is lost during winter. CH_4 stored in deep peat layers is released during warm periods but rebuilt in winter (Sirin *et al*. 1998a). A large fraction of the total emissions may occur via spring episodic events. Significant amounts of CH_4 captured below the freeze layer may be emitted during the snowmelt.

7.5 Human influence on GHG flux from peatlands

Human intervention and land-use may create multiple pressures on the GHG flux in peatlands, mainly connected with water level draw-down. There is a wide range of human activities that have a potential effect on GHG flux in peatlands. Peatland utilization for excavation, forestry, agriculture and other purposes is mostly limited by highly saturated conditions and therefore drainage is often needed. Most peatland land-use activities bring about changes in the ecohydrology of sites, together with changes in, or the removal of, vegetation. The water level draw-down is the initial factor that has an influence on GHG formation and release in peatlands. Heterotrophic CO_2 efflux from the peat increases after drainage, and litter and peat decomposition rates increase, as decomposition in aerobic conditions is always much faster than in anaerobic ones. Water-level draw-down will cause a decrease in the CH_4 emissions as substrate flux to the anoxic layers is decreased (slowing down CH_4 production), while consumption of CH_4 in the thicker aerobic layer is enhanced. N_2O fluxes from natural peatland mires are small but drainage has been shown to increase the fluxes at nutrient-rich sites.

Arable agriculture always transforms peatlands into sources of GHGs to the atmosphere (first of all CO_2 and very often N_2O). CH_4 emissions from drained peat soils are generally prevented, though they can be rather high from drainage ditches. Arable agriculture always transforms peatlands into net sources of GHGs to the atmosphere (Armentano and Menges 1986, Kasimir-Klemedtsson *et al.* 1997, Maljanen *et al.* 2004), with the exception of CH_4. Very high annual losses of C (up to ca. 1000 g m^{-2}) have been reported from Northern European peat soils (e.g. Maljanen *et al.* 2001). Similarly, N_2O fluxes may also be high in comparison to other ecosystems, at more than 10 kg N_2O-N ha^{-1}

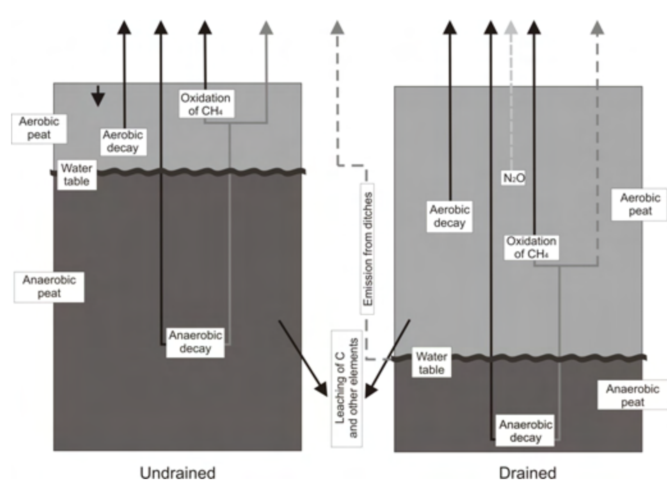

Figure 7.6: Schematic presentation of the GHG balances of undrained and drained peatland sites. The line widths show approximate relative flow rates and dotted lines indicate potential fluxes (Laine et al. 1996).

(Maljanen *et al*. 2003, 2004). Kasimir-Klemedtsson *et al.* (1997) concluded that agricultural practices on organic soils lead to a net increase in radiative forcing due to large fluxes of CO_2 and N_2O, despite decreases in emissions of CH_4. To some degree the impact on the carbon balance can be controlled by the choice of cropping method (including alternative crops) and by taking into account the depth of drainage. Ditches in drained peatlands are a cause for increased CH_4 emissions (Chistotin *et al*. 2006) and this partly offsets reductions in CH_4 emissions due to the drainage of peat soils.

Peatlands used for agriculture are major global emitters of N_2O. N_2O fluxes from natural peatland mires are small but drainage has been shown to increase the fluxes at nutrient-rich sites. Agricultural soils are responsible for most of the global N_2O emissions from soils (Kroeze *et al*. 1999). Drained organic soils with high N_2O emissions have special importance in the atmospheric N_2O load. As much as 25% (annually 4 Tg) of the N_2O emissions in Finland may originate from organic agricultural soils (Kasimir-Klemedtsson *et al.* 1997), although these soils cover only 14% of the total agricultural land in the country. Also, when peatlands are drained (or drained and fertilized) mineralization increases and inorganic forms of N increase. When organic N is available from peat matrix, the extension of aerobic layer in both depth and time could support N_2O production and cause further efflux to the atmosphere.

Drainage for forestry causes C losses from soil but decreases CH_4 emissions. On nutrient-rich sites drainage may stimulate N_2O release to the atmosphere. Following drainage, litter and peat decomposition rates increase, as decomposition in aerobic conditions is always much faster than in anaerobic ones. Consequently, heterotrophic CO_2 efflux from the peat increases (Moore and Dalva 1993, Silvola *et al.* 1996a). However, the effect of increased aeration on increased decomposition rates may be accompanied by decreases in peat pH (Laine *et al*. 1995), low peat temperature (Minkkinen *et al.* 1999) and reductions in litter quality (Laiho and Laine 1996, Laiho *et al.* 2004), all of which are important determinants of the rate of organic matter decomposition (Berg *et al.* 1993). For northern peatlands, much information is available about the effects of water level draw-down on carbon fluxes in peatlands drained for forestry (e.g. Glenn *et al.* 1993, Roulet *et al*. 1993, Laine *et al*. 1995, Martikainen *et al.* 1995, Minkkinen *et al.* 1999, Hargreaves *et al.* 2003, von Arnold 2005a, 2005b, Minkkinen *et al*. 2006a). Water level draw-down will cause a decrease in CH_4 emissions as substrate flux to anoxic layers is decreased (slowing down CH_4 production) and consumption of CH_4 in the thicker aerobic layer is enhanced (Glenn *et al.* 1993, Roulet *et al.* 1993, Martikainen *et al.* 1995, Nykänen *et al*. 1998). But CH_4 release may still take place in drained peatlands, in particular through emissions from drainage ditches. Ditches constantly covered by water may, in some cases, have a great impact on the overall CH_4 emissions from drained peatlands (Minkkinenen and Laine 2006). Minkkinen *et al.* (2006b) show that tree stand volume in peatland forests can be used as a scalar in the upscaling of CH_4 emissions. N_2O fluxes from natural mires are small and drainage has been shown to increase the fluxes at nutrient-rich sites (Martikainen *et al.* 1995, von Arnold et al. 2004). In general it has been suggested that

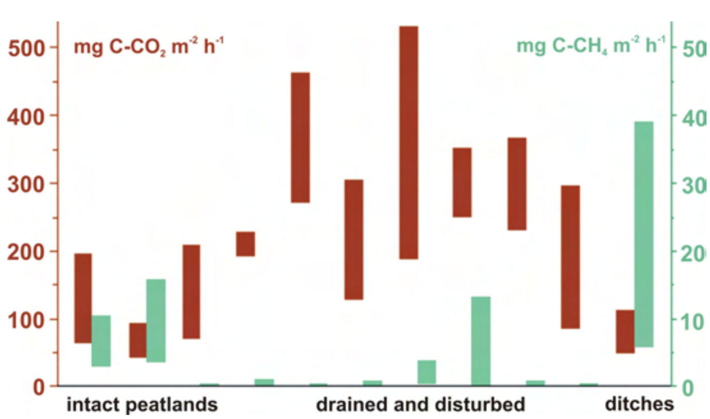

Figure 7.7: Peatlands disturbed by human activities often become sources of CO_2 but do not totally stop emitting CH_4 which is released especially from drainage ditches. (Figures represent gross emissions; GHG sequestration by peat formation and vegetation growth not included; Data based on a three year summer-fall measurements in a large number of different peatland sites in the southern part West Siberia, Russia). Source: Glagolev et al. 2008.

reduced CH_4 emissions after draw-down of the water table, together with increased C sequestration in trees, may decrease the greenhouse effect of these ecosystems during the first tree stand rotation (Laine *et al.* 1996, Minkkinen *et al.* 2002), even though soil CO_2 and N_2O emissions may simultaneously increase.

Forest harvesting in tropical swamp forests supported by drainage may increase the CO_2 released to the atmosphere and cause additional changes in the other GHG flux rates. Forest harvesting in tropical swamp forests can result in changes to the quality and quantity of organic matter inputs from vegetation and, as the work of Brady (1997) has shown, if tree root mats decline, then the net accumulation of peat may also decline. Where selective logging is combined with artificial drainage, decomposition and subsidence of the peat may proceed at annual rates of 3.5–6.0 cm (Brady 1997). This will be accompanied by an increase in CO_2 release.

Peat harvesting (including land preparation, extraction and abandonment) strongly affects the GHG flux in peatlands. The CO_2 released from dried peat rises, but CH_4 efflux from drainage ditches and under wet conditions can remain. The production cycle for peat harvesting has three phases: 1) land conversion for peat extraction, which includes drainage and removal of natural vegetation; 2) peat extraction, when peat is milled, air-dried in summer and collected into stockpiles for later collection; 3) abandonment when extraction is no longer profitable (Canadian Sphagnum Peat Moss Association 2004, Nilsson and Nilsson 2004). Generally greenhouse gas emission changes have similar features in all three phases. Removal of vegetation and intensive drainage to reach the harvesting moisture content of peat has a fundamental impact on the GHG balances of the harvesting sites. The major greenhouse gas flux in this process involves CO_2 emissions from the excavated peat area and the stockpiles as the decay of the drained peat increases. It was expected that methane flux from excavated peatlands would be negligible or almost stop (Nykänen *et al*. 1996). But relatively high CH_4 efflux was observed from main and secondary ditches (Minkkinen *et al.* 1997, Sundth *et al.* 2000, Chistotin *et al.* 2006). CH_4 emissions may take place from the harvested area when the peat is wet. Notable CH_4 flux rates were observed after the snowmelt in spring from the milled peat surface while rates reached 227±120 mg C CH_4 $m^{-2}h^{-1}$ from the stockpiles (Chistotin *et al*. 2006).

Fertilisation of drained peatlands may cause increased N_2O emissions and affect the decay rate, with subsequent changes to carbon GHG flux. Nitrogen input in the form of anthropogenic deposition via air pollution and water contamination could also have an influence on GHG flux from pristine as well as drained peatlands. Nitrogen fertilization on boreal nutrient-poor pristine peatlands did not produce increased N_2O emissions (Nykänen *et al.* 2002), but emissions increased significantly from soils drained for forestry after N addition (Regina *et al.* 1998). Increases were also observed from cropland peat soils (Maljanen *et al.* 2003), and the addition of N to rewetted peatland has caused very high N_2O emissions (Silvan *et al.* 2002). The C/N ratio of the organic matter affects the decay rate and fertilization can cause changes in CO_2 and CH_4 flux rate from peatlands. High nitrogen inputs to peatlands, for instance in the form of anthropogenic deposition, affect many parts of the N cycle and give higher rates of N mineralisation, denitrification, and N_2O emission (Verhoeven *et al.* 1996). The N may originate from air pollution or particularly from water contamination and waste deposition.

Overgrazing of peatlands can cause soil degradation. Fertilisation with manure stimulates peat oxidation and erosion. In turn this increases the release of CO_2 to the atmosphere and has an additional effect on in situ and offsite CH_4 and N_2O emissions. Peatlands are often used for grazing. All highly productive pastures in the Netherlands have a peatland origin. Many abandoned agricultural lands with peat soils in Eastern Europe are put under grass now, as are the previously excavated peatlands in the European Russia. In steppe and mountain regions with a dry climate, peatlands nowadays are the most productive and attractive lands for grazing. This is often because grasslands on mineral soils have already been destroyed by overuse and drought. Overstocking of grasslands on peat soils as observed on the Ruorgai Plateau in China, in Mongolia (Minayeva *et al*. 2004) and in the other regions, led to vegetation changes and soil degradation. Tussock formations, further burrowed by small mammals, greatly increase the soil surface, additionally stimulating peat oxidation and CO_2 emission. Overgrazing may cause peatland erosion, with peat soil loss leading to increased (offsite) CH_4 emissions from adjacent wet depressions, ponds and streams. Fertilisation of peatlands by manure from grazing animals could enhance mineralisation, denitrification, and thus the N_2O flux (see also fertilisation).

Urban and industrial building construction totally destroys peatlands and disrupts their role in GHG flux, especially their role as a sink of CO_2 from the atmosphere. Roads and pipelines built on peat cause the water table to rise and fall on the up-grade and down-grade sides, resulting in consequent changes to GHG emissions. Peatlands used as a space for domestic and industrial building construction are usually totally destroyed and as such, lose their role in GHG exchange with the atmosphere. Mainly this loss concerns their role as a sink of atmospheric carbon. The impact on climate change of this use of peatlands differs and depends on the net peatland GHG flux before disturbance. Roads, railways and pipeline networks cover many regions where peatlands exist and affect natural flows in peat. As a result very often the water table rises on the upgrade side and falls on the downgrade side. This causes consequent changes to GHG emissions. The most obvious changes take place on the upgrade side and result in an increase in CH_4 emissions. This is largely due to flooding and the additional organic material inputs originating from plants that drowned during the water level rise.

> Burning peat bogs in Indonesia are releasing massive amounts of carbon dioxide into the atmosphere, in a repeat of the environmental devastation that made headlines around the world five years ago. Tropical peat bogs, such as those beneath the forests of Indonesia, are among the planet's largest stores of carbon. They release much more CO_2 when they burn than when the trees that grow on them are burnt. It was estimated that when Indonesia's forests burned in 1997, the smouldering peat beneath released as much as 2.6 billion tonnes of carbon into the air. That's equivalent to 40% of global emissions from burning fossil fuels that year and was the prime cause of the biggest annual increase in atmospheric CO_2 levels since records began more than 40 years ago (Page *et al*. 2002)

Peat fires, which nowadays mostly result from human activities, could be one of the largest sources affecting the levels of CO_2 in the atmosphere. Post-fire effects reflected in mineralization and fertilization of a peat soil, water level rises and changes in vegetation, could lead to additional smaller but more long-term changes in GHG flux. Peatland fires ignited by lightning strikes were normal phenomena in many areas of the world (see Joosten and Clark 2000). Today peat fire is most frequently the result of human activities (for example, land clearing of forest for agriculture, of natural grasslands for cattle breeding, careless use of fire for domestic purposes, fires started while hunting and fishing etc). As such, peat fire can be treated as one of the largest sources of CO_2 in the atmosphere, as well as the most significant human-induced disturbances to peatlands' GHG fluxes. Peat fires are difficult to extinguish and may last for many months despite extensive rains. In cold regions, peat fires could survive even under the snow cover and heat up after the snowmelt. Peat can be burned to a great depth. For example, during fires in 1997 and 1998 in Kalimantan, some 7500 km^2 of tropical peat-swamp forest was destroyed with a loss of surface peat of between 0.2 and 1.5 metres. Post-fire effects reflected in mineralisation and fertilisation of a peat soil, often a water level rise, and changes in vegetation, could lead to additional smaller, but longer-term changes in GHG flux (see Hooijer et al. 2006).

Dam building for different purposes using a wide range of construction methods and resulting in a variety of different sized dams, could affect existing downstream riparian and fluvial peatlands, with subsequent changes to GHG flux rates. Numerous dams are built on rivers and streams for flood control, water supply, electricity production, shipping improvement and other purposes. Additional to the creation of a headwater reservoir, this alters the runoff regime below the dam. Allowing for differences in river valley geomorphology and climatic conditions, this could affect the water regime and hydro-periods of a floodplain on various different spatial and temporal scales. Damming could also cause the timing of the flood period to shift, particularly when natural peak flow is replaced by controlled water passage. All these changes will affect riparian and fluvial peatlands if they exist there. Even though information on the subject is scarce, we

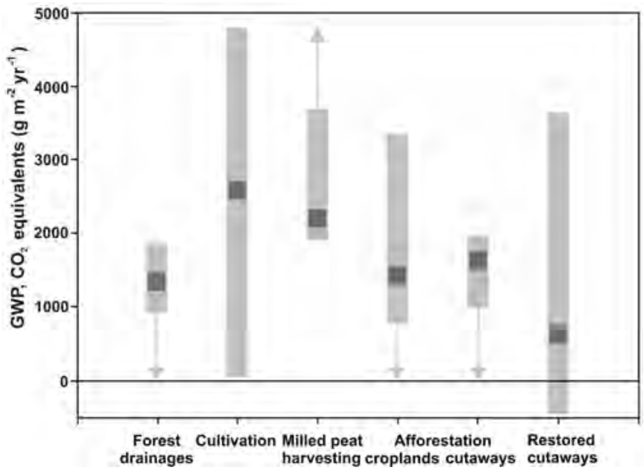

Figure 7.8: The emission values from cultivated peatlands show large ranges of uncertainty. The average values (dark squares), however, illustrate that restored peatlands have less GHG emission that drained and cultivated sites. Downward arrows represent possible additional CO_2 sequestration by vegetation growth and peat accumulation; the upward arrow represents the possible additional CH_4 emission under warm and wet conditions. Source: Alm et al. 2007.

can assume different reactions in terms of CO_2, CH_4 and N_2O fluxes in riparian and fluvial peatlands. Sedimentation of particulate organic matter from flood water could enhance the supply of substrate for methanogens (van Huissteden *et al.* 2005) and damming could suppress this influence.

Inundation of peatlands after creating water reservoirs (especially for generating hydro-electricity) could lead to significant emissions of both CO_2 and CH_4. Creating water reservoirs for hydro-electricity and other purposes very often affects lowland peatlands in the surroundings due to flooding (totally or periodically) and the raising of groundwater levels. Depending on the relief, this could affect different sized areas. Flooding would be expected to lead to an increase in CH_4 emissions. Generally CO_2 emissions may also remain relatively high (or even rise- especially during the first period after inundation when this could be caused by the rapid decomposition of young plant material (Joosten and Clark 2002). Emissions due to the flooding of Canadian wetlands were estimated to represent 5% of Canada's anthropogenic emissions (Roulet 2000).

Inundation and rewetting of degraded peatlands could restore their sequestration function for atmospheric CO_2 in the near future. However, to begin with, it could increase CH_4 emissions, keep relatively high CO_2 releases and have different effects on N_2O flux. The rewetting of degraded peatlands is generally expected to decrease CO_2 and N_2O and increase CH_4 emissions. According to the goal, inundation and rewetting of degraded peatlands could restore their sequestration function of atmospheric CO_2 in the near future (Komulainen *et al.* 1999, Waddington and Price 2000, Petrone *et al*. 2001, Waddington *et al.* 2001, 2003, Tuittila *et al.* 2004). But peatland restoration does not necessarily result in lower emission rates - especially at the beginning. In practice, peatland restoration could lead to a variety of GHG flux changes depending on the site and peat type, previous disturbance (excavation, drainage for agriculture or forestry, etc.), restoration method (inundation, damming, filling of drains, etc.), and especially the period of time passing since the measures were taken. Rewetting could increase CH_4 emissions (Marinier *et al.* 2004, Tuittila *et al.* 2004) and CO_2 release may remain continuously high (Tuittila *et al.* 2000, 2004), possibly caused by rapid decomposition of young plant material, though this is probably a transient phenomenon (Joosten and Clark 2002). Water-level fluctuations of some rewetting plots may cause a drastic increase in N_2O emissions (Flessa and Klemisch 1997, Komulainen *et al.* 1999, Joosten and Clark 2002). Rewetting of drained alder forests led to increased emissions of CH_4, but to decreasing N_2O (Augustin *et al.* 1998).

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8 Impacts of future climate change on peatlands

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Summary points

- Climate change scenarios suggest major changes in temperature, precipitation and other phenomena that will have significant impacts on the peatland carbon store, greenhouse gas flux and biodiversity.
- Global temperature rises of 1.1-6.4°C will be higher in northern high latitudes where the greatest extent of peatlands occurs.
- High latitudes are likely to experience increased precipitation while mid latitudes and some other regions may have reduced precipitation at certain times of year. All areas may be susceptible to drought due to increased variability in rainfall.
- Increasing temperatures will increase peatland productivity by lengthening growing seasons but this will be moderated by enhanced moisture stress.
- Decay rates in the surface of peatlands will increase as a result of rising temperatures, potentially leading to increased methane (CH_4) and carbon dioxde (CO_2) release, but moderated by hydrological changes.
- Tree lines in northern peatlands will shift poleward as a result of higher summer temperatures, and hydrological changes may result in increased forest extent on open peatlands. Both factors will contribute to reduced albedo.
- Increased rainfall intensity will likely enhance peatland erosion in susceptible areas. Erosion may also be enhanced in peatlands subject to desiccation, especially where there are other pressures such as overgrazing.
- Fire frequency and intensity may increase on peatlands that are subject to greater extremes of drought, although human activity is expected to remain the primary cause of fire.
- Hydrological changes, combined with temperature rise, will have far-reaching effects on greenhouse gas exchange in peatlands. Drier surfaces will emit less CH_4, more N_2O and more CO_2, with the converse for wetter surfaces.
- Melting permafrost will likely increase CH_4 emissions and lead to increased loss of dissolved organic carbon in river runoff.
- Inundation of coastal peatlands may result in biodiversity and habitat losses, as well as increased erosion, but local impacts will be highly variable depending on land surface uplift.
- The combined effect of changes in climate and resultant local changes in hydrology will have consequences for the overall distribution and ecology of plants and animals that inhabit peatlands or use peatlands as a significant part of their life cycles.
- Human activities will increase peatland vulnerability to climate change in many areas. In particular, drainage, burning and over-grazing will increase losses of carbon from oxidation, fire and erosion.

8.1 Future climate change scenarios

Current scenarios for climate changes over the 21st century suggest major changes in temperature, precipitation and some other climate phenomena that are likely to result in substantial changes to peatlands. Any assessment of future impacts of climate change on ecosystems must be based on some assumptions concerning the most likely

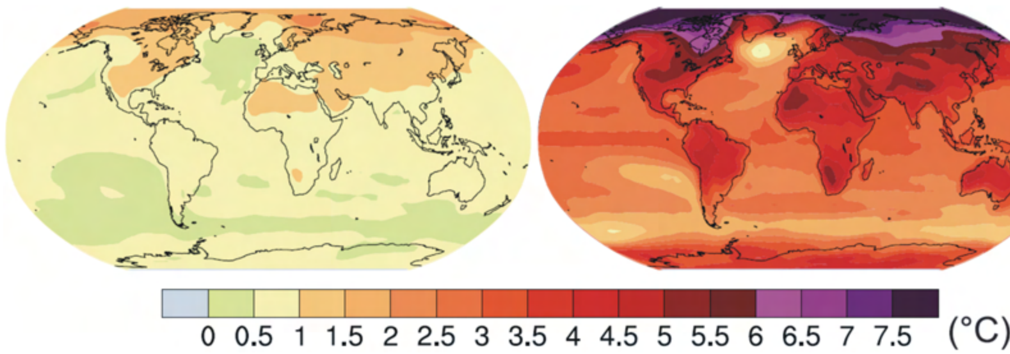

Figure 8.1: Projected changes in temperature in 2020-2029 (left) and 2090-2099 (right) compared to the period 1980-1999, based on the multimodel ensemble for the IPCC A2 emissions scenario. This scenario is chosen to illustrate the spatial pattern of temperature change compared to the global average. It is striking that key peatland areas in the northern high latitudes are projected to experience some of the largest temperature changes, much greater than the global average temperature rise.

trajectory for future climate change. Here, we use the summarised results of the IPCC Fourth Assessment Report (IPCC 2007) as the basis for an evaluation of future changes to global peatland systems, focusing on scenarios for climate change to the end of the 21st century. Based on IPCC data, the magnitude of climate change predicted suggests substantial impacts on the distribution, functioning and biodiversity of peatlands throughout the world. The most recent projections for climate change now have sufficient spatial resolution and adequate confidence levels to begin to suggest likely trajectories for peatlands at the regional scale. Figures 8.1 and 8.2 illustrate the key regional differences in temperature and precipitation predictions.

The likely [1] ***range for global average mean annual temperature rise by the 2090s is between 1.1 and 6.4^{o}C, as compared with the period 1980-1999. There are significant regional variations in the relative magnitude of change. In general, temperature change will be greatest at higher latitudes over land and less marked at low latitudes over oceans. There may also be seasonal differences in the magnitude of temperature increase for some regions.*** The globally averaged surface temperature is projected to increase by 1.1 to 6.4°C by the period 2090-2099, as compared with 1980-1999. The range of variability in predictions reflects a wide range of possible socio-economic scenarios and is based on a suite of different climate models. While these figures indicate global average annual changes, significant regional variability in future temperatures is expected. It is **very likely** that nearly all land areas will warm more rapidly than the global average, particularly in the northern high latitudes in winter. In northern regions of North America and central Asia, estimated land surface temperature increases are >40% above the global average. The only land surfaces where warming is less than the global average, are southern South America in winter, and south and southeast Asia. The rate of global temperature rise is very likely to be more than double the rate of natural climate change experienced during the 20th century, and over the next 20 years, an increase of 0.2^{o}C per decade is predicted for almost all emissions scenarios.

There will be changes in the frequency and magnitude of temperature extremes with fewer extremely cold days and more extremely warm days. It is **virtually certain** that there will be warmer and more frequent hot days and nights over land areas and with fewer cold days and nights over nearly all land areas. It is **very likely** that the frequency of warm spells and heat waves will increase.

There is less confidence over predicted changes in precipitation than for temperature, but the following changes are found in most modelled scenarios. Global average

[1] Where they refer to IPCC (2007) report results, the following terms are emboldened and are associated with subjective estimates of likelihood based on expert judgement. Virtually certain >99%, extremely likely >95%, very likely >90, likely >66% chance)

precipitation will be higher but there will be significant regional variability, with some regions seeing an increase in precipitation while others may see decreases. Greater year-to-year variability is very likely over most areas where an increase in mean precipitation is projected. Globally averaged water vapour, evaporation and precipitation are projected to increase. The magnitude of the global increase in precipitation varies between models and in line with the different socio-economic scenarios but is typically between 2 and 15% (Cubasch *et al.* 2001). Estimates of change at the regional scale show much greater variation with differences in the sign and magnitude of change, typically of the order of ± 5 to 20%. In addition, seasonal changes in precipitation are crucial to ecosystem impact assessment, especially for peatlands (Figure 8.2). It is **likely** that precipitation will increase in high-latitude regions during the whole year whereas in mid-latitudes projections suggest an increase in winter and decreases in some peatland regions in summer (e.g. Western Europe, Tierra del Fuego). Winter (December-January-February) increases in precipitation are also projected for tropical Africa and increases are noted for June-July-August in southern and eastern Asia. Australia, Central America and southern Africa show consistent decreases in winter (June-July-August) rainfall with a **likely** increase in risk of drought. Decreased summer precipitation is **very likely** for the Mediterranean, with a **likely** increase in risk of drought.

Importantly for peatlands, a general drying of the mid-continental areas during summer may occur as a result of a combination of increased temperature and evapotranspiration losses without adequate compensatory increases in precipitation, leading to increased associated risk of drought. It is **very likely** that there will be an increase in the frequency of intense precipitation events over many regions and that there will be greater year-to-year variability over most areas where an increase in mean precipitation is projected.

There may be no change in the amplitude and frequency of El Niño events, but future climate change will increase the risk of El Niño impacts occurring. Confidence in projections of the future amplitude, frequency and spatial pattern of El Niño is limited by the ability of models to simulate this part of the climate system. Current projections show only small increases or no change in the amplitude of El Niño over the next 100 years. However, even with no change in El Niño, global temperature increases are likely to lead to greater extremes of drying and heavy rainfall, increasing the risk of drought and flood during El Niño events. Furthermore, current trends for surface temperatures to become more 'El Niño like' in the tropical Pacific (east warming more than west and an eastward shift in precipitation) are projected to continue (Meehl *et al.* 2007).

Changes in storms and cyclones are less certain than many other changes, but increased intensity of tropical cyclones may lead to increased and peak precipitation and wind strength in affected regions. In higher resolution modelling studies, there is a **likely** increase in peak wind intensities and precipitation in future tropical cyclones. However, there may be fewer tropical storms overall. There may be fewer mid-latitude storms, associated with a poleward shift in storm tracks, but increased wind speeds in those regions, especially in the southern hemisphere (Meehl *et al.* 2007).

The total precipitation and interannual variability of the Asian summer monsoon may be increased. Precipitation may also increase in some areas (west African monsoon, Australian monsoon) or decrease in other monsoon areas (Sahel, Mexico/central America). The monsoon systems are important factors in seasonal water supply to many regions of the world, including for wetlands and peatlands. One of the main projections is for an increase in interannual variability in precipitation during the Asian summer monsoon. Precise changes are dependent on particular emissions scenarios. Furthermore, the size and distribution of aerosol forcing complicates this picture, especially in Asia where there are likely to be major emissions of a number of aerosols. There is thus considerable uncertainty in the degree of change in these regions (Meehl *et al*. 2007).

There are many other extreme climatic phenomena relevant to peatlands for which projections cannot yet be made. Climate models are incapable of resolving small-scale phenomena such as thunderstorms, tornadoes, hail and lightning strikes. The latter may be particularly important in determining fire frequency on peatlands.

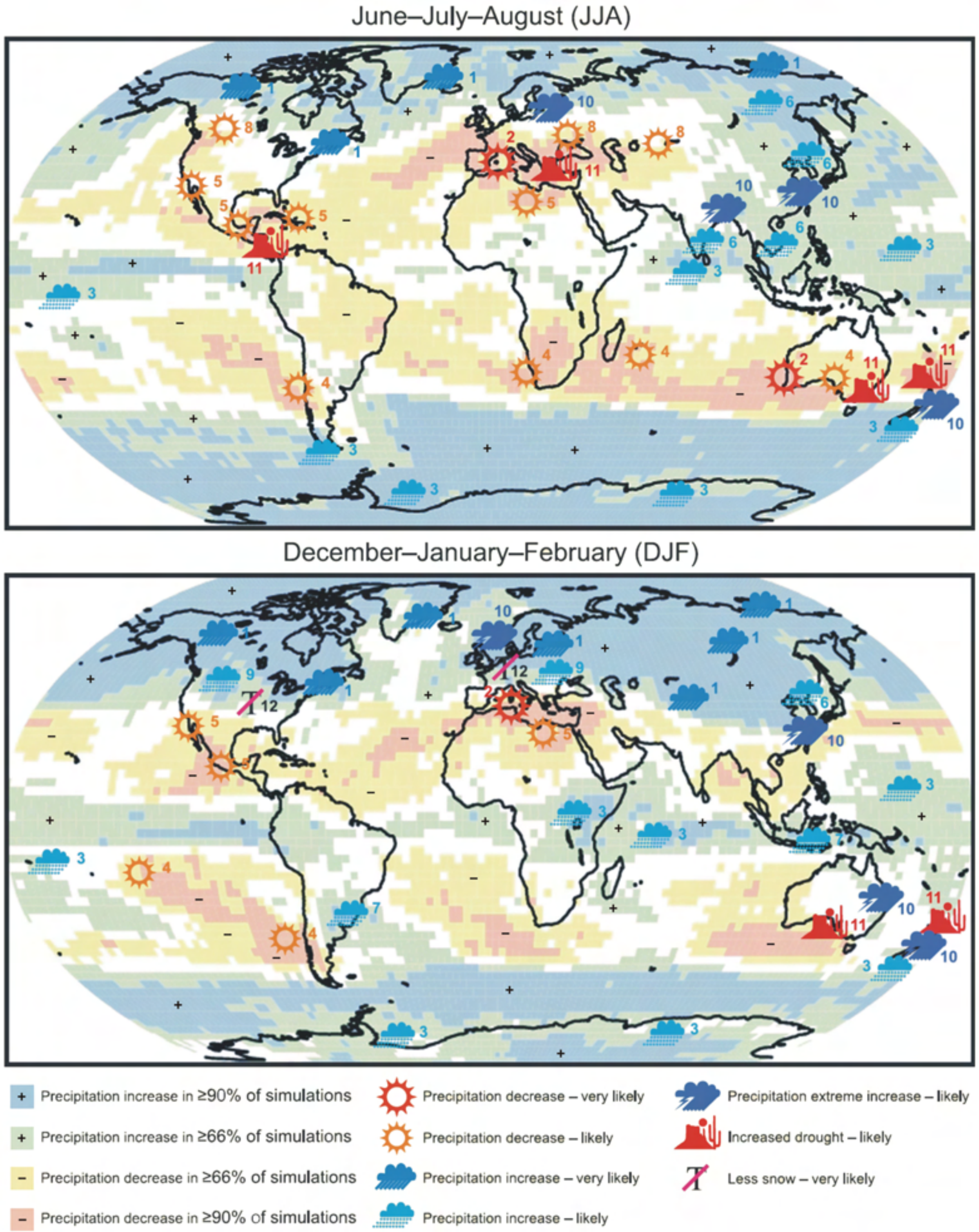

Figure 8.2: Key future changes in mean and extremes of precipitation, snow and drought. Background shading indicates level of consistency between models used (left hand side key) and symbols indicate locations of most significant regional changes. Reproduced from Christensen et al. (2007).

Numbers on figure show:

(1) Very likely annual mean increase in most of northern Europe and the Arctic (largest in cold season), Canada, and the North-East USA; and winter (DJF) mean increase in Northern Asia and the Tibetan Plateau. (2) Very likely annual mean decrease in most of the Mediterranean area, and winter (JJA) decrease in southwestern Australia.(3) Likely annual mean increase in tropical and East Africa, Northern Pacific, the northern Indian Ocean, the South Pacific (slight, mainly equatorial regions), the west of the South Island of New Zealand, Antarctica and winter (JJA) increase in Tierra del Fuego. (4) Likely annual mean decrease in and along the southern Andes, summer (DJF) decrease in eastern French Polynesia, winter (JJA) decrease for Southern Africa and in the vicinity of Mauritius, and winter and spring decrease in southern Australia.(5) Likely annual mean decrease in North Africa, northern Sahara, Central America (and in the vicinity of the Greater Antilles in JJA) and in South-West USA.(6) Likely summer (JJA) mean increase in Northern Asia, East Asia, South Asia and most of Southeast Asia, and likely winter (DJF) increase in East Asia.(7) Likely summer (DJF) mean increase in southern Southeast Asia and Southeastern South America. (8) Likely summer (JJA) mean decrease in Central Asia, Central Europe and southern Canada.(9) Likely winter (DJF) mean increase in central Europe, and southern Canada. (10) Likely increase in extremes of daily precipitation in northern Europe, South Asia, East Asia, Australia and New Zealand.(11) Likely increase in risk of drought in Australia and eastern New Zealand; the Mediterranean, central Europe (summer drought); in Central America (boreal spring and dry periods of the annual cycle). (12) Very likely decrease in snow season length and likely to very likely decrease in snow depth in most of Europe and North America.

Northern Hemisphere snow cover and sea-ice extent are projected to decrease further. The extent and duration of snow cover are expected to decline in association with increased temperatures. However, increased winter precipitation over northern high latitudes may produce greater depths of snow with important implications for the thermal regime at the peatland surface. Models suggest major decreases in sea-ice extent, with some models predicting disappearance of Arctic summer sea ice cover by the end of the 21st century under the highest emissions scenarios (Meehl *et al.* 2007). Reduced snow cover (including that on peatlands) and sea-ice reduce the albedo of land and sea surfaces, leading to further enhancement of atmospheric warming.

Atmospheric carbon dioxide concentrations will rise by between 90 and 250% above the pre-industrial natural levels. In AD 1750 before significant industrial activity and anthropogenic emissions, the atmospheric concentration of carbon dioxide was 280 ppm. By the end of the 21st century it is expected that this will have risen to 2-3 times this level unless there is a significant change in emissions. This is higher than at any time in the recent geological past during the evolution of the biota that currently occur in peatlands. The combined effects of raised CO_2 levels on peatland plant and microbial communities are largely unknown.

Global average sea level is projected to rise by between 18 and 59 cm due to thermal expansion of sea water and melting of land-based glaciers and ice caps. These figures are representative of the full range of socio-economic scenarios up until AD 2100. There are considerable uncertainties over the likelihood of acceleration of ice flow in both Greenland and the Antarctic. If these occur, they may increase sea levels by a further c. 20 cm. There will be substantial regional variability in sea-level rise due to local variations in the influence of ocean currents and thermal expansion. Projections for these regional variations are poor although there is some agreement on greater than average rise in the Arctic Ocean and less than average rise in the Southern Ocean. Further local variability will arise from isostatic and tectonic land movements. Short-term extremes in local sea-level may be greater if storms become more severe.

Sea level rise may lead to erosion of peatlands by wave action (Tierra del Fuego, Argentina).

8.2 Impacts of climate change on peatlands

Climate change will have far-reaching consequences for peatlands. There will be a wide range of impacts on biodiversity and carbon cycling. Indirect effects will follow, specifically in terms of feedbacks to the climate system through greenhouse gas exchange, and impacts on other functional values of peatlands. Preceding chapters have shown that peatlands are fundamentally linked to climate variability and conditions. Climate is a key determinant of their distribution, condition and typology (Chapters 2 and 4). Their biogeography and biodiversity are also linked to climate (Chapter 5), and variability in weather and climate is a primary control on many aspects of their functioning in relation to the carbon cycle and greenhouse gas exchange (Chapter 7). Peatlands can therefore be affected in many ways by projected future climate changes. Some of the reactions to climate change will result in feedbacks through changes in greenhouse gas fluxes and storage.

8.2.1 Effects of increasing temperatures

Increasing temperatures will increase peatland primary productivity in some regions due to lengthened growing seasons and increased average temperatures during the growing season. In other areas increased temperatures will reduce primary productivity due to enhanced evapotranspiration and increased moisture stress. The length of growing seasons has already increased in much of the northern hemisphere, as indicated by earlier flowering times of herbaceous plants (Fitter *et al.* 2002) and earlier emergence of leaves in broadleaf tree species in mid-latitude

Europe (Menzel 2000). In future, it is expected that the growing season length will increase by 20-50 days by 2100 as measured by the number of days above 5^{o}C (Figure 8.3). Whilst increased growing seasons will be experienced across many biozones, the productivity response may be greater in northern regions where peatland extent is greatest, because there will be much less drought stress to limit growth.

Climate warming leads to desiccation and desertification of peatlands in steppe regions such as in Central Asia, Mongolia. In the 1950s the pictured habitats were still described as impassable wet peatlands.

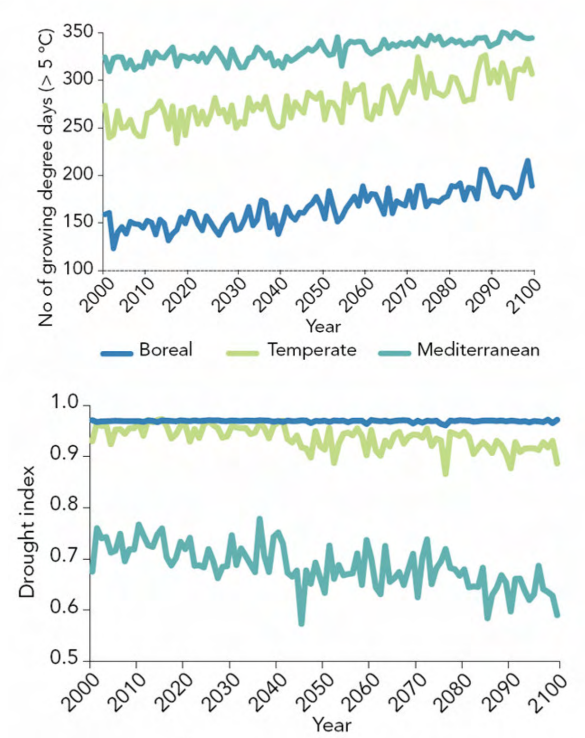

Figure 8.3: Changes in European growing season length (top) and an index of drought stress (bottom) for boreal, temperate and Mediterranean regions. In the lower graph, higher numbers indicate lower drought stress (From European Environment Agency 2004).

Increasing summer temperatures in the Arctic and mountain areas will result in the northern tree line migrating to higher latitudes and altitudes in both peatland and non-peatland areas. This will decrease the albedo (reflectivity) of the surface, further enhancing warming of the atmosphere. Tree lines (the latitudinal or altitudinal limit for tree distribution) is primarily limited by summer temperatures. The threshold for different taxa varies but trees cannot reproduce or grow after germination unless summer temperatures exceed a thermal threshold. Tree lines have varied in the past (Kullman 1999) but recent evidence suggests that northern tree lines are already experiencing northward shifts as a result of recent rises in summer temperatures (ACIA 2005). Forest has a darker surface than the open sedge and moss dominated peatland that it replaces. This leads to increased absorption of solar radiation leading to further enhancement of near-surface atmospheric warming.

Increased temperatures will generally result in enhanced decay rates and loss of carbon. However, the response of decay rates in the surface layers of peatlands to increased temperatures is complex and depends on hydrological and other conditions as well as temperature. Microbial decay is largely driven by temperature. Increased temperatures result in greater microbial activity and therefore high decay rates (Figure 8.4). However, the microbial population can only take advantage of raised temperatures if a range of other conditions are also met. A primary constraint is the nature of the substrate. Different plant materials have different intrinsic decay rates. For example, different species of *Sphagnum* decay at different rates, despite their superficially similar appearance (Johnson and Damman 1991). In addition, susceptibility to decay declines over time, so that after intense or prolonged decay, the rate of decay slows because only the most recalcitrant material remains. Overlain on the effect of the substrate are the effects of moisture availability, oxygen content (influencing the dominance of aerobic or anaerobic decay) and the impact of periods of freezing.

Increasing temperatures will generally accelerate the microbial processes responsible

for CO_2, CH_4 and N_2O emissions from peatlands. Impacts of increased temperatures on greenhouse gas emissions are difficult to distinguish from the complex effects of simultaneously changing hydrological regimes (see below). Ecosystem respiration has been observed to depend on soil temperature variations but not on water-table level in a continental bog with inherently deep water levels (Lafleur *et al.* 2005). In high latitudes, the interannual variations in CO_2 balance are mostly due to variations during the snow-free period, but the respiration efflux during the winter time is also a significant component in the annual balance. Snow melt timing appears to be the most important single factor in determining the balance, and consequently, longer growing seasons may give rise to higher rates of carbon sequestration instead of being a threat (Aurela *et al.* 2004). Methanogenesis is also highly temperature dependent and where water tables remain high, CH_4 emissions will increase (Whalen 2005).

8.2.2 Effects of precipitation changes

Responses to precipitation changes will be highly variable depending on local and regional factors. Projections of future precipitation show a much more varied response than those for temperature (Section 8.1). There are large regional variations in both the sign and magnitude of change, as well as in seasonality. In regions of increased year-round precipitation, peatlands may become wetter, but only if the increase in precipitation is not counterbalanced by increased evapotranspiration losses due to increased temperatures. In northern high latitudes where precipitation is projected to increase year-round, peatland water tables may rise, particularly in spring, when combined with the effects of snowmelt. However, increases in summer precipitation may not compensate for higher temperatures and greater numbers of very hot days, so there will be periods of increased dryness and drought during the summer. In other regions such as the northern mid-latitudes, a decrease in summer precipitation will cause a fall in water tables during the summer, exacerbated by increased temperatures. Increased winter precipitation in the mid-latitude regions will not provide any compensation for summer drought, as excess moisture will be lost through runoff. In tropical peatland regions, projections suggest decreases (e.g. Amazon basin), little change (e.g. tropical west Africa) or increases (e.g. Indonesia) in precipitation. At any particular location, the hydrological impacts will be mediated through topography and mire type. For example, ombrotrophic bogs may be more susceptible to reduced precipitation than fens, where groundwater flow can buffer some of the temporary drought periods.

Increased frequency of heavy rainfall and greater intensity of precipitation may cause enhanced erosion of susceptible peatlands. Peatlands that are susceptible to erosion through exposure of bare peat surfaces lose large amounts of peat during heavy rainfall

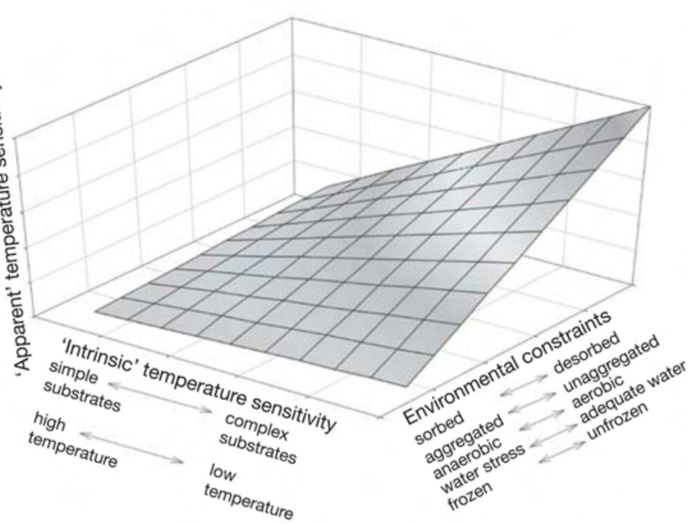

Figure 8.4: Factors affecting the sensitivity of organic matter to decay. The intrinsic temperature sensitivity is affected by the temperature and the substrate. The environmental constraints dampen the sensitivity to decay because of water availability, soil structure, freezing. Although the response is shown as linear, the relationship between these factors and decay is often non-linear (Reproduced from Davidson and Janssens 2006).

events and also through aeolian processes (Evans and Warburton 2007). In temperate and high latitude peatland regions, potential threats are wetter winters and increased drought frequency in summer. In particular, the predicted increased intensity of rainfall events may exacerbate erosion of peat in areas already disrupted by the effects of grazing, fire and pollution, and also in regions subject to other future climate-related damage. Increased severity and frequency of droughts would cause desiccation of the peat surface, resulting in structural damage such as cracking and increased susceptibility to erosion during wetter periods (Evans *et al.* 2006). In extreme cases, very wet conditions have led to mass movement of peat in 'peat-slides' both during intense rainfall events in summer and more prolonged wet conditions during winter (Warburton *et al.* 2004). More extreme hydrological conditions in future may increase the likelihood of such events.

Peat erosion on the Shetland mainland (UK) after an exceptionally heavy rainstorm in September 2008.

Where increased flooding of peatlands occurs due to higher frequency and magnitude of heavy precipitation events, there may be increased CH_4 release. The relationship between water-table depth and methane emissions is well known, with higher water tables causing increased methane emissions (Chapter 7). Increased flooding of peatlands in northern high latitudes is expected as a result of thermokarst thawing (see below), but temporary increases in surface wetness may also occur in association with winter and spring increases in precipitation, when temperature and evapotranspiration increases are inadequate to counteract this. The extent of this effect is unknown but it is likely to be minor compared to other changes given relatively low temperatures at these times of year.

8.2.3 Hydrological changes

The hydrological regime is the principal factor controlling ecosystem processes in peatlands. Any changes in water balance should be expected to have far-reaching effects on biogeochemical cycles, productivity and community composition. Increased evapotranspiration, altered precipitation, and increased frequency of extreme events (e.g. droughts, intense rainfall) are likely to result in generally lower water-table depths during the growing season (Roulet *et al*. 1993, Waddington *et al.* 1998). However, there may be exceptions to this generalisation in some regions owing to permafrost thawing, and large regional increases in summer precipitation. Impacts of the hydrological changes on ecosystems are mediated through autotrophic (vegetation) and heterotrophic (microbial) communities. The responses of these components to changing ecohydrology may alter the carbon dynamics of peatlands significantly, as observed during unusually warm and dry summers (Carroll and Crill 1997, Alm *et al*. 1999).

A combination of increased temperatures and changes in precipitation regime will determine the future hydrological status of peatlands. The direction and magnitude of surface wetness (moisture, water table) changes will vary between regions. Changes in precipitation will be particularly important in determining the local and regional changes in hydrology. The regional complexity of projected future climate change (see Section 8.1) will lead to a regionally and seasonally variable hydrological response in peatlands. However, some generalisations can be made concerning likely regional responses. First, the strongest effects are likely to be in areas where peat growth is currently marginal. The southern limit of extensive ombrotrophic peatlands across North America and Europe coincides with the region of reduced summer precipitation and is likely to see major falls in water table throughout the summer. Areas where peatlands are limited to water-collecting sites (e.g. southern Europe, southern Africa) are also likely to contract, as these generally lie within regions of reduced future water availability. Where peat growth is currently limited by productivity as a result of low temperatures at high latitudes and altitudes, there may be an expansion of peatlands in topographically suitable locations. This effect is mainly likely to be felt in the high Arctic.

Changes in water-table levels will affect the carbon dioxide and methane exchange of peatlands. The global net effect of these changes on 'global warming potential' of peatlands is not known with any accuracy, but it is likely that the carbon sink function of existing peatlands will be reduced overall. This may be compensated for in part by expansion of some peatland areas. In general, falling water tables in many peatlands will result in lower CH_4 emissions but higher CO_2 emissions. In areas where peat accumulation is already marginal, this will result in a gradual loss of the peat by oxidation. Conversely, in some regions (notably thawing permafrost areas), increased flooding will increase CH_4 release but may also increase CO_2 drawdown from increased productivity. The relationship between these two effects in terms of their feedback to radiative forcing is complex, particularly as CH_4 has a much shorter lifetime but a more powerful instantaneous impact as a greenhouse gas. Taking these effects into account, northern peatlands currently appear to have net negative effect on radiative forcing (Frolking *et al.* 2006). Predictions of future changes are more uncertain.

There is a lot of information on the impacts of water-level draw-down based on research in forestry drained peatlands (see Chapter 7). These studies may be cautiously used to represent the climate change impact because the effect of drainage on ecosystem structure and functioning is rather similar to that predicted after drying caused by climate change in the northern latitudes. Bubier *et al.* (2003) concluded that a drier climate with lowered water-table levels may reduce the CO_2 sink function of peatlands for some growth forms and increase it for others, suggesting that ecosystem carbon and climate models should account for differences in growth form responses to climate change. It also implies that plant functional types respond on short timescales to changes in moisture, and that the transition from sedges to shrubs could occur rapidly in peatlands under a drier and warmer climate. Similar observations were presented by Strack *et al.* (2006). Fairly small changes in hydrological regimes have been observed to influence the CH_4 emission rates from peatlands, with dry conditions producing clearly lower emission rates (Strack *et al*. 2004, Bubier *et al.* 2005). Exceptionally dry summers have been reported to temporarily convert pristine peatlands from sinks to sources of CO_2 (Alm *et al.* 1999, Lafleur *et al.* 2003). Increased frequency of droughts may also affect the CO_2 exchange through changes in vegetation (Laiho *et al.* 2003) and litter quality (Laiho *et al.* 2004). Alm *et al.* (1999) suggested that the ratio between moist and dry summers should be at least 4:1 to retain a positive C balance and 5:1 to retain the average long-term accumulation rate of 25 g C m^{-2} yr^{-1}. If peatlands are generally drier over large areas of the northern mid to high latitudes, the net effect will be to reduce the CO_2 sink function. However, it might be expected that this will be compensated for in part by increased productivity in some northern peatlands and expansion of peatland areas at the northern limit for peat formation.

Lower water tables will increase the rate of release of N_2O. Increased aerobic decay in the surface layers of peatlands following water-table draw-down is accompanied by increased mineralization of organic compounds including nitrogen (N). Although levels of N are often low in ombrotrophic systems, they are much higher in minerotrophic peatlands such as floodplain fens. The N is released in the form of nitrous oxide (N_2O), another powerful greenhouse gas (see Chapter 7). Although N_2O emissions from natural peatlands are generally low, peatland drainage is known to increase N_2O release (Minkkinen *et al*. 2002, Alm *et al.* 2007). This suggests that N_2O emissions may increase with water-table draw-down and increased temperatures in the future. However, such increases may be relatively small on natural peatlands and the largest emissions of N_2O are likely to be from peatlands used for agriculture, where the addition of nitrogen fertilisers stimulates further release of N_2O, even when cropping is abandoned (Maljanen *et al*. 2007).

Hydrological change will result in major changes in microbial, plant and animal communities. Hydrology is the most important influence on peatland communities and many species occur in restricted hydrological niches (Chapter 5). Changes in hydrology will inevitably result in changes to the distribution of individual species and communities. This will happen at various scales. Small-scale micro-topographical patterning provides a range of microhabitats for peatland taxa. Changes in the balance between pools, lawns and hummocks on individual sites will lead to a change in the plant and animal communities present. Specialist taxa tend to be more dependent upon the wetter microhabitats in shallow pools and hollows and loss of these habitats may lead to local extinctions of aquatic and semi-aquatic taxa. The ability of these taxa to migrate to more suitable locations may be limited in regions where peatlands have become fragmented.

Hydrological changes will result in the expansion of forest cover on drying peatlands and a reduction in tree cover on peatlands with increased surface wetness. Tree cover on peatlands is usually less dense than on surrounding mineral soils. Typically, trees become smaller and less dense towards the wetter, central area of a peatland. Tree establishment and growth is limited by high water tables that keep the rooting zone saturated. Thus when water tables fall, tree cover becomes more extensive and existing trees may be able to grow (Choi *et al.* 2007). Once trees become established on drier areas of peatlands they may further enhance transpiration, providing a positive feedback and further drying of the peatland surface beneath the trees and adjacent areas. Increases in tree cover may also add to the decrease in surface albedo arising from the more general changes in tree lines, and reduced snow extent (see above). The situation may be more complex in tropical peatlands; although some trees will increase growth if water tables fall, others may suffer increased mortality in drought years (Nishimua *et al*. 2007).

Fire frequency may increase on peatlands that are subject to greater extremes of drought. Natural fires occur throughout many parts of the world, including areas where peatlands are common. Although peatlands are some of the wettest locations in the landscape, in dry summer seasons, surface layers of peat and plant litter provide a highly combustible mixture for fire to start in or to spread to from surrounding upland. More prolonged, more severe or more frequent periods of drought may occur in some peatland regions (see above). Even in some areas where rainfall is projected to increase, there may be more severe short periods of drought if rainfall variability increases. There are many causes of peatland fires, principally related to human activities such as clearance for agriculture, improvement of grazing conditions or accidental causes. Lightning strikes may be a cause of natural fires in some circumstances but the occurrence of natural fires is limited when compared with those started by people. It is unknown if the frequency of natural fires will increase significantly in the future, because lightning strike frequency cannot be predicted with any certainty. However, any increase in droughts will make uncontrolled natural or anthropogenic fires more likely and will lead to increased intensity of burn. In particular, lowered water tables may make the loss of upper peat layers more likely during peatland fires and the areas burnt may be more extensive.

In areas where peatlands become drier, extreme events such as drought and storm rainfall will increase erosion by water and wind. Peatlands in some parts of the world, such as Central Asia, are likely to become much drier in future. Desiccation of peat surfaces is likely to make them more susceptible to erosion. Exposure of bare peat surfaces and disturbance from activities such as grazing will result in further destabilization of the peat structure. During droughts, the upper peat layers can be eroded by wind and the surface becomes deflated. During intense rainfall peat can also be moved down slope and lost in runoff. There have been relatively few studies on losses of peat from desiccation and wind-blow but measurements of peat loss from exposed peat surfaces in England show that these losses are important and are likely to increase under future climate scenarios (Foulds and Warburton 2007).

In regions strongly affected by drying during ENSO years, the frequency of drought is likely to increase due to the background increase in temperature and changes in precipitation. Several peatland regions are currently affected by ENSO. During these events, peatlands in southeast Asia and to a lesser extent, the Amazon basin, experience much drier than normal conditions. Although ENSO may not increase in frequency or intensity, the frequency and impacts of drought will increase in ENSO years because of the background climatic changes against which they occur. This will enhance fire frequency and intensity especially in drained areas and where people light fires for clearance and agriculture. During dry years, the Amazon Basin already acts as a carbon source (Tian *et al.* 1998), partly as a result of carbon loss from peat and organic soils. The number of such years is likely to increase in the future.

Climate warming raises the probability of peat fires all over the world especially in peat swamp forests in SE Asia.

Climate change will enhance incidence of peat fires. During extreme drought in 2002, even very wet raised bogs burned in European Russia.

Peat washed down from eroded mountain peatlands in Mongolia.

Changes in river runoff regime may change flood periods and other characteristics of the hydrological regime of riverine and lacustrine peatlands. The changing balance between precipitation and evapotranspiration will result in alterations to river flows and their seasonal variability. These changes will affect peatlands in floodplains and lake margins through more dynamic flood regimes from increased intensity of rainfall and droughts. Increases in precipitation and earlier snowmelt in the northern high latitudes will lead to earlier and increased runoff of rivers discharging into the Arctic Ocean. The total increase in runoff is expected to be in the region of 10-20% depending on the climate scenario used, with much greater percentage increases during winter (Walsh *et al.* 2005). This will affect the salinity, ice cover and circulation of the Arctic Ocean.

8.2.4 Changes in permafrost and snow cover

Melting of permafrost may stimulate CH_4 emissions from wet peatland sites and peat decomposition and CO_2 release from dry peatland sites such as palsas. Rapid permafrost melting has been reported to increase formation of thermokarst ponds and fen-bog vegetation with rapid peat accumulation through natural successional processes of terrestrialization (Payette *et al.* 2004). Both increased temperatures and increased snow depth (and therefore insulation) may be a cause of permafrost degradation. Contrary to current expectations, the melting of permafrost caused by recent climate change did not transform the peatland to a carbon-source ecosystem, as rapid terrestrialization exacerbated carbon-sink conditions (Payette *et al.* 2004). However, the developing fen vegetation may develop into an efficient producer of methane emissions (Wickland *et al.* 2006), which may counteract the climatic impact of CO_2 sequestration.

Reduction in permafrost extent in peatlands may lead to greater release of dissolved organic carbon in river runoff. Permafrost prevents or reduces decay of organic matter in northern high latitude peatlands. Where decay occurs, carbon is lost as CO_2 and also in dissolved organic carbon (DOC) in runoff. Much higher DOC concentrations have been found in catchments with permafrost-free peatlands than in those dominated by permafrost. Furthermore, there is a correlation between the extent of peatland cover and DOC concentrations in runoff in permafrost free catchments. On this basis it is predicted that losses of DOC in rivers draining the West Siberian region may increase by 29-46% by the year 2100 (Frey and Smith 2005).

Increasing temperatures are likely to lead to a large reduction in the occurrence of palsa mires. Palsa mires occupy a zone in the high northern latitudes (Chapter 2). They are tightly constrained climatically, suggesting they are particularly sensitive to climate change (Parviainen and Luoto 2007). Recent observations suggest that palsas are already declining in some areas (Zuidhoff 2002). In Fennoscandia, an increase in mean annual temperature of 4^{o}C would result in the loss of all palsa mires from this region. Significant reductions in the extent of palsas are likely to occur within the next 30 years and conditions suitable for palsa formation may have disappeared completely by the end of the century. Structural collapse of these relatively dry peatlands will lead to flooding accompanied by increased CH_4 release, and loss of habitat for characteristic bird species (Fronzek *et al.* 2006).

Melting of permafrost leads to degradation of palsas and expansion of fen peatlands with associated changes in GHG emissions and biodiversity (West Siberia, Russia).

Increased snow depth during winter may affect the thermal regime of northern peatlands, exacerbating the effect of increased temperatures on permafrost melt. Snow cover is important in insulating the peat surface during winter. Deeper snow leads to less intense freezing and reduced permafrost formation. For example, at the southern margins of palsa distribution, palsas only occur in particular areas where wind action is sufficient to reduce snow cover (Nihlen 2000). Increased winter precipitation may thus increase the insulation of peatlands in northern regions, leading to further reductions in permafrost formation.

8.2.5 Sea level rise

The potential extent and severity of the impacts of sea-level rise on peatlands has not been assessed in any systematic way. However, many peatlands occur in coastal areas, often as fens linked to saline wetlands (e.g. saltmarshes) or in low lying floodplains. Assessment of local and regional impacts depends on a good understanding of local land-surface movement as well as global average sea-level change. Only general speculative observations are made here.

Inundation of coastal peatlands may result in biodiversity and habitat losses with conversion of freshwater peatlands to saline marshes. A rise in base level may allow the spread of new peatlands inland if land is made available for this. Gradual sea-level rise will result in a shoreward displacement of the boundary between saltmarsh and freshwater wetland as the height of highest astronomical tide rises. Complete inundation of saltmarsh and coastal peatlands may even result in destabilisation of the peat matrix and the release of CH_4. However, due to the rise in base level, areas further inland may be increasingly susceptible to flooding and freshwater peatlands could spread inland if the topography is suitable and land use policy allows for this. Gradual sea-level rise is likely to take place only in areas that are isostatically and tectonically stable. In areas that are undergoing land-uplift at the same or greater rate than sea-level rise, sea-level change will not present a threat. For example in northern Sweden and Finland, land uplift rates of 8-10 mm pa are far in excess of the likely 3-5 mm pa of global sea-level rise. The only impact in such areas will be a slowing of new mire development on uplifted land surfaces.

In low-lying peatland areas, intrusion of saline water into aquifers may give rise to increased salinity and changes in the ecology and functioning of the system. Floodplain fens and some other peatlands close to the coast are partly dependent on groundwater for their water supply. Aquifers close to the coast are often linked to the sea and it is possible that over time their groundwater will become more saline. This will change the growing conditions for plants and the geochemical conditions at the surface.

There is an increased risk of erosion of coastal peatlands in areas experiencing sea-level rise. In some locations where peatlands meet the coast, rising sea-levels may result in incremental erosion of peat, with loss of particulate organic carbon (POC) directly into the ocean. The extent of physical erosion depends upon the wave conditions and rate of sea-level rise. Gradually increasing sea-level in a relatively sheltered wave environment is more likely to result in succession to saltmarsh and the accumulation of marine sediments rather than the loss of peat.

8.2.6 Carbon dioxide fertilisation

Increased atmospheric CO_2 concentrations may lead to enhanced growth of some peatland plants, but any response to elevated CO_2 will be moderated by competitive interactions, and other chemical and hydrological conditions. It is well known that plant growth can be stimulated by increases in CO_2 concentrations. Peatland plants are likely to respond to increased CO_2 concentration in a similar way but experiments on peatland plants and plant communities have suggested a more complex response. Laboratory studies have shown that *Sphagnum* increases its growth rate in response to rising CO_2 (Silvola 1985), but moisture may be a limiting factor and growth rates decline markedly once moisture levels are below optimal levels (Silvola and Aaltonen 1984). Likewise, community responses may be different to individual species effects. For example, competitive interactions between *Sphagnum* and vascular plants resulted in a decrease in moss cover and an increase in vascular plant cover under raised CO_2 (Fenner *et al.* 2007). Furthermore, in this same experiment, an increase in productivity of the plant community was more than compensated for by increased decay rates as a result of higher decomposition rates in the plant litter. Microbial communities are also affected by changing CO_2 levels (Mitchell *et al.* 2003), probably controlled indirectly through shifts in plant communities and the nature of plant detritus. The impacts of future elevated CO_2 concentrations on peatland carbon sequestration are therefore rather difficult to assess with any certainty, but it seems unlikely that there will be major gains from CO_2 fertilisation because of other effects on plant communities and growth rates.

8.2.7 Other impacts of climate change on peatlands

Non-linear responses to climate change may lead to 'surprise' changes in peatland systems. Some of these changes will be irreversible. Past climate change has led to sudden changes in peatlands (e.g. the so called Grenzhorizont in Europe, Chapter 4). Sometimes peat accumulation is interrupted for several hundred years by events such as fires, floods or long-term droughts. Even if climate change proceeds as a gradual process, it is unlikely that the peatland response will be smooth and monotonic. Many of the processes expected to change in response to climate change are likely to have thresholds past which changes are sudden and perhaps irreversible. For example, drying of peat surfaces can lead to cracking and desiccation to the point where rewetting the peat is extremely difficult. Once this initial severe drying has occurred, slow oxidation and peat removal by physical erosion occurs and is largely irreversible until the layer of altered peat has been lost.

There will be longer term (100-1000 years) impacts as a result of climate changes taking place this century, due to altered successional processes, and the slow response of some processes. Many peatland ecosystems have a high level of 'self-determination' due to successional processes. This means that once an initial change has taken place, it may lead to other (different) changes in the future. For example, in the case of permafrost collapse, the initial formation of pools may be succeeded by a phase of pool-infill and renewed peat growth, which leads to a very different peatland system over hundreds to thousands of years.

Climate change will interact with anthropogenic disturbance. Some of the impacts of climate change will exacerbate the impacts of activities such as drainage, grazing, burning and logging. Human disturbance to peatlands often makes them much more vulnerable to climate change impacts. Climate change is only one of many factors affecting peatlands. In Chapter 3, the range of uses of peat and peatlands was described. In most cases, human impacts on peatlands will increase their vulnerability to climate change. In a number of situations, climate change will simply act to accelerate existing degradation of damaged peatlands. For example, the occurrence of fires in Indonesian peatlands is largely due to drainage, logging and fire-setting (Page *et al*. 2002, Chapter 3), but the frequency and severity of fires is increased by changes in the length and severity of droughts. Likewise, over-grazing of vegetation in central Asia has already led to erosion and loss of peat. These impacts are likely to be accelerated by future climate change.

Unsustainable use of peatlands, like overgrazing, could strongly increase peatlands' vulnerability to climate change.

The species that are most vulnerable to climate change are those specifically adapted to peatland conditions, endemics, species at their geographical limits (latitudinal and altitudinal), and those with a disjunct distribution. Some peatland species have clear relationships with climatic variables (see Chapter 4). Those species are expected to disappear in areas where significant climate shifts occur. Changes will occur first at the geographical limits of these species. Where taxa have a disjunct distribution, perhaps due to fragmentation of the peatland habitat, these taxa are more likely to become locally extinct rather than migrating in concert with climate changes. Endemic and rare peatland taxa are the most threatened species. The Siberian Crane (*Grus leucogeranus*) is a threatened species dependent upon suitable nesting areas in tundra regions of Yakutia. This and other migratory birds dependent on open breeding areas may suffer reduced populations as the area north of the treeline becomes smaller, with expansion of northern forest areas.

The microclimate of peatlands may present opportunities for ecological adaptation to climate change. Peatlands may provide non-peatland taxa with temporary refugia as they retreat to higher latitudes and altitudes. Peatlands are often isolated within anthropogenically modified landscapes. They provide some of the last 'wild' landscapes in such areas and thus are a refuge for specialist peatland taxa which may be more widespread elsewhere, but also for other wildlife which can survive in a peatland or around its margins. Peatlands may therefore act as 'stepping stones' for the migration of more adaptable species that could not survive in agricultural or other strongly modified landscapes. In particular, they will be refuges for birds and mammals sensitive to disturbance.

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9 Management of Peatlands for Biodiversity and Climate Change

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Summary points

- The current management of peatlands is generally not sustainable and has major negative impacts on biodiversity and the climate.
- A wise use approach is needed to integrate protection and sustainable use to safeguard the peatland benefits from increasing pressure from people and the changing climate.
- Policy and management frameworks often fail to recognise the special eco-hydrological characteristics of peatlands that are so important for their sustainable management.
- Strict protection of intact peatlands is critical for the conservation of biodiversity and will maintain their carbon storage and sequestration capacity and other associated ecosystem functions.
- Relatively simple changes in peatland management (such as better water management and fire control in drained peatlands) can both improve the sustainability of land use and limit negative impacts on biodiversity and climate.
- Optimising water management in peatlands (ie reducing drainage) is the single highest priority to combat carbon dioxide emissions from peat oxidation and fires as well as address peatland degradation and biodiversity conservation.
- Restoration of peatlands can be a cost-effective way to generate immediate benefits for biodiversity and climate change by reducing peatland subsidence, oxidation and fires.
- New production techniques such as wet agriculture (“paludiculture”) should be developed and promoted to generate production benefits from peatlands without diminishing their environmental functions.
- Peatland management can be effectively integrated into land use and socio-economic development planning by taking multi-stakeholder, ecosystem, river basin and landscape approach.
- Local communities have a very important role as stewards of peatland resources and should be effectively involved in activities to restore and sustain the use of peatland resources.
- Peatland issues should be better incorporated into international frameworks (e.g. CBD, Ramsar, UNFCCC, CCD and so on) as well as regional policy processes.
- Plans for integrated peatland management should be developed at local, national and regional levels as appropriate.
- Enhancing awareness and capacity, addressing poverty and inequity, and removing perverse incentives are important to tackle the root causes of peatland degradation.
- Conservation and rehabilitation of peatlands provides a major opportunity to reduce current global greenhouse gas emissions.
- The emerging carbon market provides new opportunities for peat swamp forest conservation and restoration and can generate income for local communities.
- When properly managed, natural peatland habitats may generate economic benefits that exceed those obtained from habitat conversion.

9.1 Protection and rehabilitation of peatlands

9.1.1 Protection of remaining peatlands

Peatlands cover less than 3% of the land surface but store more carbon than the vegetation of all the world's forests combined. They are also critical for maintenance of biodiversity and other functions. Peatlands are the largest terrestrial carbon store (see Table 9.1) and play a key role in global climate regulation (see Chapter 6 and 7). However, the sustainable maintenance of remaining peatlands could yield benefits beyond those of CO_2 sequestration. It could help to maintain biodiversity, preserve water retention capacity in catchments, enhance local economic development as well as contribute towards the sustainability of rural livelihoods. To reap these multiple benefits however, a balance needs to be found between the protection and utilisation of peatland areas.

Table 9.1: How peatlands compare with other carbon stores.

Storage/area characteristic	Statistic
Area covered by peatlands	400 million ha (Joosten 2002)
Carbon stored by peatlands	550-650 billion tonnes (IPCC, 2001)
Carbon stored by all global plant biomass	694 billion tonnes
Carbon stored in the world's soils (including peat)	1,600 billion tonnes
Carbon in the atmosphere	700 billion tonnes (Gorham 1995)

The protection of remaining peatlands is one of the most important and cost-effective management strategies for minimising CO_2 emissions. Peatland degradation is becoming one of the most important global sources of CO_2 emissions from the Land Use and Land Use Change (LULUCF) sector. Emissions from tropical peatlands in Southeast Asia alone (covering 0.2% of the world's land area) are estimated to be approximately 2 billion tonnes of carbon dioxide per year, or about 7% of global fossil fuel emissions (Hooijer *et al.* 2006). Given the high density of carbon in peatlands (see Chapter 6), their degradation leads to disproportionately high carbon emissions. Since emissions from peatlands are almost always as a result of human induced degradation, the protection of peatlands may be a very important management strategy. Peatland protection is also very cost effective compared to other ways of mitigating GHG emissions.

Intact peatlands, which have not been drained or disturbed, should be strictly protected for biodiversity conservation, carbon sequestration and carbon storage. Intact peatlands with natural vegetation cover and hydrology still have the potential to sequester carbon. Once they are degraded however, they may lose this function. In regions like Europe, up to 90% of peatlands have been cleared, drained or otherwise sufficiently degraded to disrupt the relationship between the peat, plants and water (see Chapter 2). For example, many of Europe's transition states experienced widespread peatland degradation due to drainage and conversion to agricultural land during the 1950s-1980s. Almost all of the natural peatlands in the Netherlands and Poland have been destroyed/significantly modified /degraded, while Switzerland and Germany have only small areas of relatively intact peatlands remaining.

Given the limited proportion of intact peatlands in many regions (except possibly for parts of Russia, Canada and the USA) it is important that most, if not all, remaining intact peatlands are formally protected; in strictly protected areas such as conservation areas, catchment or floodplain reserves, nature reserves and national parks. In many regions the proportion of original peatland afforded total protection status is still low. Even in countries where peatlands are included in protected areas, the intact proportion of peatland is still low. For example in Finland – a country with supposedly 30% of its peatlands intact – many of the peatlands in totally protected areas have been degraded by drainage, groundwater extraction and other factors, either within or adjacent to the protected area boundary (IMCG 2006). Many peatlands form large hydrological units covering an area of hundreds or thousands of ha. In Indonesia for example, some peatland hydrological units cover about 1 million ha. Although part of the hydrological unit may be included in a protected area, development or clearance of other portions of the peatland outside the protected area may affect the integrity of the overall peatland. Protection need not mean the complete exclusion of human activities from peatland areas. Instead, it involves reaching acceptable trade-offs between the prevention of degradation and the continuation of wise use.

The high intensity of wildfires can destroy both the surface vegetation and litter as well as burning the peat layers. This can lead to a variety of environmental problems. Peat fires lead to the direct loss of peat and peatland vegetation, as well as massive CO_2 emissions. They may burn deeply into the peat layer in cases where the groundwater table is lowered due to drainage or severe drought. During the period 1997-98 peatland fires in Southeast Asia burnt more than 2 million ha (Taconi 2003). Peat fires have been recorded in Indonesia burning 5 m below the surface, making them impossible to extinguish without bringing the water table back to the surface. Peat fires in Manitoba in Canada burned for more than 10 years in the 1980s, smouldering under thick snow cover and emerging again in the spring (Gerry Hood, pers comm. 1997). Fires in Southeast Asia and other regions such as Russia generate large amounts of smoke which alone can cause several major social, economic and environmental problems. Transboundary smoke haze that regularly affects five countries in Southeast Asia (and which comes primarily from peatland fires) has been identified as the most serious environmental problem in the region. As such, it has stimulated the establishment of the ASEAN Peatland Management Initiative.

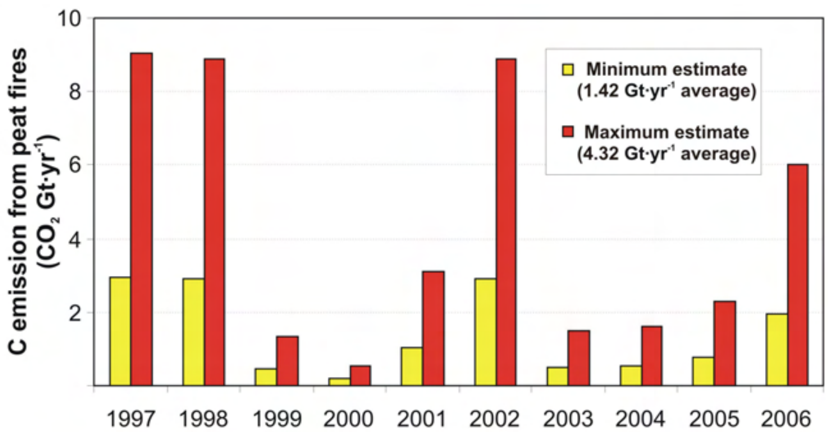

Figure 9.1: Tentative estimates of CO2 emissions from peatland fires in Indonesia 1997 – 2006 (Source: Hooijer et al. 2006).

9.1.2 Fire prevention and control

Peatland fires are one of the largest global point sources of greenhouse gas emissions from the land use sector. Fires in peatland are one of the largest global point sources of greenhouse gas emissions (Turetsky *et al*. 2002). Predictions of increased drought incidence and severity in many peatland regions due to climate change are likely to lead to an increase in carbon losses due to fire. This may change many peatlands from being net sinks for atmospheric carbon into net sources (Hogg *et al*. 1992). Reducing the incidence of peatland fires could aid carbon sequestration and storage (Garnett *et al*. 2000), which in turn could contribute towards meeting emission reduction targets under the Kyoto Protocol - particularly on peatlands that are used for agricultural purposes. Globally the largest peatland fires occur in Southeast Asia and Russia. The fires in Southeast Asia are linked with the large-scale development of agriculture and settlement schemes in the 1980s and 1990s, as well as the large-scale development of oil palm and pulpwood plantations over the past 10 years. The estimated emissions from fires in Southeast Asia over the past 10 years are between 14-40 billion tones (Hooijer *et al.* 2006) – see Figure 9.1.

Fires in upland peat in the UK have been shown to lead to increased soil erosion (and associated water colouration and siltation), as well as long-term losses of vegetation cover (also associated with biodiversity loss). This can then make the soil surface susceptible to wind and water

ASEAN Peatland Management Initiative and ASEAN Peatland Management Strategy (2006-2020)

South East Asia has more than 25 million ha of peatlands or 60% of the known tropical peatland resource. However about two-thirds of the peatlands are heavily utilized or degraded and, over the past 10 years, more than three million ha have burnt – generating smoke clouds covering up to five countries, economic losses of billions of dollars and major health and environmental concerns. In February 2003, 10 member countries of the Association of South East Asian Nations (ASEAN) endorsed the ASEAN Peatland Management Initiative (APMI) to act as a framework for collaborative activities to address peatland degradation and fires. Subsequently in November 2006, the ASEAN Ministerial Meeting on the Environment endorsed the ASEAN Peatland Management Strategy 2006-2020 (APMS) to guide the sustainable management of peatlands in the region. The goal of the strategy is promote sustainable management of peatlands in the ASEAN region through collective action and enhanced cooperation to support and sustain local livelihoods, reduce risk of fire and associated haze and contribute to global environmental management. The strategy includes 25 operational objectives and 97 action points in 13 focal areas ranging from integrated management to climate change and peatland inventory. Countries in the region are currently in the process to develop and implement their respective National Action Plans.
(Source: Anonymous 2006)

erosion and increase freeze-thaw action. Indeed, the onset of some of the major erosion episodes in UK peatlands have been linked to historic wild or human-induced fires (Mackay and Tallis 1996). Figure 9.2 shows erosion from a historic wildfire on Bleaklow, in the Peak District National Park, UK. Increases in pH are likely following wildfires (Allen 1964, Stevenson *et al.* 1996), and differences in pH have been noted between different burning regimes on blanket bog. In addition to this, ash has been shown to influence soil microbial populations (MacDonald 2000). This ash is rich in nutrients, raising soil fertility for the first two years after a burn, benefiting regeneration (Hansen 1969). However, leaching may be significant, particularly after autumn burns, and losses of phosphorus and nitrogen may inhibit regeneration. Kinako and Gimingham (1980) suggested that it may take 75 years for the phosphorus losses from one burn to be replaced. Wildfires also have a range of economic impacts, including the cost of labour or equipment costs in tackling the fire, as well as lost revenues from former land uses. For example, smoke primarily from peat fires in Indonesia enveloped 5 countries in Southeast Asia for up to six months in 1997/98, leading to estimated economic losses of US$10 billion as a result of direct damage to forests, as well as the impacts of the smoke haze on health, tourism and so on (ADB and Bapenas 1999).

Investment in peatland fire prevention and control may be one of the most cost effective ways of reducing global GHG emissions, as fire in peatlands may release very large amounts of greenhouse gases (over 2000 tonnes of CO_2/ha for a severe fire in tropical peatlands). However, fires can be often prevented through better water management and enhanced vigilance and fire control measures. In Indonesia, fire prevention activities have involved the blocking of abandoned agricultural or forestry drainage channels, revegetation of degraded sites, fire awareness campaigns with local communities, and the provision of equipment and training for local volunteer fire prevention and control teams. No single measure will be effective in reducing the risk of fire in peatlands. However, wise preparation and the use of several mechanisms together can help protect peatlands from fires. In doing so, a reduction in fires can reduce the emission of GHGs from peatlands.

In some cases fire has been used as a management tool by local communities and land owners in the management of peat soils. In Wasur National Park near Merauke and Pulau Kimaam in SE Papua province, Indonesia, local communities have used fire to control vegetation growth for thousands of years. Burning the vegetation helps to stimulate good grazing conditions for the hunting of wildlife such as wallabies and deer in shallow peatlands (Silvius and Taufik, 1989).

9.1.3 Rehabilitation of degraded peatlands

Rehabilitation of degraded peatlands can maintain carbon storage and other values. In addition to totally protecting undisturbed or intact peatlands, it is also important to rehabilitate those peatlands that have to some extent been degraded (usually due to draining in order to make the land suitable for forestry and agriculture). These degraded peatlands may represent the majority of peatlands in a given country. It is therefore advantageous to rehabilitate them so that they can continue to support biodiversity and provide ecological services such as carbon storage and water supply. Rehabilitation strategies need to be developed in accordance with the specific situation at the various sites but may include the restoration of hydrology and natural vegetation or other management interventions. Initial work has indicated that provided the peatland has not been too degraded it is possible to restore natural vegetation and stimulate further carbon sequestration

Figure 9.2: Erosion feature resulting from an historic accidental fire (top) and an eroded area resulting from the same fire that has been reseeded and treated with heather brash (bottom) on Bleaklow, Peak District National Park, UK (photos: M. Reed).

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Fire in peatlands in the UK

Although many peatlands are naturally forested, many were cleared. In some areas clearance started as early as the mid-late Holocene. In the UK in particular, much of this cleared area has been burned regularly since the 19th century to manage *Calluna vulgaris* (Heather) and sometimes grass, for sheep, deer and grouse production (Figure 9.3). The aim was to maintain cover of *C. vulgaris* (and grass for grazers) along with suitable nesting habitat for grouse. The impacts of fire on vegetation and erosion have been raised in many scientific studies, but land owners argue that managed burning reduces the likelihood of more intense accidental fires that are more likely to burn into the peat. Despite this, policy measures such as the use of cutting rather than managed burning are starting to be put in place in the UK to reduce the level of peatland fires.

In some areas, fire risk can be compounded by an expansion in public access to peatlands for recreation. However, access management, for example through the provision of surfaced paths and limited access points, can significantly reduce the area of land used by the public. Educational programmes have also been successful. For example the Moors for the Future partnership project "Moor Care Initiative" has provided leaflets and cigarette butt pouches to Peak District National Park visitors in the UK (Moors for the Future, 2006). Restoration initiatives that raise the water table may go some way towards reducing fire risk, though this is unlikely to reduce risk during prolonged droughts, when most wildfires occur. Alternatively, increased provision of firebreaks and fire-fighting resources in remote areas (e.g. water tanks and beaters) can minimize the impacts of wildfires (Reed *et al.* 2005). Such precautions may be particularly relevant around areas popular with visitors and tourists.

Restoration of degraded peatlands is often complex, expensive and takes significant time. Changes to peat soil pH, nutrient status and structure are often irreversible. While vegetation recovery may be rapid in the immediate vicinity of a blocked channel, it may take decades for the effects to be felt down-stream. In addition to this, the scale of the problem is enormous. There are hundreds of thousands of kilometres of land drains and gullies throughout the world and the costs associated with blocking ditches and gullies on this scale are enormous. There are cheaper restoration alternatives (for example using wood or heather bales on heather moorland), but in a system with a moderate slope, it is necessary to block channels every five to fifty metres for successful restoration. Costs can be minimised by using landscape models that can help prioritise blocking locations. Priority locations are selected because they optimise the effects of blocking on the water table with the minimum number of dams (although channels on steeper slopes are likely to be eroding fastest) (Holden *et al.* 2006a).

Restoration or rewetting of peatlands reduces fire risk, CO_2 emissions and may generate benefits for biodiversity and local communities. Peatland restoration through rewetting and revegetation has been shown to significantly reduce fire risk and encourage regrowth of natural vegetation. In Belarus, restoration of Yelnia peatland through the blocking of over 20 major drains has led to elimination of regular fires. Large scale peatland rewetting is now underway in Belarus.

In Indonesia a pilot project in the abandoned mega rice project area in Central Kalimantan has led to significant recovery of the peatlands after the drains were blocked and water levels were maintained within about 40-50 cm of the soil surface (Suryadiputra *et al.* 2006) (see Figure 9.4). In the three years since blocking, fires have stopped, subsidence has reduced and vegetation has recovered. In the UK blocking of drains has led to a significant reduction in dissolved organic carbon and particulate organic carbon in runoff water. In turn, this has reduced downstream water treatment costs and lowered risks to human health (Holden *et al*. 2006b).

Peatland restoration strategy for The Central European Peatland Project (CEPP)

The CEPP was started in 2000 to ensure that the natural heritage of peatlands would not be lost – indeed that it would be enhanced – during the challenging period of economic transition, stabilisation and growth in the CEE region. Its role was to assist eight participating countries to implement the Ramsar Convention, through the development of a Strategy and Action Plan for Peatlands in Central Europe (Bragg et al. 2001). The strategy included an overview of peatland distribution and identified peatlands with a high biodiversity value. In addition, the strategy aimed to increase awareness about values and function of peatlands, including their significance with respect to carbon storage, flood attenuation and water purification.

Restoration of peatlands can generate important new sustainable livelihood opportunities, as well as generating biodiversity and climate change benefits. The restoration of peatlands can create new sustainable livelihood opportunities, as well as providing benefits for climate change and biodiversity. For example, restored peatlands in southern Thailand are part of an award-winning ecotourism centre. In Indonesia in 2005, abandoned logging channels were blocked by local communities in one village in Central Kalimantan. This was initially undertaken to prevent peat fires but they subsequently were able to harvest over 2 tonnes of fish from the

Figure 9.3: Managed burning on UK peatlands for grouse and sheep management showing a fire being lit (top left), burning (top right), being put out (bottom left) and after the fire (bottom right) (photos: M. Reed).

blocked channels as they functioned like fish ponds.

Figure 9.4: Peatland restoration
Blocking of a canal in degraded peat swamp forests in Central Kalimantan, by local communities using manual traditional techniques. (Photo: Marcel Silvius, Wetlands International).

Restoration of tropical peatlands is essential to re-establish peat swamp forests and the associated timber and non-timber forest products such as rattan which sustain local communities. In eastern Germany a new industry for sustainable biomass energy has been created following establishment of reed farms and wet alder forests on formerly degraded peatlands.

9.2 Modification of peatland management strategies

9.2.1 Improved water management

Improved water management is a fundamental step to support the sustainable management of peatlands. Water is probably the most fundamental component of a peatland, with most peatlands being approximately 90% water. The extent, nature and depth of the peat are frequently a function of water extent and depth. Drainage thus has one of the most important and long-lasting impacts on peatlands. Drainage of temperate and tropical peatlands which lowers the water table by 1m, leads to a CO_2 emission of between 30 and 100 tonnes of CO_2/ha/year respectively (Wosten 2002, 2006). Drainage also increases vulnerability to fire; one of the most significant courses of peat degradation and GHG emissions. Fire does not normally occur continuously, but when burning does take place it may lead to the emission of up to 4000 tonnes of CO_2/ha in the tropics and 2000 tonnes of CO_2/ha in temperate regions. Peatland fires are becoming more frequent in some regions, e.g. Southeast Asia. This is generally a result of accelerated rates of land clearance as well as the large-scale drainage of peatlands. More than 2 million ha of Southeast Asia's peatlands were burnt in the past 10 years. Fires were persistent, with many burning for between 1-3 months, leading to large CO_2 emissions. Indonesia is now considered to have the 3rd highest CO_2 emissions globally, primarily as a result of persistent peatland fires (Silvius *et al*. 2006).

Restoring degraded peatlands in Belarus

In 1950, there were 2,939,000 ha of natural peatland in Belarus. As a result of large-scale drainage programmes between the 1950s-1990, more than 54% of peatlands were drained for peat extraction and agriculture (First National Report on Implementation of the UNCCD in Belarus 2002). This had a number of negative environmental impacts, including: biodiversity loss, local microclimatic changes, the drying of small streams and rivers, increased nutrient runoff and subsequent eutrophication of water bodies, shrinking fen areas, increased soil erosion, fires and huge net carbon dioxide emissions. Following an ongoing UNDP-GEF supported pilot project (GEF 2004) to restore 17 sites across Belarus with a total area of 42,000ha, Belarus aims at restoring a further 260,000ha of peatlands. The objectives are to avoid emissions of several million tones of carbon dioxide and to improve the biodiversity of these highly degraded sites. The funds for the current phase of restoration and management are being raised through the planned sale of high quality carbon credits on the voluntary carbon market.

Drainage has greatly improved the ability to farm peatlands, but it leads to loss and subsidence of peat soils. A balance between drainage and conservation is needed in order to protect peatland soils. Drainage has greatly improved the ability to farm peatlands. However, it can lead to significant subsidence of peat soils (depending on the drainage period and depth and temperature), as well as large amounts of CO_2 being lost to the atmosphere. Excessive drainage of peatlands can also cause the shrinkage or loss of wetland area, as well as the reduction of water levels in adjacent wetlands and mineral soils.

Peatland and livelihood in Indonesia

A number of people in the sub-village of Muara Puning, Central Kalimantan, have built long ponds in the peatland (length: 10-50m; width 1.5-3 m; depth: 1-2m), see pictures below. The ponds are known locally as *beje*, and trap wild fish when the river overflows during the rainy season (October – February). The fish are left in the pond for several months, and are harvested (while at the same time scooping out sediment) throughout the dry season (July – September).


In the same area, channels up to 10km long were dug into the peat swamp forest by local community members to facilitate logging activities. During the dry season these lead to drying of the peatland and increase the susceptibility to fire. The Climate Change Forest and Peatland (CCFPI) Project worked with local communities in 2003-2005 to block the ditches in order to reduce fires and associated GHG emissions. The blocking of the channels resulted in the formation of a number of ponds which are similar to *beje* ponds. A total of at least 16 species of fish (including *Chana sp., Clarias sp., Anabas testidineus, Trichogaster sp.,* among others) were recorded in the blocked sections of the ditches. A total weight of almost 2 tonnes of fish was harvested by the local community in 2004. This acted as a strong incentive for other community members to block other abandoned channels in the peatlands.


As peat subsides, the depth of the fertile topsoil also decreases and risk of flooding increases. This means that further drainage, cultivation and pasture renewal are needed to maintain productivity, therefore increasing the cost to farmers. When managed properly, peat is a valuable and highly productive resource.

To be able to farm on peat soils over the long-term, farmers must find a balance between keeping the water table low enough for production, but high enough to minimise peat losses and CO_2 emissions.

It is possible to use peatlands for agriculture without draining by using species such as sago palm, or yams in the tropics or maintaining natural peatland sedges for hay production in the temperate regions. These plants require little or no drainage.

Appropriate management is critical to maintain water pollution sink, flood control and water supply functions of peatlands. Although it is not ecologically appropriate for peatlands to be deliberately used for water purification in heavily-polluted areas, in some regions they may be found downstream of polluting operations. As a result, they play an important role in the removal of pollutants from streams. For example in the river systems of South Africa's highveld, peatlands downstream of industries and mines are important for filtering out and temporarily storing pollutants such as uranium from gold mining operations. As a result, subsequent degradation of peatlands or extraction of peat for use in horticulture may lead to significant pollution (Wyatt 2006).

Drainage and gully erosion are major causes of peatland degradation and associated losses of carbon storage, biodiversity and ecosystem

Restoration of Reitvlei Peatland for water storage and water quality improvement

Rietvlei peatland near Pretoria, South Africa was recently rehabilitated by a team of more than 50 local people through the Working for Wetlands programme. This degraded peatland was drained in the 1960s for peat mining, dryland cropping and irrigation purposes. In addition, poorly timed annual burning of reeds led to peat fires, while upstream, urban townships and industrial areas caused serious pollution. Rietvlei supplies nearly 20% of water supplies to South Africa's capital city, Pretoria, and is owned by the municipality. Since the remaining 80% of water has to be bought in from elsewhere, there is a strong economic imperative to manage water wisely and to restore the former diffuse flow of water through the wetland, which previously provided natural water purification services free of charge. Working for Wetlands has enabled the diversion of water from the central drainage canal out to the edges of the peatland, re-flooding previously dried-out areas. Small gabions (rock-filled wire baskets) placed at 30 m intervals allow the water to back up and then overflow into the desiccated wetland. This has enhanced water storage as well as the water quality (Working for Wetlands, South Africa 2008).

services around the world. Gully erosion occurs when vegetation cover is lost, for example due to inappropriate burning or overgrazing. The effects of gullying and drainage are similar, though the problems associated with gullying tend to be more severe. Drainage of lowland peats in much of the western world took place mainly in the 19th century to improve land for agriculture by lowering the water table. But in the 1960s and 1970s, upland drainage became more common. In Europe, this was carried out primarily to improve land for grazing and grouse production, and remove hazards for stock (Ratcliffe and Oswald 1988). However, there is little evidence that these aims were met (Stewart and Lance 1983).

By lowering the water table, drainage and gullying increase the air-filled porosity of the peat, leading to shrinkage, cracking and subsidence, increasing decomposition rates and altering microbial processes. These changes have important implications for peatland hydrology, water quality and ecology. For example, aerobic decomposition in drained peat enhances the mineralization of nutrients, leading to significant losses of carbon, phosphorus, nitrogen and sulphur, which may affect soil fertility. Water flow paths through and over peatland soils are altered (Holden *et al*. 2006a), leading to a complex hydrological response (Holden *et al.* 2004). This includes increased loss of particulate and dissolved organic carbon in stream water, and has implications for the carbon balance of drained or eroding peatlands. As outlined earlier, as the water table is lowered, peatland fires become more of a risk. This is a problem that can only get worse under projected climate change scenarios and is likely to further contribute to carbon losses in a possible positive feedback loop (Hogg *et al*. 1992). Thus, drainage and gullying can lead to environmental problems of increased fire risk, increased incidence and severity of down-stream flooding, carbon loss, water colouration, changes in peatland ecology including reduced biodiversity, and the sedimentation of reservoirs and fish spawning beds. Careful management is therefore paramount in ensuring the adequate control of these practices.

Blocking drains and gullies in peatlands can stem carbon losses, and sequester and store carbon as channels re-vegetate. Blocking drains and gullies in peatlands can reduce subsidence and fires and hence stem carbon losses by sequestering and storing carbon as degraded peat and channels re-vegetate (Worrall *et al.* 2003). Ditches and gullies are blocked to raise the water table to its former level and to re-wet the peat. If this does not lead to natural re-vegetation, reseeding or the planting of wetland species can be undertaken (Price 1997, Evans *et al*. 2005).

9.2.2 Modification of agricultural practices

Conversion of natural peatlands for agriculture is one of the main root causes of the loss of peatland biodiversity and functions. In terms of area of peatland affected, the most extensive impacts on natural peatlands have come from the drainage and utilisation of peatlands for agricultural purposes. Agricultural use generally involves the drainage of peat by 30cm-1.5m, and the replacement of the natural vegetation with crops such as potatoes, cabbage, vegetables, oil palm, maize, buckwheat or pineapples. The selection of species depends on the climatic and ecological situation and water levels (degree of drainage)

Agriculture in peatlands in Heilongjiang, China

The natural wetlands in China and the biodiversity they support are under a constant threat of degradation, mostly associated with human development pressures, such as drainage, over-use of water resources, conversion to agricultural uses, unsustainable harvesting and resource use. Sanjiang Plain in Heilongjiang Province is a vast, low-lying alluvial floodplain of about 5 million ha in the apex of the Heilongjiang and Wusuli rivers, which is dominated by peatlands. In its former natural state, the floodplain ecosystem consisted of a mosaic of sedge and reed marshes, wet grass meadows, ox-bow lakes, riverine scrub and wooded hummocks of birch and poplar. During the past 30-40 years more than 90% of the peatlands of the Sanjiang Plains have been converted to agriculture, primarily for rice and soya bean production. This has led to significant degradation of the natural resource, loss of locally and globally important biodiversity, significant GHG emissions, and reduced flood mitigation capacity.

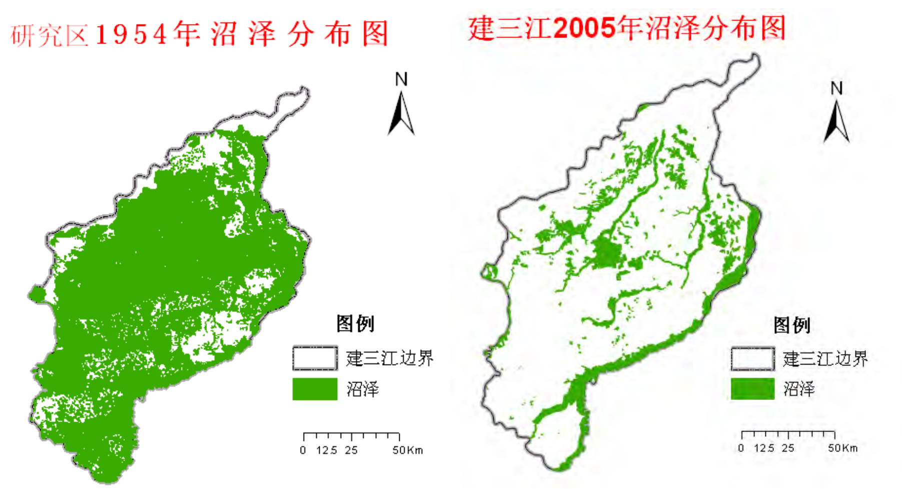

Figure 9.5 Change in area of remaining natural wetlands (Marshes) in Sanjiang plain, Heilonjiang Province, China 1954-2005 (Source:Zhang Shuqing, by TM 2005, UNDP-GEF, 2007)

as well as the macro-economic and agriculture commodity situation of the time.

Agricultural activities that involve peatland drainage will lead to the loss of peatlands and their associated functions, and cannot be classified as sustainable. Any agricultural practice that involves drainage of peatland will lead to loss of the peat layer through oxidation, compaction and erosion. In addition the natural processes which lead to peat formation stop so that no further growth of the peat layer takes place. As a result, drained peatlands will continually subside and eventually (providing drainage continues) the entire peat layer will be lost, exposing the underlying mineral soil.

Agricultural drainage in peatland areas is frequently badly designed and leads to peat degradation as well as reduced agricultural yields. In many places the agricultural drainage system may be too deep and have inadequate water management systems. This can lead to over-drainage of the peatlands. In Malaysia for example, most of the drains developed in peatland areas were based on the designs of drains in mineral soils. As a result they lowered the water levels too much and led to rapid subsidence. The peatlands of West Johor in Peninsular Malaysia were drained in the 1970 with funding and technical guidance from the World Bank. As a result of poor design and a lack of water management structures there was over-drainage and severe subsidence, leading to the collapse of most of the infrastructure, failure of the agricultural projects, flooding of coastal towns, acidification of water supply and other problems.

Agricultural production techniques that maintain or increase peatland carbon stores need to be developed and promoted. Agricultural or agro-forestry activities that do not involve the drainage of peatlands, that maintain natural water levels and that can maintain or increase the natural carbon stores should be developed or promoted, over and above those techniques that drain or lead to the loss of carbon storage. Agriculture or agroforestry systems what can maintain or

Management of the Peatlands of the Ruoergai Plateau, China

The Ruoergai peatlands cover an area of about 500,000 ha at an altitude of 3400-3900m on the eastern edge of the Qinghai-Tibetan Plateau. The peatlands are found in a shallow basin surrounded by hills and mountains, and comprise part of the headwaters of the Yellow River. The peatlands are of global importance for biodiversity conservation, as well as playing important roles in water storage and supply, and carbon storage. The peatlands are also important for the livelihood of local communities - especially nomadic Tibetan herders.

In late 1960s-early 70s, as part of a national agricultural expansion scheme, about 300 km of drainage canals were dug by more than 50,000 workers, in order to drain many of the peatlands to allow increased access by grazing animals. With rapid economic development and an increasing population, the overgrazing has severely damaged large proportions of the grasslands in this area. Livestock populations have increased from 400,000 to 1 million animals. The peatlands degraded as the grass could not regenerate and this has caused desertification to expand year-on-year. The local government realised that the overgrazing leads to peatland degradation and some measures were taken to reduce economic losses to the local communities. Some parts of peatlands are strictly protected for hay production for livestock in winter. Local herders are encouraged to reduce the numbers of the livestock by increasing their quality or breeding in captivity to encourage rangeland regeneration.

A pilot project to block drains in degraded peatlands was developed In Ruoergai and Hongyuan Counties in the Ruoergai Plateau in 2004. The project was undertaken by Wetlands International China, Global Environment Centre in partnership with the Local Government with support from UNEP-GEF. Following initial success, the State Forestry Administration, State Development and Reform Commission and The EU China Biodiversity Programme (ECBP) have provided additional resources to expand the programme. More than 50 km of drains have now been blocked and water levels have been raised in a number of peatlands reducing the rate of degradation and leading to recovery of some of the Peatland systems and enhanced water resource management (Source: Chen and Zhang 2007).

enhance Peatland carbon storage include sphagnum farming, cultivation of reeds, alder, jelutong (chewing gum tree), and sago as well as hay making.

9.2.3 Modification of livestock management on peatlands

In many parts of the world, grazing-induced erosion is a major cause of peatland degradation. Erosion induced by overgrazing is a major cause of peatland degradation in many parts of the world (Evans *et al*. 2005), and in some areas this is expanding rapidly. Peatlands generally cannot sustain high stocking densities. *Calluna vulgaris* (heather) which grows on upland peatlands in the UK is only of high value as a winter feed for hill sheep when grasses have died back, and only grows when grazing densities are below 2 sheep ha^{-1}. In Europe, in response to headage payments (subsidies based on number of animals) from the Common Agricultural Policy in the 1970s and 1980s, stocking levels increased above this level on many moorlands (e.g. 29% of UK moors were stocked above this level in 1977 and by 1987 this had increased to 71%). However grazing densities of over 0.55 sheep ha^{-1} can instigate erosion in some areas (Rawes and Hobbs 1979). Similar problems have been described in Ruoergai Peatland in China and the Lesotho highlands in southern Africa.

Grazing can have a major impact on peatland vegetation dynamics which can affect carbon storage as well as biodiversity. A number of studies have examined the effect of grazing on peatland vegetation dynamics. Grazing has a profound effect on species composition (favouring grazing-tolerant species such as tussock grasses), and depending on its intensity, can reduce competitive vigour and potentially kill plants. Overgrazing has been blamed for the loss of heather moorland in some peatland areas in the UK (Shaw *et al.* 1996). Grazing can have both positive and negative effects on seed dispersal. Browsing can prevent tree establishment and seed production, but consumption of seeds and dispersal in dung can cause some species to spread (Thompson *et al.* 1995). Since the mid-1990s, there have been calls for a large reduction in sheep numbers on peatlands in the UK (Thompson *et al.* 1995). This trend is likely to continue as the EU's Common Agricultural Policy shifts from headage to area-based payments, reducing the incentive to overstock and taking a more environmentally-considerate approach. This

Guidelines issued by the Waikato Government in New Zealand to livestock farmers operating in peatland areas

1. Avoid deep drainage
Deep drains in peat cause over-drainage and rapid subsidence of peat soils. As the peat dries it shrinks and cracks, making soils difficult to re-wet. Rainwater flows down into the subsoil through cracks in the peat. When peat dries it becomes waxy and cannot reabsorb water easily. By keeping drains shallow, you will help keep the water table high enough to protect your peat.

2. Maintain the water table over summer/dry periods
Keeping the water table high in drier periods is important for pasture growth and maintaining soil quality, for both peat and mineral soils. This can be achieved by putting weirs or stop gates in your drains. Water table management can be difficult to achieve on an individual farm. This is because groundwater is a resource that spans property boundaries. It may be useful for you to get together with your neighbours to discuss summer water-table management. Better water-table management will minimise shrinkage, allowing you to extend summer grass growth and farm your peat soils profitably for longer.

3. Fence drains and spray weeds
Controlling weeds and fencing drains to exclude stock reduces maintenance costs associated with machine cleaning drains. Weeds should be sprayed in summer (January/February) before they seed. Note that glyphosate ('RoundUp') is the only herbicide approved for use over water. Less machine cleaning of drains saves money. It also reduces impacts on water quality and the risk of drain deepening. Drains only need to be cleaned if their ability to function has been reduced by silt or weed growth. Most silt in drains comes from stock damaging the drain banks. By fencing off your drains you will greatly reduce the need to machine-clean them. A single electric wire is usually enough on most dairy farms.

4. Do not deepen drains during maintenance
Continual deepening leads to over-drainage, and makes pasture less productive. Keep your drains shallower and protect your valuable pasture.

(Source: Environment Waikato 2006)

highlights the importance of policy considerations when managing peatlands, as they can both encourage and discourage appropriate management and wise use.

Reduction and removal of grazing from peatlands can stop degradation and lead to recovery of peatlands, but other measures may be needed to restore peatland functions and vegetation. The effect of reducing and removing grazing from peatland has been investigated in a number of exclosure studies. Rapid recovery only occurs in the total absence of grazing (Marrs and Welch 1991), but for some peatland habitats, a combination of herbivores using the land (including grazers and browsers) at different intensities and times of year, has been found to optimise biodiversity.

Some low intensity management of livestock may locally enhance biodiversity. Grazing and the cutting of hay in shallowly-drained meadows reduce the competition between grasses and other plants and also create possibilities for pioneer species to colonise the area. Lightly grazed areas also may have a mosaic of microhabitats with differential relief and nutrient status. As a result, peatland grazing meadows that have been managed for long periods in a traditional low intensity manner for hay cutting or light grazing may support a higher diversity of plants (including many rare or restricted species). Following the abandonment of grazing meadow management in Eastern Europe in the 1980s and 1990s following political and economic changes, the quality and natural diversity of these grazing meadows declined.

9.2.4 Modification of forestry practices

Management or rehabilitation of natural forest on peatlands is an important management strategy. Peatlands in many regions of the world (e.g. the Boreal zone, Africa, South-east Asia and North and South America), are naturally forested. They therefore need to be managed.

Clear felling, over extraction and high impact logging techniques in forested peatlands are a major cause of peatland degradation, leading

to a loss of biodiversity and reduction in carbon storage. Clear felling and over extraction of trees in forested peatlands may lead to changes in the peatland water balance, as well as degradation and the loss of biodiversity. In tropical peat swamp forests, large-scale harvesting leads to the drying of surface peat layers and increases the chances of fire. In addition, the open conditions are often unsuitable for the growth of most peat swamp forest species, leading to the development of secondary forests dominated by a limited number of pioneer species. High impact log extraction techniques include the use of heavy excavators. These compact peat, and alter the drainage of peatlands prior to logging in order to facilitate access. Logs may also be extracted via drainage canals. Such logging techniques have been shown to significantly reduce the chances of natural regeneration, while the drainage leads to significant subsidence and enhanced fire risk (Danced 2003).

Figure 9.6: Jelutung (Dyera sp.), an indigenous latex producing peat swamp forest species is being planted along the banks of blocked drainage channels in abandoned agricultural land in Central Kalimantan, Indonesia (Photo: Marcel Silvius, Wetlands International).

Forest resources from peatlands that are naturally forested can be sustainably harvested using low impact logging/extraction techniques. These techniques help maintain biodiversity and carbon storage. Resources can be sustainably harvested using low impact logging/extraction techniques, while also maintaining biodiversity and carbon storage. For example, in Southeast Asia, peat swamp forest has been logged in many places using the so-called "kuda-kuda" system, where trees are hauled along skid tracks by manual labour or winches to railway lines placed on logs laying on the peat surface. The rail systems do not involve any drainage and so do not induce subsidence or other problems. In Europe extraction routes over deep peat can be covered with a layer of logging residues (known as "slash roads"). Research in the UK has shown that peat soils under slash roads exhibit only minor changes despite high levels of traffic, and can improve vehicle traction (Wood *et al*. 2003). In boreal peatlands in Canada, trees are harvested in winter when the peatland is frozen. This results in little or no impact from the log extraction activities. A similar approach is used to harvest reeds in fen peatlands in China which are harvested by machinery traveling on ice across the frozen water surface in winter,

Afforestation of naturally unforested peatlands can have important negative effects. The afforestation and associated drainage of naturally un-forested peatlands can cause significant changes in hydrology and ecology, leading to a reduction in water quantity and quality, loss of biodiversity and reduced carbon storage. Although forest managers now attempt to maintain or increase biodiversity through careful planting design (Anderson 2001), there is a still an increasing area of peatland that is being commercially afforested in some countries. For example in the UK, 9% of upland moors have been afforested (Cannel *et al*. 1993), mostly in the form of commercial coniferous plantations, and this area is growing. In Finland and Russia the area of afforested peatlands is very large, covering millions of ha of peatlands.

Afforestation of peatlands is often associated with drainage and fertiliser application which together lead to major ecological changes. Drainage ditches lower the water table, while the trees, whose roots reach far deeper into the soil profile than the natural vegetation, can cause the water table to lower even further. Compression and shrinkage can lead to subsidence and cracking of the peat surface (Shotbolt *et al.* 1998, Anderson *et al.* 2000). This alters conditions for ground layer plants, and reduces the availability of the fresh-water habitats that characterize many peatlands (e.g. blanket bogs). Fertiliser application can change the species composition of ground layer plants by altering the nutrient availability and pH. Also, as the trees grow, they can change the microclimate for the ground layer plants. This in turn can lead to further changes in species composition. Combined with changes in the soil, these alterations can cause an increased prevalence of earthworms, slugs, moths and beetles (Makulec 1991), while spiders and wasps may become less abundant (Coulson

1990). Birds that favour open ground are gradually replaced by forest birds. These impacts can be felt far beyond the forested area, as bird communities may be affected up to a kilometre from the edge of the plantation (Moss *et al.* 1996). Although tree felling can cause the water table to rise again, the soil structure (and consequently the drainage) may have been irreversibly altered by the forest. Given the unique biodiversity value of many peatland habitats, these types of environmental changes may be associated with the loss of rare and endangered species, and are therefore cause for concern.

Although trees sequester and store carbon in their biomass, the changes that take place in the soil after peatlands are afforested lead to significant carbon loss. Peatlands are significant carbon stores – for example, peatlands are the UK's largest carbon store, holding more than all the forests of the UK, France and Germany combined (Worrall *et al*. 2003). Although trees sequester and store carbon in their biomass, the changes that take place in the soil after peatlands are afforested lead to significant carbon loss (Cannell *et al*. 1993). Research has indicated that peatland afforestation can result in a net release of carbon dioxide into the atmosphere (Holden 2005). Fertilisation of peat soil also leads to significant emissions of N_2O which has a global warming potential 310 times higher than that of CO_2.

Improvement of management measures for forest plantations on peatlands can reduce losses of biodiversity) and GHG emissions while at the same time reducing risks for production. In Indonesia large-scale tree plantations have been developed in peatlands to supply pulp and paper mills. These plantations are currently in Sumatra and cover an area of about 800,000 ha. The main tree planted is *Acacia crassicarpa* which is not an indigenous peat swamp forest species. The peatlands are thus drained to a depth of 0.8-1.5 metres to enable the trees to grow and minimize the chance of roting of the root mass. Although the trees are relatively fast growing and achieve canopy closure in one year, they are harvested on a 4-5 year cycle which leads to regular clearance and opening up of the land. High levels of peat subsidence linked to the drainage have led to significant management problems which are now being assessed.

9.2.5 Modification of Peat extraction

Peat extraction operations can affect biodiversity and impact GHG emissions, both directly and in adjacent areas. The extraction of peat for use in energy generation or horticulture is one of the significant uses of peatlands worldwide, although the area used is much less than for forestry and agriculture purposes. Extraction of the peat normally involves the clearance of surface vegetation, drainage of the peat and extraction using machinery. The extracted peat is then stockpiled before transportation and utilisation. The clearance of the vegetation directly impacts the biodiversity while the drainage and extraction of the peat often leads to changes in the hydrology of adjacent areas which can affect GHG flux.

Management of Acacia plantations on peat in Indonesia

Peatlands in Indonesia have, over the last 20 years, been developed for large-scale Acacia plantations for pulp for paper production. Plantations covering hundreds of thousands of hectares have been developed in Riau and South Sumatra provinces, particularly by Riau Andalan Pulp and Paper (RAPP, APRIL) and Asian Pulp and Paper (APP, Sinar Mas, Indah Kiat). Plantations by APRIL were until recently quite deeply drained by 1-1.5m but recently the company has altered its water management strategies by raising water levels to decrease subsidence and greenhouse gas emissions from the peat. In some areas the plantations have been established in already deforested or heavily degraded peatlands, whereas in other areas they were developed in peat swamp forest areas. A recent area of contention between both companies mentioned, as well as conservation organisations, is the Kampar peninsula in Riau Province, which is the largest remaining relatively undisturbed peat swamp forest area in Sumatra. Options for win-win scenarios are being considered by APRIL, where the pulp plantations could be developed in a narrow ring around the peninsula and the peat swamp forests further inland would be protected for their biodiversity values, as well as for their essential water management functions for the plantations (preventing floods and droughts). The company's management capacity could be used for monitoring as well as for fire control.

Use of peat as a substrate for horticulture is a significant source of peatland degradation and

carbon emissions. This problem can be reduced through the careful selection of extraction sites and development of appropriate alternative growing media. The extraction of peat for horticulture has led to significant impacts on conservation sites in some countries and has led to long-term conflicts. This has, in turn, stimulated consumer boycotts of horticultural peat in some countries. In response the peat industry has developed codes of practice which ensure that mining is focused on those sites with little conservation value, including abandoned agricultural land. In addition, in some countries the peat industry has actively developed post-mining restoration techniques and has introduced sphagnum farming methods. Development of alternatives to peat for use in horticulture, such as compost or coco-peat (from processed coconut husk fibres), is also underway.

9.3 Integrated management of peatlands

Uni-sectoral planning of peatland management/use is one of the root causes of peatland degradation and so peatlands must be planned and managed in an integrated manner. In most countries there is significant conflict between different user groups or economic sectors such as forestry, agriculture, water supply, industry and also between government, private sector and local communities over the development and management priorities and strategies for peatlands. These contrasting interests lead to conflicting decisions and ad-hoc planning. This is further complicated by the fact that large peatlands are single hydrological units that may cover up to one million ha, but which may be subdivided by different administrative boundaries and land use zones. Since each part of the peatland is interconnected, drainage or vegetation clearance on one site will have an impact on other portions of the same zone. It is therefore imperative that each hydrological unit is addressed as a single entity for the purposes of development planning and management and care should be taken that activities approved for different parts of the peatland are compatible.

Peatlands across the world are managed by a number of different people and groups, each with different aims, values and goals. It is increasingly recognised that local communities are critical stakeholders within peatland management systems. Community-based approaches can be used to raise awareness about climate change and the key role that appropriate peatland management can play in terms of carbon storage and sequestration. Local involvement can also promote sustainable management and avoid conflicts, as different stakeholders familiarize themselves with the views of others (Mathews 1994). Vitally, local participation in peatland management can also achieve social goals; contributing towards poverty alleviation, increased livelihood sustainability and social empowerment (Middendorf and Busch 1997).

Communities can be included in peatland management through use of a number of different methods and mechanisms. In helping decision-makers and researchers learn about different uses and understandings of peatland areas, methods such as transect walks with land managers, livelihood analyses and the development of participatory resource maps can be useful. Local knowledge about the peatland can be used to complement more technical scientific knowledge and together, combined knowledge can contribute to more acceptable, appropriate, and ultimately more sustainable management and policy (Berkes 1999, Kelsey 2003). Communities can also be involved in monitoring and assessment exercises. These kinds of activities can provide decision-makers with important information on the rate and nature of any changes to the peatland, assisting the development of policies for more sustainable use of the resource.

Despite benefits, participatory approaches are not without their problems. Participatory approaches have certain constraints (see Cooke and Kothari 2001, Hickey and Mohan 2004, Stringer *et al.* 2006). For example, by involving local communities, expectations can be raised. If these expectations are then not fulfilled, it can lead to disillusionment. Participatory approaches also acknowledge diversity and complexity, rather than helping to simplify environmental management situations. Although this is one of the main strengths of the approach, and by involving local people in the analysis and interpretation of results, errors can be avoided, taking several different diverse viewpoints in account can make the results difficult to analyse and interpret. Finally, there is a danger that participatory methods can be applied mechanically, without an appreciation of underlying principles. This can prevent the

Peatland management in the UK's Peak District National Park

The Peak District National Park straddles four UK Government regions that together contain around 48% of England's population. The 22 million people a year that visit the Park make it one of the most visited National Parks in the world. However, the demands these visitors place on the landscape must be balanced with the needs of the residents who live there.

The Dark Peak part of the Park is characterised by extensive heather moorland and blanket bog, surrounded by enclosed pastures in deep, narrow valleys. These habitats are both nationally and internationally important for their biodiversity. However, the multiple competing uses of the Park place complex demands on the landscape and current management practices fail to integrate the range of social, economic and environmental pressures. Management plans are required that can adapt to social values and changing scientific understanding.

Dougill *et al*. (2006) carried out a scoping study to explore the different kinds of moorland use and management employed by different stakeholders in the Dark Peak. A variety of participatory methods (including semi-structured interview and focus groups) were used to enable the researchers and other stakeholders to learn about the different management goals of each group. Scenarios of likely future change to the peatland were developed and discussed with the stakeholders, and indicators were identified that could be used to monitor progress towards the management goals under the different scenarios. The research is ongoing but preliminary analyses suggest that by bringing different stakeholders together to learn from each other, more sustainable management strategies are possible.

benefits of participatory approaches from being realised.

Generally, a combination of top-down and bottom-up peatland management approaches is favoured, since it is sometimes necessary to increase local awareness of changes and threats to the peatland, and build local capacity for monitoring and more sustainable management.

Effective approaches to peatland management problems can be developed in regions with shared management issues or transboundary problems related to peatland management. There is a need to develop mechanisms to harmonise or integrate approaches to the management of peatlands across regional or national boundaries or within river basins. The need for transboundary cooperation is needed where the peatland physically crosses the boundary, or where there are issues of common concern on peatland management that can be shared and discussed between neighbouring countries. Examples of this include the exchanges by the Grupo Paramos on the Andean peatlands in South America or between the countries of Southeast Asia working through the ASEAN Peatland Management Initiative (APMI). There is also a need to explore the options for the transfer of resources between different stakeholder groups that play a role in the management of peatlands. For example, upstream pastoralists or farmers could moderate peatland management practices to benefit downstream users of the water supply.

9.4 Peatlands in relation to policy processes

9.4.1 Peatlands and policy

Policy frameworks tend to treat peatlands either as forests or marshes, and often fail to recognize the special eco-hydrological characteristics of peatlands which are so important for their sustainable management. Policy makers and sectoral agencies (e.g. forestry, agriculture, water resources agencies) often do not specially recognise peatlands as a separate landform or ecosystem type needing special consideration. Peatlands are generally classified by sectoral agencies as grasslands, forests or wetlands. As a result the special management issues and requirements of peatlands as described in the sections above are not recognised. Even the Ramsar Convention on Wetlands classifies peatlands as either marshes or forested wetlands and does not provide peatlands with a class of their own. There are also few countries that have national or local peatland policies or strategies which specifically include separate management prescriptions for peatlands.

There are around 40 countries with National Wetlands Policies, of which only some are specifically mention peatlands. Peatlands are often not mentioned or not recognized as a priority for biodiversity conservation in many national Biodiversity Conservation Strategies either. The limited prioritisation of peatland conservation in the overall context of biodiversity conservation may be partly due to their relatively low species biodiversity in some regions of the world. This may be combined with a lack of awareness of their high degree of biological diversity at habitat level and the relative high occurrence of characteristic species and endemics. Sometimes it may even be linked to a plain lack of awareness of the existence of peatlands and their special management needs.

Definitions used within the Article 1 of the UNCCD

- **Desertification** means land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities;
- **Land degradation** means reduction or loss, in arid, semi-arid and dry sub-humid areas, of the biological or economic productivity and complexity of rainfed cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from land uses or from a process or combination of processes, including processes arising from human activities and habitation patterns, such as: (i) soil erosion caused by wind and/or water

(ii) deterioration of the physical, chemical and biological or economic properties of soil

(iii) long-term loss of natural vegetation

A review of policies and practices in tropical peat swamp forest management in Indonesia (see Silvius and Suryadiputra 2005) found that while many of the Indonesian sectoral policies and legislation bear great relevance to peat swamp forest management, only a few refer to or address specifically the special management requirements that are linked to the particular eco-hydrology of peat swamps. The most important of these is Presidential Decree No. 32/1990, which stipulates that peat areas deeper than 3 meters should not be developed but retained in view of their water retention capacity. However, even this policy fails to recognise the need for an ecosystem approach when dealing with rain-fed peatlands: the policy allows reclamation and drainage of the outer zone of a peat dome with a depth of less than 3 meters which will invariably lead to subsidence of the deeper parts of the dome. This process could continue until the entire dome is lower than 3 meters and thus "eligible" for reclamation.

In many countries relevant policies and government regulations are clearly conflicting and can lead to confusion. It would be pertinent to review policies in this light, and to develop guidelines for land-use planning and management of peatlands taking into account their multi-functionality and their ecological and hydrological characteristics. In this regard it is important to note the particular applicability of an ecosystem approach for peat swamp management, as intervention in one part of the ecosystem can have significant impacts on other parts. Moreover, the management of separate peat land areas cannot be seen as separate from the management of their surroundings and the ecological and hydrological interconnections between the different habitats and land-uses within the entire water catchment.

The UNCCD's definitions of desertification and land degradation focus mostly on arid, semi-arid and dry sub-humid areas. However, a number of countries have used the UNCCD framework and its synergy with the other Rio Conventions to address problems of peatland degradation. For example, large scale drainage projects in Belarus in the 1950s-1990s led to extensive peatland degradation. GEF Funding under land degradation and biodiversity has recently been approved for rehabilitation and sustainable use of peatland forests in South East Asia through IFAD-GEF.

9.4.2 Addressing root causes and enhancing Implementation Mechanisms

In developing countries and countries in transition where poverty may be a root cause of unsustainable peatland resource exploitation, development may be the only way to create opportunities for peatland conservation. On the other hand, where development of peatlands coincides with the need for drainage and mining, it will generally be unsustainable and non-conducive to the conservation of the peatland carbon stores and biodiversity. Without appropriate economic alternatives and incentives it may often be impossible to maintain and manage conservation areas or invest in rehabilitation of degraded peatlands. Poor people must have a livelihood before being able to refrain from over-exploitation of natural resources. In poverty-stricken regions, governments argue that they often need to generate sufficient economic growth – even by unsustainable means - before being in a position to take environment into consideration. Therefore, incentives for short-term unsustainable development, including for instance, logging and land conversion, remain high. Development is therefore central to peat swamp forest conservation and the sustainable management and rehabilitation of degraded peatlands.

Russian Peatland Policy and Action Plan

Peatlands cover over 8% of the Russian Federation and are sites of nature management within many sectors of the economy. The complex nature of peatlands requires an integrated approach and the Russian economy has traditionally been organised according to a sectoral principle. To integrate modern methods of peatland conservation and wise use into the system of state management, a federal Action Plan on Peatlands Conservation and Use was developed by all interested stakeholder organisations, under the supervision of the Ministry of Natural Resources (Anonymous 2003).

Considering the declining incomes from agriculture and forestry on peatlands, there is a pressing need to enhance alternative income opportunities for local rural populations. In the meantime it is important to ensure that their land and resources are no longer degraded, and where agriculture and plantation forestry is practiced on peat it, that it is optimised in terms of sustainability. Without sufficient revenues from the land, poor people may be forced to go for the cheapest but not necessarily the most sustainable land-use management options. For example, this could include the use of fire for land clearance.

9.4.3 New emerging innovative options

Conservation and rehabilitation of peatlands thus provide a major opportunity to reduce current global greenhouse gas emissions). The huge, but only recently recognised, CO_2 emissions from tropical peatland deforestation and degradation, represents one of the single largest but also most concentrated sources of greenhouse gas emissions from the land-use/agriculture sector.

Whereas tropical deforestation in general covers hundreds of millions of ha worldwide and generates annual emissions of 1-2 billion tonnes of CO_2, the degradation of peat swamp forests which is mainly confined to 12 million ha of degraded peat swamps in Southeast Asia, leads to a larger total emission. Hence this should be considered as a global priory for reducing emissions from deforestation and forest degradation (Silvius 2006, Hooijer *et al.* 2006. Significant emission reductions can also be achieved through peatland conservation and restoration in other parts of the world such as In China, Russia and eastern Europe where large peatlands have been degraded through agriculture and other activities. Linkages to poverty issues (see Chapter 3) and biodiversity loss ties it to two other globally recognised priorities.

Some newly-emerging possibilities for conserving peatlands, particularly for their carbon storage function, are payments for Reduced Emissions from Deforestation and Degradation (REDD), as currently being developed by Parties to the UNFCCC. The World Bank and other institutions are exploring options to establish REDD funding mechanisms to support pilot schemes, including the option of carbon fund payments to national and local governments which need to be based on a national baseline monitoring, and the option for payments to private and community stakeholders and beneficiaries for their “environmental services”. As peatlands cut across all forest management, conservation and land use (production, industrial and agricultural) types, maintaining the welfare of traditional local communities in peatlands is a major concern.

Parallel to this are numerous private sector initiatives. This indicates a strong interest in investment in avoiding emissions through peatland rehabilitation and reforestation as a means to compensate for industrial emissions elsewhere. Some investors see opportunities for trade in “Carbon futures”. These interests could well provide the local people in peatlands with opportunities to develop a new community-based public service. According to Butler (2007) preserving tropical forest and peat swamp that would otherwise be converted and collecting the resulting recurrent revenue provided by the carbon offset market may be more lucrative for landowners in some areas than conversion to palm oil. With a carbon emission reduction price range of US$14-US$22/tonne, similar level profits may be derived over a period of 25 years.

However, much will depend on how the funding is used and how much of it can be channeled to local stakeholders. The carbon market provides a significant opportunity for a pro-poor approach, in which consideration should be given to the equitability of the development in terms of revenue sharing between investors and local stakeholders. Funding schemes that will enhance the access of local stakeholder groups to carbon funding, for example, through special REDD micro-financing facilities, could create new economic incentives and help to empower these stakeholders. This would the increase chances of successful development of an innovative community-based environment management service sector as part of the voluntary carbon market.

Carbon financing mechanisms (CDM): Under Article 3.4 of the Kyoto Protocol, activities that enhance carbon sequestration in agricultural soils can be counted towards emission reduction targets, and can be traded on the international carbon market via the Protocol's "flexibility mechanisms". Since a large proportion of peatlands are extensively grazed or under some form of agriculture, money from this source could be used to finance drain and gully blocking on a far larger scale than is currently possible.

The option for local communities to provide services to the emerging carbon market in terms of peat swamp forest conservation and restoration represents a major opportunity for linking climate change mitigation to poverty reduction. It also enhances options for other types of strategies or combinations, particularly relevant to countries with no substantial agricultural subsidies. These include for instance, the development of innovative financial instruments such as Bio-rights (Silvius *et al*. 2002). The Bio-rights approach involves establishment of business contracts, providing micro-credit for sustainable development in exchange for the conservation or rehabilitation of globally important biodiversity or environmental values. The business partners are "the global community" (represented by a broker, e.g. an NGO or bank) and a local partner (e.g. a local community or a major community-based stakeholder group). The local (community) business partner will pay interest over the micro-credit not in the form of money, but in terms of biodiversity conservation services – defined by mutually agreed environmental or biodiversity related indicators. One frequently used indicator is the survival rate of planted tree seedlings after 5 years of reforestation. The micro-credit level is linked to the opportunity costs of sustainable use and conservation of the natural resource base and biodiversity. As such, the Bio-rights approach removes the incentive for unsustainable development and allows the public value of key biodiversity wetland/peatland areas to be transferred over time to local stakeholders as a direct economic benefit. The incentive can be increased by allowing the credit itself also to be repaid through such services, enabling the development of community-based revolving funds for sustainable development. This again will trigger community-based monitoring, as the whole community will stand to lose out if the activity is unsuccessful.

The Bio-rights approach can also include such indicators as carbon store conservation and carbon sequestration, as well as the maintenance of wider ecosystem services such as water management and biodiversity values. As the micro-credit levels in the Bio-rights approach are directly related to the opportunity costs of sustainable development and conservation, the approach does not require economic valuation of biodiversity or the ecosystem services that are maintained. This distinguishes it from the Payments for Environmental Service (PES) approach. Bio-rights schemes are operational in the buffer zones of the Berbak national park in Jambi, Sumatra, and are also used in many other community-based wetland restoration projects in Indonesia, such as in the Tsunami hit region of Aceh (involving sustainable coastal development and mangrove reforestation) (See www.bio-rights.org).

Evidence has been accumulating that in many cases, natural peatland habitats generate marked economic benefits, which exceed those obtained from habitat conversion. Economic costs associated with damage to ecosystem services can be substantial. For example, the damage of the 1997 Borneo fires to timber, tourism, transport, agriculture, and other benefits derived from or linked to the forests, is estimated at $4.5 billion - in addition to the actual cost of fighting the fires (Tacconi 2003). Significant investments are often needed to restore or maintain non-marketed ecosystem services, such as the costs of flood prevention in down-stream areas.

Payments for Ecosystem Services are already operational in many parts of the world, but so far not yet practiced in peatlands. In some regions these innovative payment schemes are supported by policies and trust funds. However, techniques and local capacity for monetising ecosystem functions are generally under-developed. Some ecosystem functions cannot be valued because their precise contribution is unknown and indeed, unknowable, until they cease to function. Other functions cannot be monetised because there is no equivalent to put in their place. Intrinsic values are, by definition, without price. Consequently, any weighting can only be partial and whole ranges of values, benefits or disadvantages escape monetary evaluation. Studies valuing multiple functions and uses, and studies which seek to capture the 'before and after' states as environmental changes take place, are rare. By and large it is the latter types of analyses that are most important as aids to more rational decision making in ecosystem conservation versus development situations involving different stakeholders (local, national and global). Aggregate (global scale) estimates of ecosystems value are problematic, given that only 'marginal' values are consistent with conventional decision-aiding tools such as economic cost-benefit analysis. Despite these difficulties, valuation data are useful in decision-making by illuminating tradeoffs.

Valuation studies of industrialised countries focus on recreational and existence values held by urban consumers (travel cost models, contingent valuation). In developing countries, on the other hand, ecosystem values related to production and subsistence remain relatively important, although this is changing in regions characterized by rapid urbanization and income growth. In general, valuation data provide support for the hypothesis that net ecosystem service values diminishes with biodiversity and ecosystem loss.

9.4.4 The need for local policy embedding of innovative mechanisms

There is an urgent need to create an enabling policy environment for innovative mechanisms such as the emerging market in Verified Emission Reductions from peatlands and forests. In order to provide the necessary basis for long-term commitments from all stakeholders and management frameworks that will give carbon buyers sufficient guarantees that their investments – represented by the preserved and rehabilitated sub- and above-soil carbon store – are safe, new policy environments are needed. This will require more than the usual five-year plans, and commitments must be binding well beyond the legislative periods of current elected authorities.

Also, for carbon projects that are based on business deals at the local – community – level, such long-term commitments are needed. For instance, investment in reforestation of community-owned buffer zones adjacent to protected areas needs the development of contracts that are binding to future as well as present generations. This poses considerable new challenges, as it is impossible to predict the incentives or disincentives that may arise in the future and tip the balance leading to a change in priorities of local stakeholders.

Many other risks need to be assessed in relation to the selling and buying of avoided emissions from peatlands, including the risk of fires. This risk has particularly predominated Southeast Asia during the recurring El Niño drought events, but also occurs in large parts of eastern Europe. Such risks may need to be covered by new new government policies and legislation, and perhaps involving also new types of insurance that caters for this sector.

Current developments of REDD and private sector initiatives are being pushed hard to become operational soon. However, the question arises as to whether these ideas and initiatives have sufficiently matured. Immature ideas and projects will lead to failures and disappointments and can discredit and endanger the new emerging sector. They can further affect carbon prices and create risks that so far have not been part-and-parcel of community- and government-based natural resource management planning. It is very important that any voluntary carbon credit scheme will adhere to a common set of standards and criteria. For peatlands, with their special eco-hydrological character and management requirements, as

Biofuel policies and subsidies

Policies and subsidies that generate the opposite effect to their original intention include the recent development in the EU regarding the use of biofuels for transport and energy. The EU promoted the use of renewable energy including setting a target of 10% use of biofuels in the transportation sector by 2015. This was intended to reduce the net emissions of greenhouse gasses. The biofuels could come from locally produced biofuels, e.g. rapeseed, corn, but also from imported biofuels such as palm oil. EU governments have responded by providing special subsidies for cultivation and processing of biofuels. The Netherlands in 2006, for example committed to 740 million Euros in subsidies in support of the development of two small palm oil fueled power stations as well as offering more general subsidies for biofuels in the transport sector. The large scale use of edible oils in Europe for biofuel production also stimulated international interest in biofuels and contributed to a nearly 8% increase on the price of palm oil in the international market. This stimulated a rapid expansion of palm oil in Se Asia which currently produces more than 80% of global production. However, a substantial part of the Southeast Asian palm oil plantations occur on peatlands and a significant portion of the the palm oil expansion is expected to take place on peatland areas (Hooijer *et al.* 2006). Oil palm plantations require relatively deep drainage (at least 60cm), causing significant CO_2 emissions. Use of palm oil could therefore lead to 3 to 10 times more CO_2 emissions compared to using fossil fuels (Silvius 2007). The concerns about the cultivation of biofuel feedstock on peatlands has been highlighted widely since 2006 and this has led to withdrawal of some subsidies for palm oil grown on peatlands. However with the enhanced market price – expansion of palm oil on peatlands is still occurring even without subsidies.

Subsidies and policy incentives are also encouraging the cultivation of other biofuel feedstocks on peat such as corn in Europe and North America, sugar cane in the Americas and soya bean in Latin America and Asia. Many of these crops have a much lower yield of biofuel per ha compared to oil palm so their emissions of GHG per tonne of biofuel produced may be higher than for palm oil.

Oil palm plantation on peatlands. When oil palm and other crops are grown on peatlands with drainage the peat decomposes releasing up to 100+ CO_2/ha/year. This offsets any climate benefit from biofuel use of the crops.

Windfarm development on peatlands

Projected GHG emission reductions from wind farms on peatlands may need to be reduced to account for the release of CO_2 from peatlands drained or impacted by the construction of the windmills and access roads.

well as their complex social and economic setting, these criteria have not yet been developed. Pilot schemes will be needed, and therefore there is a strong need for coordination and sharing of lessons learned between all projects and efforts that relate to peat CO_2 management and the promise this holds for poverty reduction, biodiversity conservation and climate change mitigation.

It is now widely recognised that the peatland issue is part and parcel of the REDD agenda. This creates a strong basis for international cooperation and support. There are many signals of strong interest to assist from both the donor community as well as private sector, and many initiatives are being developed at present. A new market is emerging that can be supplied by a community-based service sector. It will create significant opportunities for local community development as well as private sector investments. However, there is an urgent

Basic approaches for sustainable peatland management to be considered in policy and practice

In defining requirements for management of peat swamp forests, we can draw up the following basic lessons to be considered when planning interventions in peatland areas.

Precautionary approach

1. In the planning of land-use in peatlands, it is advisable to use the precautionary approach. Large-scale developments in peatlands should be pursued only after considerable research and after the successful completion of pilot projects.

Ecosystem approach

2. Land-use planning in peatlands should follow the ecosystem approach, taking special account of the hydrological vulnerability of peat domes and the ecological relationships with the surrounding habitats and land-uses. Particular regard should be given to the place of the area within the water catchments/ watershed, and the potential impacts of and on upstream and downstream habitats and land-uses (including potential land-uses). It may even be necessary to consider multi-river basin complexes, as multiple watersheds may be dependent on shared peat domes, so the impacts on one river basin may affect the shared hydrological basis.

Integrated approach

3. Wise management of peatland ecosystems requires a change in approach from single sector priorities to integrated, holistic planning strategies, involving all stakeholders to ensure that consideration is given to potential impacts on the ecosystem as a whole. Land-use planning in peatlands should involve all relevant sectors and major stakeholder groups, including local people, from the outset of development planning. A precondition for successful integrated planning is the (enhancement of) awareness of the various groups regarding peatland ecology and hydrology, and the full scale of values that peatlands may have.
4. The use of a peatland for a specific purpose may have considerable side effects and all other functions must be taken into account in the full assessment of the suitability of a particular use.
5. With respect to side effects, a use could be considered permissible when:

- Negative side effects will not occur
- The resources and services affected will remain sufficiently abundant, or
- The resources and services affected can be readily substituted, or
- The impact is easily reversible

In all other cases, an integrated cost benefit analysis should be carried out involving thorough consideration of all aspects of the proposed use.

Allocation of land-use status

6. Allocation of land-use status in peatlands should take account of the hydrological vulnerability of peat swamp forests, their susceptibility to subsidence and oxidation (leading to CO_2 emission), their vulnerability to fires and their values for biodiversity conservation, water retention and climate change mitigation.

need to create an enabling policy environment for these developments. Voluntary carbon initiatives will require certain guarantees that the investments will not be in vain and can be efficiently channeled to where they can be most effective. For effective development of the REDD market, long-term commitments are needed, backed up by policies and legislation.

9.4.5 Harmful subsidies, policies and taxes

Peatlands have been negatively impacted by a wide array of perverse and harmful incentives in the form of policies and subsidies. In many countries peatland drainage is still encouraged under various kinds of policies, subsidies and tax breaks. There are ample examples in Western Europe where high mountain peatlands were significantly affected by former EU subsidies for sheep (encouraging more sheep to be held then the carrying capacity of the peatlands) and national subsidies and tax breaks for afforestation which have encouraged draining and planning of peatlands with

	Integrated Peatland management can generate benefits in relation to:	Business of the following intergovernmental Process:
Win 1	Climate change	United Nations Framework Convention on Climate Change
Win 2	Land degradation	UNCCD
Win 3	Loss of biodiversity	CBD, Ramsar Convention
Win 4	Poverty	Commission on Sustainable Development

monospecicific plantations. Sometimes land tenure is linked to productive use of peatlands, providing a disincentive to conservation and restoration. In Indonesia, for instance, there are local policies that require clearance of land every three years, without which the land tenure can be lost. This creates an incentive for burning as it is the cheapest option for land clearance.

In recent years, one of the most important negative impacts on peatlands globally have come from policy incentives and subsidies for biofuel production – which were originally designed to enhance environmental protection.

9.4.6 Synergy between conventions to develop integrated policy frameworks

Peatlands are a habitat where current global priorities in climate change mitigation, combating land degradation, stopping the loss of biodiversity and reducing poverty come together. This Assessment has indicated in various ways the disproportionate relevance of peatlands in relation to climate change mitigation, combating land degradation, biodiversity conservation and poverty reduction, and as such the need to consider peatlands within the context of the major global policy platforms, including the UNFCCC, UNCCD, World Water Forum, CBD, Ramsar Convention on Wetlands, and the Commission on Sustainable Development. The synergy between the conventions and policy platforms in this regard calls for enhanced coordination and cooperation. The donor community is increasingly recognising the need for integration of these agendas, but current global policy processes fall short of sharing lessons-learned and best practices regarding the development of inter-sectoral approaches to the conservation and wise use of peatlands world-wide. The figure below illustrated that integrated Peatland management can simultaneously address a variety of problems and generate multiple benefits.

Conclusion

The current management of peatlands is generally not sustainable and has major negative impacts on biodiversity and the climate. A wise use approach is needed to integrate protection and sustainable use to safeguard the peatland benefits from increasing pressure from people and the changing climate. Strict protection of intact peatlands is critical for the conservation of biodiversity and will maintain their carbon storage and sequestration capacity and other associated ecosystem functions. Relatively simple changes in peatland management (such as better water management and fire control in drained peatlands) can both improve the sustainability of land use and limit negative impacts on biodiversity and climate.

Restoration of peatlands can be a cost-effective way to generate immediate benefits for biodiversity and climate change by reducing peatland subsidence, oxidation and fires.

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