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1. Carex limosa *and* Sphagnum cuspidatum *growing on a bog pool in the central of a raised bog in the foothills of the German alps (Photo: J. Rieley).*

2. *Aapamires are predominantly minerotrophic mires where the centre is composed of wet flarks and strings (hummock ridges). The strings run across the gradient of the mire surface (Photo E. Lappalainen/Global Peat Resources).*

3. *Close study of the vegetation on Nigula mire in Estonia (Photo M. Kosk/ Global Peat Resources).*

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THE IMPACT OF LOGGING ON LAND USE CHANGE IN CENTRAL KALIMANTAN, INDONESIA

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SUMMARY

The province of Central Kalimantan contains about three million hectares of peatland, which is one of the largest contiguous areas of tropical peatland in the world. Peat Swamp Forests (PSF) are among the earth's most endangered and least known ecosystems. They have a huge carbon storage capacity but are extremely fragile and liable to disturbance. Local communities have used them extensively for centuries without significant impact on the environment. This changed in 1995 when a programme of massive peatland conversion, the so-called Mega Rice Project (MRP), was initiated with the aim of converting one million hectares of peatland, in Central Kalimantan, Indonesia, into rice fields. Between 1996 and 1998 more than 4000 km of drainage and irrigation channels were constructed in the designated area. Boosted by the El Niño Southern Oscillation (ENSO) episode in 1997, many fires initiated for land clearance purposes spread into pristine forest areas where they continued to burn with great intensity. The newly established drainage and irrigation system aggravated fire impacts, fostering this disaster. The multi-temporal analysis of six LANDSAT TM images acquired between 1991 and 2000 shows extremely high rates of deforestation during this time. Between 1991 and 2000 the area of forest was reduced at the rate of 3.2% per year. If the situation continues there is a very high risk that most of the peat swamp forest resource in Central Kalimantan will be destroyed within a few years with grave consequences for the hydrology, local climate, biodiversity and livelihood of local people. Unless land use policies are changed to control logging and the drainage of the peatland is stopped recurrent fires will lead to an irrecoverable loss of this unique rainforest ecosystem and release of huge amounts of carbon to the atmosphere.

Keywords: logging, remote sensing, GIS, land use, deforestation, tropical rainforest, peat swamp forest, Kalimantan, Borneo

INTRODUCTION

Approximately half of the study site (2 million hectares) around Palangkaraya, the provincial capital of Central Kalimantan, is covered by peatland that supports a natural vegetation of peat swamp forest (Rieley *et al.*, 1996). The forest consists of secondary, logged and clear-cut areas (Sieffermann *et al.*, 1988). In recent decades the size of this peat area has been shrinking because of land-use conversion, mainly to agriculture and exploitation of the forest timber resources. If these forests are removed completely, either by large-scale cutting or by uncontrolled forest fires, as happened in 1982/83, 1987, 1994, and 1997, it will take centuries for new forest with similar species diversity to re-establish (Anderson, 1983; Barber & Schweithelm, 2000; Boehm *et al.*, 1997; Boehm & Siegert, 2000). In 1996 the Indonesian Government commenced the One Million Hectare Mega Rice Project (MRP) for rice cultivation, linked to transmigration (Notohadiprawiro, 1998). In order to open this area and make it suitable for growth of crops, large drainage and irrigation channels were excavated through the peat-covered landscapes between the Sebangau and Barito Rivers. Over 4000 km of parent, main, secondary, third and quarter level channels were constructed between January 1996 and July 1998, when the project was halted. The total area affected by this project was actually 1.5 million hectares that, for operational purposes, was divided into five landscape units known as Blocks A, B, C, D and E. The MRP became a major location of fire "hot spots" because of burning of vegetation for land clearance, especially in the dry season (Jaya *et al.,* 2000; Page *et al.,* 2000). In June 1997, months before fires and smog had become a serious health hazard to millions of people in Southeast Asia, areas upstream of the land development project were already suffering serious food shortages (Barber & Schweithelm, 2000; Boehm & Siegert, 2000). A marked drop in the water level of major rivers, combined with poor visibility owing to smog, hindered food transport, and a lack of water for irrigation made the planting of crops impossible. Droughts, forest fires and famine were the results. In many areas uncontrolled illegal logging preceded the exploitation and conversion of tropical rain forest. This study was carried out in order to document the extent of official logging and illegal logging in the peatland areas of south-east Central Kalimantan and analyze how this affected land use in this area, and susceptibility to future fire damage.

Methods

LANDSAT TM images Path 118 Row 61 and Path 118 Row 62 from three acquisitions, June 30, 1991, May 29, 1997 and July 16, 2000, were analysed. The geographic location covers an area of 60,000 km² (Upper left corner: Latitude -0.57°, Longitude 113.73°, lower right corner: Latitude -3.57° Longitude 114.62°). Basic image processing included geo-referencing, mosaicking of Row 61/62 and image to image registration using a Global Positioning Sensor (GPS) to determine the exact location of ground control points (GCP). For visual image interpretation bands 3, 4 and 5 were selected to produce a colour RGB image, Band assignment was 5, 4, 3 = RGB. This band combination proved to be the best in this region and allowed for the separation of more than 20 vegetation and land use classes (Fig. 1A). Each channel was interactively contrast enhanced in a reference LANDSAT TM5 image (1991) in order to maximise overall image contrast. The six Landsat TM scenes were spectrally adjusted to the reference image by histogram matching.

The basic land cover legend was adapted from the TREES classification scheme (Stiebig *et al.,* 2000). Interpretation of Landsat TM images was carried out by visual on-screen digitising at a scale of 1:100,000 (minimal mapping unit 50 ha) (Fig. 1B). The interpretation key for land cover was established from GPS measured ground observations. The LANDSAT TM image mosaic Path 118 Row 61-62 was used as reference for the land cover map. In the subsequent image mosaics of 1997 and 2000 only areas in which changes in land cover occurred have been mapped. Clouds, haze and non-overlapping areas were masked out. A change assessment was done by comparison of historical and more recent satellite images within the overlapping area (change 1991-1997, 1997-2000) and a change matrix was produced which included all land cover classes and the percentages of changes between these classes. Logging roads and logging railways were clearly visible in band combination 5, 4, 3 images. Even logging roads/railways established before 1991 were visible in the year 2000 Landsat ETM image. Logging roads/railways were delineated on-screen as line features. All area and length calculations were done using a Geographical Information System (GIS).

Extensive ground surveys on foot and by boat, car and small aeroplane were carried out in 1998, 1999 and 2000 in order to check image classification of land use and vegetation within the study area. More than 2000 GPS measurements were collected using the continuous track mode of the GPS instrument acquiring measurements every 10 to 30 seconds (aerial surveys) or 20 to 60 seconds (ground surveys). The accuracy of the vegetation and land use interpretation was determined using 258 GPS recorded ground observations. In addition four hours of GPS synchronized digital video material acquired during two aerial surveys were used to check areas that could not be accessed on foot (peat swamp forest is flooded for up to 10 months of the year, the ground surface is very uneven, the vegetation is almost impenetrable). For the accuracy assessment in these areas we used 148 randomly selected digital video images. Overall classification accuracy for vegetation types was >95%.

Results and Discussion

An overview of the vegetation changes and classes of land use, which occurred within a 9-year period between 1991, 1997 and 2000, is presented in Table 1a. Table 1b gives the TREES (Tropical Ecosystem Environment Observation by Satellite, an initiative funded by the European Commission and headed by the Joint Research Center in Ispra, Italy) classification legend. The total area analyzed was 5.18 Mha. 8.6% was covered in accumulated cloud over all three of the LANDSAT image mosaics.

To assess peat swamp forest conversion processes in detail, it is essential to have knowledge of the type of conversion. Our analysis shows that the highest

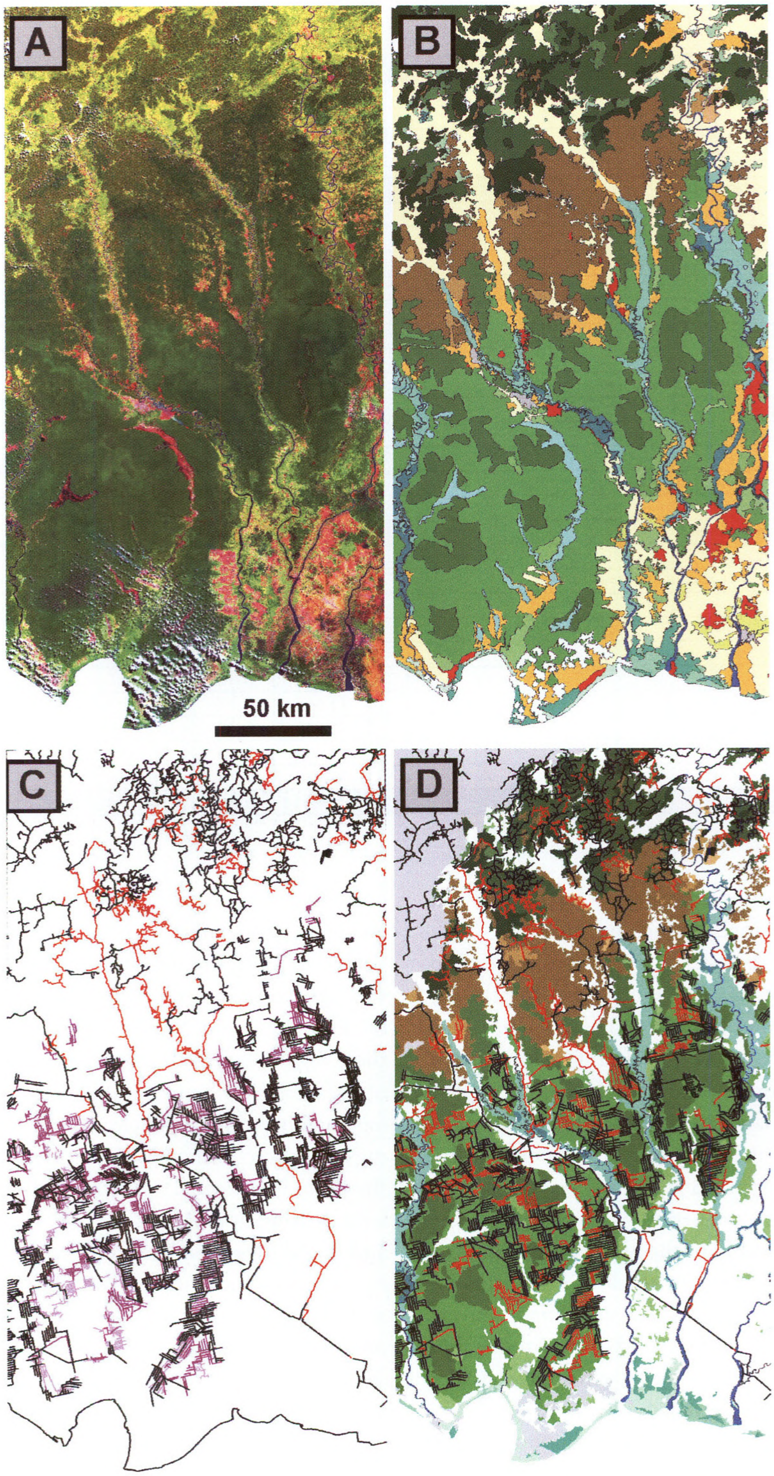

Fig. 1. A. Landsat TM mosaic (1991, RGB=5,4,3). B. Land cover classification of A. C. Logging roads (curved lines) are visible in the upper half of the study area (black: 1991, red: 1997). Logging railways (straight lines) are visible in the lower part of the study area (black: 1991, purple: 1997; bright purple: 2000). D. Logging roads and logging railways superimposed on forest classification: dark green colours: lowland Dipterocarp forest, blue green colours: peat swamp forest (low pole: dark blue green, medium: medium blue green, tall: bright blue green), brown colours: heath forest, bright blue-green: mangrove forests.

Table 1: Vegetation and land cover changes in the study area of Central Kalimantan from 1991 to 2000

TREES legend	TREES land cover classification	TM 5 June 1991		TM 5 May 1997		ETM 7 July 2000	
		ha	%	ha	%	ha	%
111a	Closed, high density, evergreen lowland forest	286,773	5.5%	96,679	1.9%	90,032	1.7%
111b	Closed, medium density, evergr, lowland forest	373,007	7.2%	351,591	6.8%	334,077	6.5%
111c	Open evergreen lowland forest	73,425	1.4%	21,027	0.4%	30,258	0.6%
111d	Fragmented evergreen lowland forest	0	0.0%	9,482	0.2%	15,743	0.3%
114a	Closed, high density, heath forest	528,332	10.2%	477,873	9.2%	443,117	8.6%
114b	Closed, medium density, heath forest	41,651	0.8%	39,042	0.8%	43,975	0.8%
114d	Open heath forest	10,051	0.2%	14,770	0.3%	15,082	0.3%
131a	Closed, high density, periodically inundated fo,	81,405	1.6%	27,215	0.5%	22,631	0.4%
131d	Fragmented, periodically inundated forest	199,188	3.8%	230,134	4.4%	228,245	4.4%
134a	Closed, high density peat swamp forest	540,669	10.4%	362,073	7.0%	317,705	6.1%
134b	Closed, medium density peat swamp forest	1,231,738	23.8%	1,217,075	23.5%	845,405	16.3%
134c	Open peat swamp forest	29,680	0.6%	44,906	0.9%	35,827	0.7%
134d	Fragmented peat swamp forest	87,789	1.7%	89,015	1.7%	85,606	1.7%
160	Forest Regrowth	55,324	1.1%	38,307	0.7%	34,059	0.7%
170a	Closed, high density mangrove forest	47,747	0.9%	30,504	0.6%	30,504	0.6%
170c	Open mangrove forest	28,600	0.6%	15,519	0.3%	15,518	0.3%
170d	Fragmented mangrove forest	16,572	0.3%	42,369	0.8%	43,431	0.8%
210	Shifting cultivation mosaic	572,988	11.1%	493,043	9.5%	503,030	9.7%
23	Forest Mosaics, other vegetation & forest	348,582	6.7%	362,939	7.0%	608,406	11.7%
321	Dry grassland	6,465	0.1%	7,330	0.1%	7,330	0.1%
322	Swamp grassland	84,486	1.6%	87,617	1.7%	85,466	1.6%
412	Rain-fed arable land	293,266	5.7%	306,358	5.9%	314,781	6.1%
420	Plantations	28,815	0.6%	47,684	0.9%	47,135	0.9%
51	Urban	11,666	0.2%	12,038	0.2%	12,038	0.2%
59	Bushland (Non-vegetated)	87,043	1.7%	252,368	4.9%	467,722	9.0%
62	Rivers	57,462	1.1%	57,135	1.1%	57,133	1.1%
81	Clouds	59,888	1.2%	446,279	8.6%	446,124	8.6%
	Total	**5,182,614**	**100%**	**5,180,374**	**100%**	**5,180,380**	**100%**

deforestation rate observed was for closed, medium density peat swamp forest, which decreased by 7.5% (23.8%-16.3%, 134b) over a period of 9 years. The second highest rate was 4.3% obtained for closed, high-density peat swamp forest (10.4%-6.1%, 134a) followed by 3.8% (5.5%-1.7%, 111a) for closed, high density, evergreen lowland forest. The land occupied by deforested bushland and forest mosaics together with other vegetation and forest types increased by 7.3% (1.7%-9.0%, 59) and 5.0% (6.7%-11.7%, 23), respectively, over the time period of 9 years.

Blocks A, B, C and D of the MRP were subject to the most intensive changes in the last 36 months by clear cutting and forest fires. The overall forest conversion rate for the 5 MRP Blocks A-E is shown in Table 2 where comparison can be made with the relatively pristine PSF of the Sg. Katingan – Sg. Sebangau area. It is evident that both authorized concession logging and illegal logging increased between the Barito and Kahayan Rivers and, more recently, between the Kahayan and Sebangau Rivers as a direct result of the MRP.

The rate of reduction of the forest area between 1991 and 1997 was approximately 2.0% per year. Between 1997 and 2000 the rate of deforestation increased to about 6.5 % per year, as a result of the land clearance associated with the MRP activities that peaked in 1997 and the peatland fires that occurred in the same year. The average rate of forest disappearance between 1991 and 2000 was about 3.2 % per year in the 6 regions selected in this study. The major causes of deforestation between 1991 and 1997 were legal logging operations, land clearing for small-scale farming and land clearing for plantations. This changed in the period between 1997 and 2000 when large-scale land clearing by fire for the MRP accelerated in 1997 and illegal logging operations intensified throughout the whole region after the end of the Suharto regime and collapse of law and order in the hinterland of provinces such as Central Kalimantan. The extent and impact of logging activities between 1991 and 2000 are shown in Figure 1c. The length of logging roads increased between 1991 and 1997 from 4419 km to 6621 km (34% increase), the length of logging railways and extraction tracks increased from 7136 km to 9406 km (25% increase). By the year 2000 the length of the logging railways and extraction tracks increased by another 1920 km making a total of more than 11,000 km.

Table 2: Change detection of forest areas between 1991, 1997 and 2000 for 5 MRP regions (A, B, C, D, E) and between rivers Katingan and Sebangau.

Central Kalimantan		Landsat TM5 30-06-1991	Landsat TM5 29-05-1997	Landsat TM7 16-07-2000
MRP with 5 Blocks:	Regions ha	PSF-Forest ha	PSF-Forest ha	PSF-Forest ha
Block A	315,894 (100%)	135,585 (42.9%)	107,330 (34.0%)	39,838 (12.6%)
Block B	161,461 (100%)	109,134 (67.6%)	82,816 (51.3%)	51,008 (31.6%)
Block C	440,760 (100%)	233,275 (52.9%)	180,196 (40.9%)	73,387 (16.6%)
Block D	145,707 (100%)	3,159 (2.2%)	0 (0%)	0 (0%)
Block E	504,022 (100%)	399,475 (79.2%)	383,042 (76.0%)	359,988 (71.4%)
Rivers Katingan and Sebangau (relatively pristine PSF)	838,888 (100%)	682,056 (81.3%)	631,262 (75.2%)	573,921 (68.4%)
Sum for 6 regions	**2,406,732 (100%)**	**1,560,377 (64.8%)** (100%)	**1,377,442 (57.2%)** (88.3% in 6y) (100%)	**1,110,151 (46.1%)** (71.1% in 9y) (80.6% in 3y)

Table 3: Increase of the logged-over area between 1997 and 2000 in different types of peat swamp forest.

Logged over forest type	1997	2000	% increase
	ha	*ha*	
Low pole peat swamp forest	3,056	3,649	19.4 %
Medium peat swamp forest	26,371	43,293	64.2 %
Tall peat swamp forest	7,575	9,799	29.4 %
Total logged area	39,566	56,891	43.8 %

The 1997 superimposition of logging roads and railways (including extraction tracks) on the different forest types (Figure 1D) shows that the extraction network is especially intensive in Dipterocarp forests (dark green to the North) where almost all forests containing merchantable timber have been opened up and logged. Roads and railways are absent only from forests of minor commercial value, such as low pole peat swamp forest (dark blue-green) and heath forest (brown colours).

Illegal logging can be discriminated from legal logging operations in Landsat ETM images by differences in their spatial pattern. Legal logging operated by concessionaires involves investment in infrastructure such as substantial logging roads and railways along which the logs are transported after tree felling (Fig. 2A). Roads and railways are clearly visible in Landsat TM images even 9 years after construction, i.e. railway routes visible in 1991 are still visible in the year 2000 image. They appear in bright green colours due to growth of secondary vegetation. Previously logged areas appear as a mixture of bright green and dark green pixels representing secondary vegetation and remaining primary vegetation (Fig. 2A). A recent removal of trees by logging appears as a change in signature in the Landsat TM image because some of the reflectance comes from soil (appearing as orange in Fig. 2B). Illegal loggers do not have the money and equipment to establish regular roads and railways and their access tracks into the forest appear as irregular patterns that

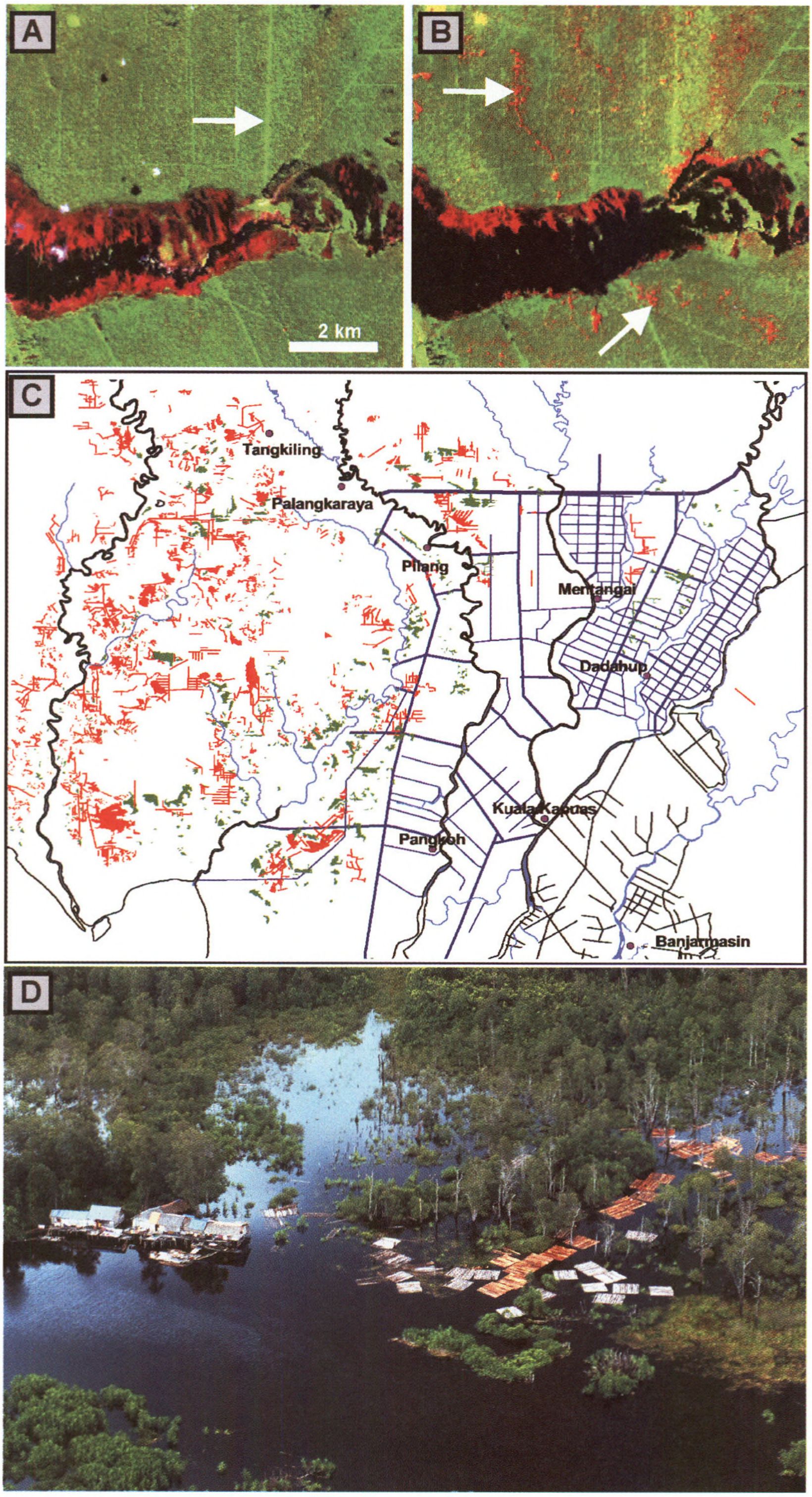

Fig. 2. ***The detection of logging operations.*** *A. Logging railways appear bright green in the 1997 image (arrow) B. Logging activity in the 2000 image (arrows, orange colours indicate opened canopy). C. Logged over area in 1997 (green) and 2000 (red) and MRP irrigation system (right part of figure in blue and older channel system in black) D. Aerial photograph of an illegal logging camp.*

follow natural features such as small streams or abandoned logging railways (Fig. 2B).

Another difference between legal and illegal logging is evident from the pattern of harvesting. In official concessions all commercial size trees are harvested along strips of forest approximately 500 m wide on both sides of the access roads and railways creating a herringbone appearance on a satellite image. In contrast, illegal loggers take only those trees that are easily accessible from their tracks this shows as an irregular pattern on the Landsat ETM image as a result of their discovery of trees in the forest. (Fig. 2B).

Examination of the logged over area within the upper Sungai Sebangau catchment shows that the area logged increased by 43.8% (Table 3) between 1997 (green) and 2000 (red) (Figure 2C), especially within medium pole peat swamp forest (64.2 %). There was much less illegal logging activity in low pole forest, which contains only small numbers of merchantable trees. The large increase can be attributed mostly to illegal logging, a fact that was confirmed for 23 sites by field checks and aerial reconnaissance (Fig. 2D). Another alarming feature emerged that in 2000 most logging activity occurred between the Sebangau and Katingan river (left in Fig. 2C) and hardly any in the former MRP area (right in Figure 2C) because almost all valuable forest trees in the latter had been either felled in the land clearance operations that commenced in 1996 or destroyed by the 1997 fires. The area between the Sebangau and Katingan rivers is the last remaining large, contiguous block of peat swamp forest in Kalimantan. As logging opens the canopy and huge amounts of logging waste are deposited on the ground (illegal logging even more than legal operation) there is an extreme danger of another fire disaster happening in the near future.

Conclusion

The major causes of forest conversion between 1991 and 1997 were legal logging operations and land clearing for small-scale farming and plantations. Legal logging concessions prepared the ground for further degradation of the forests by fire, illegal logging and farming (Siegert *et al.*, 2001). In 1997 large-scale land clearing by fire for the MRP and, in 2000, illegal logging became the major causes of deforestation. Between 1997 and 2000 the logged-over area increased by 43.8 %. If the deforestation rate remains as high as it has for the years 1991 to 2000 (3.2 % per year) there is a very high risk that most of the peat swamp forest resource in Central Kalimantan will be destroyed within a few years with grave consequences for the hydrology, local climate, biodiversity and livelihood of the local people (Page & Rieley, 1998, Boehm & Siegert, 2000). NOAA/AVHRR hotspot data indicate that land clearing is continuing although the Indonesian Government formally abandoned the MRP in 1999. Satellite images show a rapid conversion of peat swamp forest mostly into unused fallow land. Roads and the drainage channels of the MRP allow loggers and farmers unprecedented access into previously highly inaccessible forests. Even when commercially viable trees have already been cut, illegal loggers take smaller trees of only 10cm – 20cm diameters. Countless floats transport timber over black-water lakes and along channels and rivers all over Central Kalimantan. Huge areas of ecologically damaged peat landscape are visible from the air and satellite imagery. Logging and the drainage of the peat swamps by the channels have greatly increased the risk of fire. Drought and/or low water tables in peat areas cause trees to die and make the forests even more susceptible to fire. Recurrent fires do not allow forests to recover and ferns and grasses invade that in turn produce much combustible debris. Unless land use policies are changed to control logging and the drainage of the peatland is reversed recurrent fires will lead to an irrecoverable loss of this unique rainforest ecosystem.

Acknowledgements

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THE LAW OF THE JUNGLE: JURIDICAL ACTION AGAINST DESICCATION OF MIRE RESERVES IN THE NETHERLANDS

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Summary

Recent developments in the desiccation of mire reserves in the Netherlands and juridical aspects of their protection are illustrated by examples from the Peel area (The Netherlands). As administrative law was revealed to be highly ineffective and time-consuming, a tendency to increased use of civil law can be observed. Complicating aspects, including "proof of harm" and "weighing of interests" are discussed.

"Ontwateringsschade in natuurreservaten zou vaker aan de rechter voorgelegd moeten worden."
(Desiccation damage to nature reserves should more often be brought to court).
Ab Grootjans 1985.

Keywords: peatland conservation, drainage, desiccation, law, juridical action

Introduction

Mires are wetlands in which, under permanently waterlogged conditions, plant remains accumulate as peat. Mires consist of over 90% water; they are "too wet for coaches, too dry for boats". Three thousands years ago, half the present-day area of the Netherlands was covered with mires; approximately 10,000 km^2 of bogs and 5,000 km^2 of fens. Human activities have changed this character completely. Enormous areas of mire have virtually vanished as a result of peat extraction and agricultural exploitation. What are left of these formerly dominant landscape types are 150 km^2 of "fen" and 100 km^2 of "bog" remnants. All remaining mire areas are officially designated as nature reserves. They still support many internationally threatened plant species and communities, and are important as palaeo-ecological archives. Furthermore, the mire relics are valuable for animals, especially birds. As a consequence, many mire remnants have international protection under the Ramsar Convention, the European Birds Directive and the European Habitats Directive (Vermeer & Joosten, 1992, Joosten, 1994a). The conservation values of the mire reserves are dependent on nutrient-poor conditions, and a high and stable water level. Both these characteristics are threatened by changes in hydrology.

In this paper, I will review some recent developments in desiccation of mire reserves in the Netherlands. Juridical aspects of their protection will be illustrated by examples from the Peel area, where private conservation groups have been extremely active in testing legal actions against both pollution and desiccation (Joosten, 1995a).

The Nature of Conservation

Nature conservation aims to preserve natural biodiversity. Nature includes all spontaneous processes (*e.g.* growth, succession, evolution) and their resulting patterns and systems (*e.g.* mountains, species, communities).

Nature conservation is not applied to all types of nature. Its interests are restricted to those natural patterns, processes, and systems that are threatened under the prevailing socio-economic and technological conditions. Natural aspects that are not threatened are still part of nature, but are not priority objects of nature conservation (Joosten, 1995b; 1996).

Nature conservation relies on two complementary strategies. On the one hand, it is continuously trying to establish positive feedback mechanisms with modern socio-economic processes. Aspects of nature that become the spontaneous (= natural) outcome of prevailing economic activities are not threatened anymore and cease to be priority objects of nature conservation. The Groote Peel National Park (The Netherlands), for example, derived its initial conservation interest from the presence of one of the few colonies of Black-headed Gulls (*Larus ridibundus*) in the Netherlands. Now, half a century later, the species has expanded immensely, (as a result of heavy manuring of the surrounding agricultural lands), and the birds are actively discouraged (Joosten & Bakker, 1987; Joosten, 1988a).

On the other hand, nature conservation has to continue its care for those natural aspects for which no place is spontaneously available in contemporary society. Their survival requires effective isolation from threatening factors. This isolation can be maintained by favourable landscape-ecological conditions of the areas for nature conservation ("intangibility") and/or by juridical instruments ("veto-regulation").

In a densely populated and intensively used country such as The Netherlands, nature conservation necessarily had to start with the "left-overs" of socio-economic development. Only those parts that could not be exploited any further were granted a conservation objective and were made into nature reserves. As a consequence of this negative selection, the location, configuration and extent of these reserves is often unfavourable. This situation inevitably leads to conflicts between neighbouring types of land use with contrasting hydrological requirements.

Mire conservation and Desiccation

Water plays a crucial role in the functioning of mires, as all mires require a high and stable water level. Changes in the hydraulic regime may therefore have a major impact on mire ecosystems.

Mires can be subdivided into bogs and fens. Bogs are recharged mainly by precipitation and their surface is isolated from groundwater influence. In natural conditions only a minor part of the bog water is discharged by downward seepage to the subsoil. As the rate of this flow is a function of the gradient in hydraulic head and the porosity of the medium, an increase in hydraulic gradient will result in an increased flow rate and increased water level fluctuations. Lowering the hydraulic head in the subsoil by activities in the surroundings will therefore change the water balance of the bog and may eventually preclude further bog growth (Vermeer & Joosten, 1992). This will especially apply to bogs in which former peat exploitation diminished the resistance to vertical flow (Van Walsum & Joosten, 1994).

Groundwater supply and the interaction of groundwater with atmospheric water are important ecological factors in fens (Wassen & Joosten, 1996). Diversity of fen communities is to a large extent determined by fine-scale patterns as these different types of water mix together. Lowering the hydraulic head of the groundwater may change the balance between groundwater and precipitation water. Even when mire water tables do not change, the effects will generally be dramatic. Attempts to compensate for this decreased supply of groundwater by an increased storage of atmospheric water may be counter-productive as they accelerate the changes towards more "rainwater" conditions, leading to acidification. Supplying the mire system with surface water from the surrounding agricultural area leads to nutrient enrichment (eutrophication), and eventually to the disappearance of the nutrient-poor communities. All these effects are included in the term "desiccation" in this paper. Control of the regional hydrology is therefore a prerequisite for mire conservation and management (Vermeer & Joosten, 1992).

- hydrological changes in the Netherlands in recent decennia resulted from a complex of activities, including groundwater extraction for drinking water supply and industry, increasing from 700 mln $m^3\ y^{-1}$ in 1957 to 1088 mln $m^3\ y^{-1}$ in 1986;
- increased evapotranspiration resulting from increased productivity of agricultural crops since the early 1950's, leading to a decrease in groundwater recharge of 20 - 60 mm y^{-1};
- application of agricultural sprinkler irrigation, increasing from 24,250 ha in 1958 to 566,000 ha in 1986;
- urbanization and associated sewerage and surfacing, increasing from an area of 150,000 ha in 1950 to an area of 289,000 ha in 1985;
- changes in drainage and water supply, *e.g.* following land consolidation programmes;
- changes in weather conditions (Querner *et al.*, 1994).

Most of these developments affected the Peel bog reserves. This has led to juridical conflicts between the originators of the problems, local and national authorities, and non-governmental nature conservation groups (NGOs). In these conflicts, various legal instruments were used. Initially the focus was primarily on administrative law but, as this instrument proved to be highly ineffective and time-consuming, the NGOs increasingly used civil law. Criminal law has, until now, played a less significant part.

THE ADMINISTRATIVE APPROACH: THE GROOTE PEEL CASE

Introduction

The Groote Peel bog reserve (1360 ha) is a typical example of the "degenerated" bog remnants found in the Netherlands. The bog has been cutover for centuries (up to the 1970's) and, as a consequence, little peat is left. Presently, it contains a great variety of landscape types, including marshes and heathlands, stretches of purple moor grass (*Molinia caerulea*), scrub and forest, and a considerable extent of open water. Bog communities and plants are confined to old peat pits in which a renewed accumulation of ombrogenous peat is taking place ("bog regeneration") (Joosten & Bakker, 1987). The reserve also contains a substantial area of internationally threatened wet heath (Joosten & Van Noorden, 1992). The Groote Peel bog reserve was established in 1951 and has gradually expanded to its present size. Because of its tranquillity and the presence of large marshy areas and lakes, the Groote Peel is of great value for its avifauna. In 1980 the area was designated an internationally important wetland site under the Ramsar Convention, followed by designation as "Special Protection Area" under the EC Birds Directive in 1986.

The Groote Peel reserve is situated in the most intensively used agricultural area of the Netherlands, where agriculture is striving for maximum yields. With respect to hydrology, this involves drainage of wet soils, and implementation of sprinkler irrigation on drier soils. The designation and installation of hydrological buffer zones around the reserve in order to restrict these activities has been an important issue of discussion since the beginning of the 1980's. A plea for buffer zones by the National Forestry Service (Stoffels & Speet, 1982) raised a stream of protests in the region. In 1984, the first primitive hydrological calculations pointed to a necessary width of buffer zone of 600 m (Werkgroep Behoud de Peel 1984, 1986).

The procedure to make the Groote Peel into a national park was initiated in 1985. An extensive geohydrological research programme was begun to study the hydrological relationships between the nature reserve and its surroundings. Reacting to these developments and anticipating possible future restrictive legislation, the farmers in the surrounding area began to install subsurface drainage. Non-governmental conservation groups asked, demanded, and begged the government for a hydrological moratorium, until final research results would be available (*e.g.* Statement by NGO's attending the Third Conference of Contracting Parties of the Ramsar Convention, Regina, Canada, 1 June 1987; Werkgroep Behoud de Peel, 1988). The only moratorium to be observed, however, was a halt in governmental policy enforcement and as a result some 40 % of the wetter soils surrounding the bog reserve were actually drained in the period 1985 - 1987 (Landinrichtingsdienst, 1988). Meanwhile, the NGOs and (some) authorities continued striving for a moratorium by invoking the Nature Conservation Act and the Physical Planning Act. Additionally, several other administrative procedures were found and applied.

Admissibility

When harm is (expected to be) done to natural values, an administrative procedure can be activated by challenging a (real or fictional) decision of the government. In their attempts to restrict desiccation, the NGOs had the advantage of existing jurisprudence with respect to admissibility. Until the mid-seventies, admissibility had erected a formidable obstacle in administrative court procedures in the Netherlands. Natural and legal persons had to be affected "directly in one's interest" to be able to lodge an objection or an appeal. Only authorities could plea in court for the interests of nature and the general environment. An important change in this attitude took place in 1975, when the administrative judge took into consideration that a private organization "by virtue of its aim and according to its actual activities, as such promotes an interest". On the basis of their "statutory aim" and "actual activities" private organizations have, ever since, been admissible in proceedings of administrative law (Van der Zwiep, 1994).

The Nature Conservation Act

The main goal of the Dutch Nature Conservation Act is territorial protection (section 7, subsection 1). State property can be designated as "state nature monument", other territory as "protected nature monument" (section 7, subsection 2). Section 12, subsection 1 of the law prohibits performing or allowing acts, that are harmful to the natural beauty or the scientific significance of a protected nature monument or that disfigure a protected nature monument without a permit or contrary to conditions set in a permit. Section 12, subsection 2 states that harmful acts include, in any case, those acts that affect the essential characteristics of a protected nature monument. These characteristics are described in the decree of designation. Those acts regarded as "harmful" therefore strongly depend on that decree. Section 12 has an "external effect": also acts outside the area with a negative effect within the area fall under permit obligation.

Official designation as a nature monument and granting of permits or exemptions were within the competence of the Minister of Agriculture. Other administrative levels were not involved; provinces and municipalities could only give advice. Concerning granting of permits they were not even consulted. (Since the General Act of Administrative Law coming into force, 06.01.94, this situation has changed. Furthermore, as from 1 January 1996, enforcement of major parts of the Nature Conservation Act has been decentralized towards the provinces). Publication of permits is not enacted, although objection against the granting would result in the permit being suspended. (Bakker & Van Wijmen, 1988; Backes, 1993; Van der Zwiep & Backes, 1994).

The external effect of the Nature Conservation Act would have been an ideal instrument to stop the expansion of drainage in the surroundings. In the Groote Peel case, however, effective application of the Act was hampered by the responsible Ministry having a conflicts of interests: the conflict had to be solved by a Ministry responsible for both agriculture and nature conservation and involved in many internal conflicts between those policy spheres (Glasbergen & Groenenberg, 1989). Furthermore, the then Minister of Agriculture, being a farmer's son from the Peel region, did not appear very eager to put his supporters under restraint. As long as possible, he pursued a "strategy of denial".

In February 1987, an interim-research-report was presented, indicating that extension of agricultural drainage in a zone of 2 km surrounding the Groote Peel would have negative effects on the hydrology of the nature reserve (Poelman & Bakker, 1987). At the end of 1987 the final report reached the same conclusions (Poelman, 1987; Joosten & Bakker, 1987). The Minister ordered a review of these findings by his own agricultural hydrologists, who endorsed the conclusions in March 1988 (Landinrichtingsdienst, 1988). In response, the Minister announced ambitious technical measures inside the Groote Peel, enabling him to leave the farmers outside the nature reserve in peace (Swinkels, 1989). These technical internal measures were, however, heavily criticized (Bakker *et al.*, 1988). Parliament and Nature Conservation Council urged the enforcement of the Nature Conservation Act to stop further drainage of the surrounding lands. The Act was eventually applied in November 1988, but in an enfeebled way: the explanatory note to the "external effect" of section 12, prohibiting (non-limitatively) numerous harmful acts, contained one explicit and striking exception: ... drainage...

This exception was remarkable, since restriction of the force of law was not within the competency of the Minister (Bakker & Van Wijmen, 1988). The procedure was politically covered by providing Parliament with incomplete and manipulated research data, supporting the ministerial conclusion that the effects of drainage were negligible (Joosten 1992). Conservation groups immediately appealed against the exception of section 12. To counteract the reasoning of the Minister, they ordered a contra-assessment. Its first aim was to expose the hydrological conjuring of the Minister by using the same data, but deriving more accurate conclusions from them. These would be hard for the Minister to enfeeble without straining the basis of his own conclusions ("dog-bites-tail-construction"). Secondly, the ecological effects of drainage could be highlighted.

This aspect had not been sufficiently reviewed yet: official reports on that subject had been kept low key. The contra-assessment, published in March 1989 (DHV, 1989a, b), stressed that each lowering of the water level and each increase in water level fluctuations would lead to impairing the natural values of the Groote Peel. It was stated explicitly that threshold values do not exist in these matters. Ecosystems are, contrary to what had been suggested, not "wheel-works" but "networks". Wheel-works collapse when their thresholds are crossed, whereas networks change gradually (During & Joosten, 1992). The contra-assessment was thoroughly studied by governmental research agencies, which endorsed its conclusions in broad outline.

But still the Minister was not giving in. He set up an Advisory Expert Committee, because, as he wrote to Parliament, "on present showing, no final, unequivocal conclusion can be drawn". In October 1989, on request of the conservation groups, the Netherlands was held liable by the European Committee for the infringement of the European Birds Directive. At the beginning of 1990 the Expert Committee presented the advice to prohibit further drainage around the Groote Peel. At the same time, the project group that had been elaborating internal technical measures reported to the Minister that such measures would not be effective on the long run (Projectgroep de Groote Peel, 1990).

Then, in July 1990, the Minister of Agriculture finally proclaimed a 2 km wide buffer zone around the Groote Peel, based on the external effect of section 12 of the Nature Conservation Act, to prevent further drainage and sprinkling irrigation from groundwater. In their sentence concerning the appeals against this designation, the State Council in 1994 confirmed the external effect of section 12 and the extent of the indicated 2 km wide buffer zone. Furthermore, the Council gave the verdict that the external effect also applies to State Nature Monuments, something that the Minister of Agriculture had always implicitly denied.

What were the practical consequences of the undisputed legal protection of the Groote Peel from thereon?

The most important result was that offences against the prohibition rarely occurred from this point on, because of the deterrent effect. Incidental offenders, however, have not been prosecuted, nor the offences cancelled, in spite of a clear verdict of the State Council that the Minister was allowed to take coercive measures. A permit for expansion of groundwater pumping at a distance of 6 km from the reserve to supply drinking-water was refused by the Minister: the negative hydrological consequences for the bog reserve were expected to be too large. An illegal expansion of drink water pumping on less than 3 km distance, on the other hand, was tolerated for years. Evidently, the responsible administrative authority kept shrinking away from proceeding actively against violation of the Nature Conservation Act.

It is also illuminating to examine the Ministerial behaviour in granting permits. Although permits for harmful activities have been refused, the Minister has consented to damage in several cases, where economic profits were involved. An adequate procedure for the weighing of the interests involved, however, was not applied.

The Physical Planning Act

The most important plans in Dutch physical planning legislation are the Municipal Plans, which centre on planning at a local level. By way of legally binding regulations, the plans determine how land within the boundaries of a municipality should be used. Regional plans, drawn up by the provinces, are used as criteria for integrating and testing municipal plans, but the guidelines are not binding and cannot be enforced (Van der Zwiep & Backes, 1994). Only in exceptional cases provincial and national governments will impose legally binding regulations on a Municipal Plan.

The Groote Peel and its hydrological interaction zones are situated in two provinces and five different municipalities, leading to complex and contrasting regulations in physical planning. In 1984 new municipal plans were in preparation in the two principal municipalities surrounding the Groote Peel. One municipality adopted a permit obligation system for drainage for areas adjoining the Groote Peel, while the others did not. Subsequently, the one province expunged the system from "its" municipality, while the other province did exactly the opposite: it prescribed such a permit system to be implemented for a zone of 300 m surrounding the Groote Peel in the next revision of the plan. Local conservationists meanwhile demanded a hydrological buffer zone of 300 - 600 m wide. All cases were brought to the Crown. After hearing the statement of a responsible alderman, that "he probably would not implement a permit system if the Crown would advise the municipality to do so", the Crown (*i.e.* the Minister of Physical Planning) made an extraordinary move. Following section 29, subsection 8 of the Physical Planning Act, an obligatory permit system regulating drainage in a 600 m wide buffer zone, was imposed. Similar action followed in other municipalities.

Other legislation

A third possibility to prevent further drainage was applied by the provinces. After vain requests to the Minister of Agriculture to implement the Nature Conservation Act, they decided to prevent further drainage with provincial water management legislation. Regional water boards can regulate drainage under the provincial Water-course Regulations, in which water discharge into watercourses is prohibited. Normally, exemptions for agricultural drainage are readily granted. The water board may, and may only, refuse exemption if granting would be opposed to good water management. The province may reverse an exemption under section 22 of the Water Management Act. As good water management both concerns agricultural and nature conservation areas, a juridical instrument is available to refuse exemptions. In June 1988, both provinces declared that they would not endorse further permits granted by regional water-boards for drainage in the 2 km zone. Furthermore, they announced future restrictions in sprinkler irrigation under section 14 of the Groundwater Act.

Environmental protection legislation was also applied in the Peel area in an effort to reduce desiccation. A permit following the Environmental Protection Act is necessary for every "furnished building" in which possible harmful acts take place. Environmental protection legislation has been used in case of establishment or expansion of glasshouses in the hydrological interaction zones of the mire reserves. Glasshouses may contribute to desiccation by interception of rainwater and consequent rapid run-off as a result of surfacing, leading to decreased groundwater recharge. This effect may be augmented where the rainwater is stored and used for irrigation (Querner *et al.,* 1995). The State Council has therefore decreed that the rainwater falling on a glasshouse within the hydrological buffer zone of a nature reserve must be infiltrated into the soil.

A last administrative procedure, applied to restrict desiccation in the Peel area, has been legislation with respect to extraction of raw materials (Mine Act). A decision to grant concession for the extraction of sand and gravel near the Deurnese Peel reserve resulting in negative hydrological effects for the reserve was partly reversed by the State Council, who also attached additional hydrological conditions to the concession.

THE CIVIL APPROACH: THE DEURNESE PEEL

As demonstrated by the Groote Peel case (*cf.* Joosten, 1994b), the available instruments through administrative law were not applied sufficiently to prevent wetland reserves from being damaged. Shortsighted political interests make local, regional, and national administrations often very reluctant or slow to perform their legal duties and to exercise their responsibilities. In the period 1985 – 1995 the Werkgroep Behoud de Peel, a local NGO, has conducted approximately 1300 cases in administrative law. Although the vast majority of these cases were won (Joosten, 1995a), these actions have never resulted in active compulsion to prevent, restrict or repel illegal and injurious interventions.

Consequently, from 1990 onwards, the private conservation groups operating in the Peel area started to use civil law in order to defend the natural values more effectively. An ideal object in this respect was the Deurnese Peel, being a protected nature monument under the Nature Conservation Law since 1979. In its sentence concerning the appeals against the designation, the Crown had stated explicitly:

> "that further some appellants fear that the designation will have adverse effects for the adjacent agricultural areas and for the improvement of the hydrology of these areas....
> that acts, aiming at intensified use, both inside and outside the nature monument, might injure the scientific significance of the area, so that these should fall under the action of the permit system of the sections 12 and following of the Nature Conservation Act, and, as each case arises, it should be considered whether the interest of the protection of the values concerned may permit such changes to take place."

The availability of an explicit "external effect" was an especially valuable instrument in the protection of this "protected nature monument", because the Nature Conservation Act is not very clear, whether this effect also applies to "state nature monuments". (This obscurity and inconsistency was finally resolved in a verdict of the State Council of 8 June 1994.) In contrast to the Groote Peel, however, the Minister of Agriculture had always (up until now!) refused to indicate its view on the extent of the hydrological interaction zones, although detailed data were available (Joosten, 1988b; Van den Munckhof & Joosten, 1990; Van Engen & Joosten, 1994).

The most important jurisprudence precedent was made with the "Kuunders" case, in which firstly administrative and eventually civil law were used to prevent a new pig stable from coming into operation close to the Deurnese Peel. After five unavailing State Council trials under the Environmental Protection Act, and next to administrative legal actions under the Nature Conservation Law, and after a negative sentence in short cause, the Court of Justice prohibited Kuunders from running the pig stable as long as he did not possess an irrevocable permit as expressed in section 12 of the Nature Conservation Act. The Court gave its verdict that the private groups were admissible, that the civil judge was competent also in the case that administrative judicial process is possible, and that Kuunders was liable in tort towards the conservation groups by running the stable without disposal of a permit under the Nature Conservation Act. On appeal, the finding was upheld. The inflicted penalty (Dfl. 5000 per day!) guaranteed a rapid ceasing of the injurious activities...

Following this jurisprudence, the Peel conservation groups started to apply for immediate judgement in desiccation cases. In short cause, the digging of ditches and deep ploughing of agricultural lands could immediately be stopped, because of lack of an adequate permit under the Physical Planning Act. Only after the short cause, the Ministry of Agriculture informed the offender (the municipal alderman of Environment and Physical Planning....), that he had been violating the Nature Conservation Act. Thereupon, the municipality refused to grant the permit. In a similar civil case, the digging of ditches could be stopped on lands bordering the Deurnese Peel nature monument because of lack of a permit under the Nature Conservation Act. Only after this judgement, the public ministry prosecuted the offender for infringing the Nature Conservation Act. Up to then the public prosecutor had always refrained from action, with as motive that if the responsible administration does not act, the offence will not be so severe...

Civil law proves to be a highly effective instrument to protect nature reserves, because inflicted recognizance fines are a strong deterrent. Furthermore, civil law procedures are rather simple and clear, when they are based on the lack of irrevocable permits in administrative law. It is expected that the importance of civil law will grow as a result of this effectiveness. Liability in tort may not only be used in connection to various national laws, but also with respect to international legislation, as many wetland areas are protected under the Habitats Directive. Section 6.3 of the Habitats Directive prohibits to a large extent permission to carry out projects and plans which might be detrimental to the natural characteristics of the designated areas. The granting of permission has been made dependent on "imperative reasons of overriding public interest" (Van der Zwiep & Backes, 1994).

COMPLICATIONS

Our experiences in fighting desiccation of mire reserves by using juridical instruments lead to the distinction of various complicating aspects, including "harm", "weighing of interests", and "claiming damages".

Harm or injury in desiccation cases is difficult to prove unequivocally. The effects of desiccation are often irreversible, and should therefore be "proven" in advance. The results of scenario studies, however, depend on the degree of detail contained in hydrological simulation models. It is often technically impossible to quantify local ecological impacts of regional hydrological interventions. Particularly in areas with a large fine-scaled diversity (as is the case with many mires), obtaining all necessary hydrological data in a non-destructive manner is impossible. For this reason, it is necessary to devise approximate procedures for downscaling results of regional hydrologic modelling to local ecological impacts (Van Walsum & Joosten, 1994).

The effects of minor hydrologic interventions, and of interventions over larger distances, are often so small that they fall within the error margins of the modelling results. Neglect of such small effects, as often proposed, will always lead to steadily worsening conditions for the mire, in the same way as a drunk, reeling along a pavement bordered by a wall, will ultimately always end up in the gutter. Small negative actions will not be spotted and counteracted, and small positive actions will not be pursued.

Limited harm resulting from individual interventions is often considered to count as zero. This is also a wrong and dangerous approach. As threshold values often do not exist, ecosystems change gradually. In cases where harm is a matter of degree, minor actions should not be considered to cause no harm, but to cause a part of a detectable harm. This principle is nicely illustrated by Glover (1975): "Suppose a village contains 100 unarmed tribesmen. As they eat their lunch 100 hungry armed bandits descend on the village and each bandit at gunpoint takes one tribesman's lunch and eats it. The bandits then go off, each one having done a discriminable amount of harm to a single tribesman. Next week, the bandits are tempted to do the same thing again, but are troubled by newfound doubts of the morality of such a raid. Their doubts are put to rest by one of their number who does not believe in the principle of divisibility. They then raid the village, tie up the tribesmen, and look at their lunch. As expected, each bowl of food contains 100 baked beans. The pleasure derived from one baked bean is below the discrimination threshold. Instead of each bandit eating a single plateful as last week, each takes one bean from each plate. They leave after eating all the beans, pleased to have done no harm, as each has done no more than sub-threshold harm to each person"....

Similarly, simulation of installation of subsurface drainage on one hectare of agricultural land often leads to model results that are extremely small, and therefore are considered to be zero. In such cases, effects can be shown in a "cumulative" approach, by simulating the effects of draining 1000 ha. The effect of draining one ha can than be assessed to be at least 0.1 % of that from draining 1000 ha (DHV, 1989a). In 1995, the State Council of the Netherlands approved such an approach explicitly:

> "For, if one would assume that an individual expansion of drainage as at issue would only have such a small influence on the water level in the nature monument, that no decisive significance may be at-

> tached to it, every such individual expansion of drainage would have to be permitted, which leads to the risk, that through cumulation of such individual expansions the nature monument will suffer irreparable damage."

The Council has thus forbidden interventions that would lead to a fall in water level in the Groote Peel of less than 0.1 mm!

These often-limited effects of individual interventions complicate the weighing of interests as prescribed in various regulations. In its verdict regarding the designation of the Groote Peel as a nature monument, the State Council considered:

> "as each case arises, it should be considered whether the requested expansion [of drainage] is harmful to the protected nature monument. Furthermore, a weighing of interests shall take place in the framework of a permit obligation. There is no question of an absolute prohibition of interventions, that are considered to be under permit obligation in the explanatory note of the designation".

This weighing of interests is a complex procedure that is often executed in a methodically unsatisfactory way (Ott, 1996). The first question to be asked is whether there is something to weigh at all. The European Habitats Directive, for example, requires that projects, which might be detrimental to the natural characteristics of designated areas, may only be carried out for "imperative reasons of overriding public interest". If only benefits for individual citizens are involved, no weighing of interests should take place.

The process of weighing of interests should follow a clear set of explicit criteria and priority rules in order to counter personal preferences and arbitrariness and to guarantee a rational, verifiable justification. Every assessment is thus founded both on specific individual circumstances and on underlying rules. As these rules should be generalizable, a weighing "as each case arises" is actually impossible. Furthermore, weighing "as each case arises" may be contradictory to the cumulative approach that the State Council has prescribed. A cumulative approach means that the results of earlier (and later) weighing in similar cases are direct arguments pro or contra in the weighing/assessment process of the issue at stake. In cases "of overriding public interest" such cumulative effects should also be taken into account.

A continuous "status-quo-minus", in which small deteriorations of natural values are permitted because of large individual interests, is ultimately incompatible with any protection system. This insight should lead to a stringent reversal of the burden of proof. Conservationists should not have to justify why something is not allowed; the applicant should state why he couldn't act otherwise, or somewhere else, or with much less impact... Natural values are often damaged irreversibly. For these values much more is at stake than for persons and institutions, which may supply their wants in alternative ways.

The nature and magnitude of the "weights" are furthermore strongly dependent on the temporal scale of judgement. Business-economic interests are an expression of parameters that, in the long term, are neither measurable nor predictable since they vary according to world-market, personal and even meteorological conditions. The short-term reality of individual socio-economic interests makes a weighing against societal long-term nature conservational objectives meaningless. Economic interests may also differ according to the spatial scale of observation. Research in the Peel area showed that the installation of subsurface drainage could be positive for the income of an individual farmer, because losses resulting from too wet conditions are reduced. The same action, however, causes larger losses to his immediate neighbours, because of increased dry conditions. The overall economic efficiency on larger (national, European, global) may well be even more negative.

Individual (business) interests cannot meaningfully be weighed against interests of nature conservation, as the spatial, temporal and functional scales of both categories are not compatible. Weighing should therefore take place at a higher level. This may imply that compensation is given in cases where existing rights are violated.

Which interventions do infringe existing rights, and how should inequalities be dealt with, when constraints are imposed? Lost chances are not equal to granted rights. If compensation must be given in case of reduced opportunities, it must be noted that every restrictive intervention will affect groups that are benefited and other groups that are harmed. Saudi Arabia, for example, stressed at the United Nations Conference on Environment and Development (Rio de Janeiro, 1992) that a greenhouse effect avoidance policy must include compensation to oil producers for the sales they lose because of reductions in fuel consumption. Inhabitants of other parts of the world, including the Canadian and Siberian taiga, would benefit from increased agricultural productivity if global climate change occurred, but would not benefit if it were avoided. Similarly, restrictive hydrological buffer zones may injure farmers financially, but may also give them new economic opportunities in, for example, producing "buffer zone cheese".

Should losses be compensated if they result from a governmental policy, and not from free market developments? The concrete effect of a restrictive intervention is always an exponent of both (Hurka, 1993). In my opinion, compensation related to restricted opportunities always concerns policy related to financial income, which should be executed apart from considerations regarding "business-interests" and "nature conservation".

CONCLUSION

Desiccation and consequent juridical actions should be avoided, because, even when most cases are won, ultimately nature conservation always loses, for every juridical "gain" is actually only a "non-loss" (Joosten, 1993). Therefore, conservation policy should aim at a better separation of conflicting types of land use, and on an enlargement of nature conservation areas. At the end of the 1980's, the Dutch government acknowledged that the rate of decline of natural values in the Netherlands had not slowed down. As a result, a new pro-active long-term strategy was adopted. This Structure Plan for the Rural Areas in the Netherlands, an integral policy document on rural planning, aims at a realization of approximately 15,000 ha of new wetlands on present-day agricultural land in the next 20 years. Some 1500 ha of new mires are planned in the Peel area in order to weld together the scattered bog reserves in that area (Van Engen & Joosten, 1994). This will reduce the number of legal conflicts in this area considerably (Joosten, 1991).

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SOIL ASSOCIATIONS IN THE SURROUNDINGS OF ^{X}OLIGOTROPHIC MIRES IN THE BERLIN REGION

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Summary

Polygenetic soils, surrounding oligotrophic kettlehole mires on sandy sediments in the Berlin region, were investigated. The typical soil catena in the surrounding of kettlehole mires with a natural groundwater level is formed by the sequence of Ombric Histosol (= Niedermoor according to the German soil classification), Ombric Histosol/ Epigleyic Podzol (Moor-Podsol-Gley), Epigleyic Podzol (Naßpodsol-Gley and Podsol-Gley), Endogleyic Arenosol (Gley-Podsol-Braunerde) and Dystric Arenosol (Podsol-Braunerde). In the surrounding of peatlands, where the groundwater level was lowered during the last few decades, occur Ombric Histosols, Epigleyic Podzol, Endogleyic Podzol, Carbic Podzol (Humuspodsol) and Dystric Arenosol with relict hydromorphic properties. Field and laboratory analysis showed that the investigated soils were strongly related to each other and that their development depends on the trophic state of the fen and groundwater fluctuations during the Holocene. Compared with the Bh-horizon of terrestrial soils the Chr-horizon is nearly free of Fe and Mn, but very rich in pedogenic Al-oxides and rich in organic matter. The genesis of the soils is explained as follows:

1. The development of different Epigleyic Podzols resulted from rise in groundwater level. Consequently the Bh- and Bs-horizons of Haplic Podzols surrounding the fen were converted to Chr- and Cr-horizons.
2. Humic substances and Al in the Chr- and Cr-horizons were not re-mobilised owing to the rise of groundwater, while Fe and Mn were reduced and removed by groundwater.
3. At the periphery of the fen Fe was enriched in the Bg-horizon of the Epigleyic Podzol (Podsol-Gley) and Endogleyic Arenosol (Gley-Podsol-Braunerde) but not Mn.
4. The fact that the fens are surrounded by Bg horizons, which are strongly enriched by iron, indicates, that groundwater movement from the central parts of fens towards the periphery is an essential pedogenetic factor for the development of Gleyic Podzols.
5. At the present time, depending on the lowering portion of groundwater, the Ombric Histosol/Epigleyic Podzol is converted to a Carbic Podzol (Humuspodsol).

Keywords: Soil association, oligotrophic mires, podzolisation, Gleyic Podzol, Carbic Podzol

Introduction

In the surroundings of oligotrophic mires, which have developed on sandy sediments of Weichselian age in the Berlin area, are polygenetic soils, strongly enriched by humic material (Alaily *et al.* 1997). These soils are classified as Carbic Podzol and hydromorphic Podzols of different subtypes. Neumann (1976) assumed that the development of the Gleyic Podzols found in the margins of the fen are caused by rise of groundwater during the Atlantic chronozone. Grenzius (1986) presumed that the Chr- and Bg-horizons of the Gleyic Podzols were developed by means of the displacement of humic acids and Fe with the groundwater from the fen to its periphery. It is unknown if the organic matter of the Chr-horizon is leached from the topsoil, laterally translocated from the fen by groundwater or translocated from the elevated area by stagnant water and whether or not the Bh-Horizon of the Carbic Podzol represents a relict Chr-Horizon.

The aim of this investigation was to clarify the genesis and relationship (association) between the different soil units surrounding oligotrophic mires (fens) and detailed soil surveys were carried out in the surroundings of several oligotrophic fens with different groundwater levels. The goal of the survey was to describe the exact soil association in the surroundings of the fens and to investigate relationships between the different soil horizons, relief and groundwater level. Based on the results of the field studies, samples of representative soils were selected for laboratory analysis. The fens investigated are located in the vicinity of Schmöckwitz, Spandau and Ferch near Berlin (Figure 1). Preliminary results concerning the genesis of soils surrounding oligotrophic fens with unaffected groundwater level have been published previously by the authors (Alaily & Brande, 200; 2002).

SITE DESCRIPTIONS

The climate in the Berlin region is weakly continental with 550 mm annual rainfall and 8°C mean annual temperature. The sites are located in the Warsaw-Berlin glacial meltwater valley. Some geophysical properties of the fens investigated are presented in Table 1. The site at Schmöckwitz consists of three oligotrophic fens: Langes Luch, Kleines Luch and Kleines Fenn. One fen was studied in each of Spandau and Ferch. The largest of the fens investigated is the Langes Luch (at Schmöckwitz) and the fen with the deepest groundwater level is at Ferch. The land surrounding the fens at Schmöckwitz and in Spandau is weakly undulating whereas at Ferch it is strongly so.

Landscape development

The Berlin region was built up by sediments of the Weichselian glaciation and the Holocene (Woldstedt and Duphorn, 1974; Blume, 1981). The areas investigated in Spandau and Schmöckwitz lie within a glacial meltwater valley known as the "Warsaw-Berlin Urstromtal". It is filled with fluvial sand and separated by several ground moraine plates (such as the Teltow and the Barnim Plate). Ferch is on the northern border of a sandy ground moraine plate. The depressions of all of the fens were formed by dead-ice blocks, which remained after the mass of the glaciers melted. The dead-ice blocks melted during the late glacial leaving behind small lakes. During the Alleroed chronozone sedimentation of gyttia took place, followed by accumulation of several metres of peat. During the late glacial period aeolian sand and dunes accumulated on top of the glacial sediments.

Hydrology

The natural groundwater level in the glacial meltwater valley of the Berlin region lies between 1 and 4 m below the soil surface (Blume 1981), although in the dune areas it is much deeper. The main river draining

Fig. 1. Localities of the sites investigated

Table 1: Some geophysical properties of the investigated mires (the co-ordinates give the central point of the mire)

	m above sea level		m			ha	
	Groundwater level	Mire surface	Depth[3]	Length	Width	Size	Co-ordinates
Schmöckwitz:							
Langes Luch	32.15-32.45	32.30	5.15	310	45	1.5	52° 22´ 26.40´´ N 13° 40´ 03.72´´ E
Kleines Luch	32.60-32.72	33.00	2.30	96	23	0,2	52° 22´ 21.56´´ N 13° 40´ 48.07´´E
Kleines Fenn	32.70-32.85	33.00	3.40	95	29	0.3	52° 22´ 19.06´´ N 13° 40´ 56.07´´ E
Spandau	28.00-30.50[1]	30.50	2.15	110	55	0,5	52° 34´ 57.54´´ N 13° 11´ 34.26´´ E
Ferch	36.25-36.65[2]	38.60	12.00	156	70	1,1	52° 18´ 20.46´´ N 12° 54´ 52.38´´ E

[1]Al-Karawi 1999

[2]Rowinsky 1994

[3]Depth of peat and mud

the Warsaw-Berlin Valley is the Spree, the water level of which has been elevated by several dams since the beginning of the 13th century for grinding corn. Since then its water level has been maintained between 32.3 and 32.6 m above sea level. In comparison with most fens in Berlin, the groundwater table at Schmöckwitz has been lowered only slightly (Table 1). The highest level of groundwater in Schmöckwitz occurs during March and April and its average fluctuation is 30 cm. Aey (1996) and Linder (1997) found that, in the central part of Langes Luch fen, groundwater is between 15 and 27 cm higher than in its periphery.

MATERIALS AND METHODS

Soil survey and sampling

In the field, soil was investigated in the periphery of the fens at a distance of mostly less than one metre, otherwise at a distance of 5 to 10 m. Soil description was done according to the AG Bodenkunde (1994) and Schlichting *et al.* (1995) methods that focus on stratification, decomposition intensity of the peat, groundwater depth and eluvial as well as the illuvial horizons of humic material and/or iron.

Laboratory analysis was carried out according to Schlichting *et al.* (1995). The pH-value and the electrical conductivity (EC) were measured in water extract (with a ratio of dried fine earth : water of 1 : 2.5). The total amount of C_t and N_t was measured with a gas chromatograph. As the soil samples are free of carbonates the amount of organic mater was then calculated by C_t x 1.724. The amount of Al_t, Fe_t and Mn_t were measured with an X-ray fluorescence analyser (XFA). Samples rich in organic mater were first heated at 550 °C for two hours. The amount of oxalate soluble Fe_o, Al_o and Mn_o were measured with an atomic absorption spectrophotometer. The grain size distribution was determined after treating the samples with H_2O_2, Na-pyrophosphate and ultrasonic. Grain sizes were obtained by using different sieves and with the Köhn pipette and the amounts were measured gravimetrically.

Description of the investigated soil profiles

Several soil profiles were investigated in the field and sampled for laboratory analysis. Figures 2 and 4 show ideal topo-sequences of the soil units and their diagnostic horizons. The description of five representative soil profiles are presented below in the following sequence: colour dry, colour moist, soil moisture, soil texture, carbonate content, carbonate enrichment form, humus content, humification intensity, mottles, bulk density, remarks and transition quality to the next horizon. Soil unit and horizon symbol are given according to "World Reference Base for Soil Resources" (FAO-Unesco 1998) with the equivalent German soil classification system (AG Bodenkunde 1994) presented in brackets.

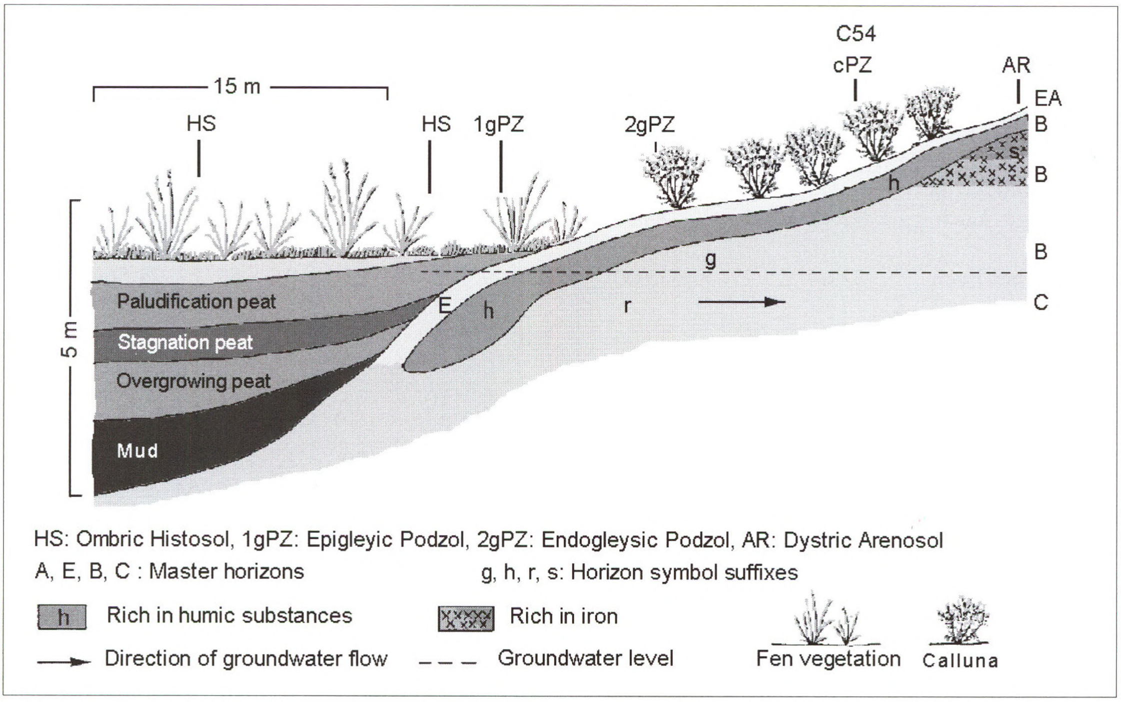

Figure 2: Scheme of the soil catena of the investigated sites in Spandau and Ferch as well as the position of the investigated Carbic Podzol (C54)

Profile Nr.	C53
Soil unit, humus form:	Ombric Histosol (Niedermoor), Peat
Parent material:	Peat over fluvial glacial sand
Topography:	Depression
Vegetation:	Eriophoro-Sphagnetum recurvi

Depth in cm	Hor.	Horizon characteristics
0 - 7	O	10YR3,5/1, 10YR2/1, moist, humus content >30 %, very loose, the transition to next horizon is sharp
7 - 16	H	10YR3,5/2, 10YR2/1, moist, humus content >30 %, Sphagnum peat, H 2, very loose, Transition to
16 - 67	H	10YR3,5/2, 10YR2,5/1, moist, humus content >30 %, Eriophorum-Sphagnum peat, H 5, loose, the transition to next horizon is sharp
67 - 71	Ah	10YR4,5/1, 10YR2/1, moist, fS, coherent, humus content 10 %, loose to moderately dense, the transition to next horizon is gradual
71 - 82	Eg	10YR5/2, 10YR3,5/2, moist, fS, coherent, humus content 3 %, moderately dense, the transition to next horizon is gradual
82 - 98	Chr1	10YR5/3, 10YR3/2, wet to moist, fS, free from stones, coherent to blocky, humus content 5 %, moderately dense, the transition to next horizon is gradual
98 - 100	Chr2	10YR6,5/3, 10YR5/3, wet, ffS, free from stones, coherent, humus content 2 %, dense

Profile Nr.	C35
Soil unit, humus form:	Ombric Histosol/Epigleyic Podzol (Moor-Podsol-Gley), Carex peat
Parent material:	Peat over fluvial glacial sand
Topography:	Depression
Vegetation:	Carici-Agrostietum caninae

Depth in cm	Hor.	Horizon characteristics
0 - 9	H	dry, very loose, humus content 90 %, Carex peat, H 3, the transition to next horizon is sharp
9 - 33	Ah	10YR4/1, 10YR3/1, moist, fS, coherent to platy, humus content >30 %, moderately dense, the transition to next horizon is sharp
33 - 39	Er	7,5YR6/2, 10YR4/1, the upper 2 cm consists of a rAh-horizon, wet, fS, coherent, humus content 1 %, moderately dense, the transition to next horizon is sharp
39 - 60	Chr	10YR4/3, 10YR2/2, wet, fS, coherent, humus content 5 %, moderately dense, the transition to next horizon is gradual
60 - 80	Cr	10YR7/2, 10YR5/2, wet, fS, coherent, moderately dense.

Profile Nr.	C34
Soil unit, humus form:	Epigleyic Podzol (Podsol-Gley), raw humus
Parent material:	Fluvial glacial sand
Topography:	Slope foot
Vegetation:	Pino-Quercetum molinietosum

Depth in cm	Hor.	Horizon characteristics
0 - 8	O	10YR3/3, 10YR2/2, moist, fS, platy, humus content >30 %, moderately dense, the transition to next horizon is sharp
8 - 15	O	10YR5/1, 10YR2/1, moist, fS, platy, humus content >30 %, moderately dense, the transition to next horizon is gradual
15 - 23	E	10YR6/1, 10YR4/1, moist, fS, coherent to blocky, humus content 3 %, moderately dense, the transition to next horizon is sharp
23 - 32	Bhs	10YR5/3, 10YR4/2, moist, fS, coherent, humus content 2 %, moderately dense, the transition to next horizon is gradual
32 - 36	Bg	10YR6/3, 10YR4/3, wet, fS, coherent to blocky, humus content <1 %, moderately dense, rust mottles on roots hallway, the transition to next horizon is sharp
36 - 60	Cgr	10YR7/3, 10YR5/3, wet, fS, coherent to platy, moderately dense, weakly mottled

Profile Nr.	C40
Soil unit, humus form:	Endogleyic Arenosol (Gley-Podsol-Braunerde), Moder to Raw humus
Parent material:	Aeolian sand over fluvial glacial sand
Topography:	Slope foot
Vegetation:	Pinus sylvetris forest

Depth in cm	Hor.	Horizon characteristics
0 - 7	O	Humus content >30 %, very loose, the transition to next horizon is sharp
7 - 10	O	10YR3/2, 10YR3/2, moist, humus content >30 %, very loose, the horizon is not always present
10 - 20	EAh	7,5YR5/2, 7,5YR4/2, fresh, fS, single grain, humus content 2 %, loose, the transition to next horizon is sharp
20 - 30	Bhs	10YR5/4, 10YR3/4, fresh, fS, single-grain, humus content 2 %, loose to moderately dense, the transition to next horizon is gradual
30 - 48	Bg1	10YR7/4, 10YR5/4, fresh, fS, coherent to single grain, humus content <1 %, moderately dense, humus-spots and mottles, the transition to next horizon is gradual
48 - 67	Bg2	10YR7/6, 10YR5/4, moist, fS, coherent to blocky, dense, strongly mottled, weakly cemented, the transition to next horizon is gradual
67 - 100	Bg3	10YR7/6, 10YR5/4, moist, fS, coherent to blocky, dense, strongly mottled, weakly cemented, the transition to next horizon is gradual
100 - 130	Cgr	10YR8/3, 10YR6/3, moist, fS, coherent to single grain, moderately dense, weakly mottled, the transition to next horizon is gradual
130 - 151	Cr	10YR8/2, 10YR6/2, wet, fS, coherent to single grain, moderately dense.

Profile Nr.	C54 (Spandau)
Soil unit, humus form::	Carbic Podzol (Humuspodsol), raw humus
Parent material:	Aeolian sand over fluvial glacial sand
Topography:	Slope foot
Vegetation:	Pinus sylvestris forest

Depth in cm	Hor.	Horizon characteristics
0-20	H	7,5YR2,5/1, 10YR2/1, dry, very loose, humus content 90 %, peaty litter, H 7, the transition to next horizon is sharp
20-35	EAh	7,5YR2,5/1, 10YR2/1, fresh, fS, single-grain to fine angular blocky, loose, the transition to next horizon is gradual
35-48	E	10YR5/1, 10YR3/1, fresh, fS, single-grain to fine angular blocky, loose, the transition to next horizon is gradual
48-77	Bh1	7,5YR4/6, 7,5YR3/4, fresh, fS, fine to medium angular blocky, moderately dense, the transition to next horizon is gradual
77-87	Bh2	7,5YR4/6, 7,5YR2,5/2,5, fresh to moist, fS, medium angular blocky, moderately dense

Results and Discussion

Results of the field investigation show that all soil horizons consists of well sorted sandy material (fine sand). The sand content is more than 80 % and is mostly fine sand. This indicates that the parent material originated from fluvial and aeolian deposits and is relatively homogenous. The soil pattern at all locations is also very similar. The soil pattern surrounding fens in Schmöckwitz, actually weakly influenced by groundwater lowering, is presented in Figure 4. The soil catena in the surroundings of the fens at Schmöckwitz consists of Ombric Histosol/Epigleyic Podzol, Epigleyic Podzol and Endogleyic Arenosol (Neumann 1976, Alaily *et al.* 1981). The Ombric Histosol/Epigleyic Podzol usually consists of the Horizons H/Ah/Er/Chr/

Table 2: Some chemical characteristics of representative soils surrounding oligotrophic fens

Sample Nr.	Depth cm	Hor.	pH (H_2O)	EC $\mu S.cm^{-1}$	C_t %	N_t $mg.kg^{-1}$	Org %	C/N
Ombric Histosol (C53)								
C53.01	0-7	O	4,2	44	43,1	25800	74,3	16,7
C53.02	-16	H	4,5	71	35,3	23800	60,9	14,8
C53.03	-67	H	4,8	158,	42,1	23519	72,6	17,9
C53.04	-71	Ah	5,0	335	6,3	2200	10,9	28,6
C53.05	-82	Eg	5,2	943	2,7	872	4,7	31,0
C53.06	-98	Chr1	5,0	264	3,5	1150	6,0	30,4
C53.07	-100	Chr2	5,3	36	1,0	392	1,7	25,5
C53.08			5,6	131	0,5	229	0,9	
Ombric Histosol/Epigleyic Podzol (C35)								
C35.01	0-9	H						
C35.02	-33	Ah	4,0	168	6,5	4210	11,3	15,4
C35.3a	-36	AEr	4,1	138	1,9	600	3,3	31,7
C35.03	-39	Er	4,5	41	1,1	650	1,9	16,9
C35.04	-60	Chr	4,8	77	2,9	1270	5,0	22,8
C35.05	-80	Cr	5,4	20	0,2	420	0,4	4,8
Epigleyic Podzol(C34)								
C34.01	0-8	O	4,0	211	8,4	2015	14,5	41,6
C34.02	-15	O	3,6	224	3,9	1135	6,8	34,6
C34.03	-23	E	4,1	89	1,3	700	2,3	19,0
C34.04	-32	Bhs	4,3	83	1,1	690	1,9	15,5
C34.05	-36	Bg	4,3	62	0,7	600	1,1	10,8
C34.06	-60	Cgr	4,8	61	0,3	45	0,4	5,6
Endogleyic Arenosol (C40)								
C40.01	00-07	O						
C40.02	-10	O	3,9	119	14,17	4350	24,4	32,5
C40.03	-20	EAh	4,2	53	1,18	450	2,1	26,7
C40.04	-30	Bhs	4,6	27	1,48	500	2,6	29,9
C40.05	-48	Bg1	4,5	48	0,15	85	0,3	17,6
C40.06	-67	Bg2	4,5	35	0,06	40	0,1	18,6
C40.07	-100	Bg3	4,3	42	0,04	30	0,1	17,3
C40.08	-130	Cgr	4,7	55	0,01	20	0,04	12,0
C40.09	-151	Cr	4,7	71	0,00	20	0,04	10,5
Carbic Podzol (C54)								
C54.01	0-20	H	3,7	442	17,63	6808	30,40	25,9
C54.02	-35	EAh	3,4	328	18,21	5784	31,39	31,5
C54.03	-48	E	3,7	92	1,75	613	3,03	28,5
C54.04	-77	Bh1	3,9	84	1,75	493	3,01	35,5
C54.05	-87	Bh2	3,9	228	1,73	516	2,98	33,5
	114-149	C*			0,68	220	1,17	30,9

* The data of the C-Horizon were taken from Alaily *et al.* (1981)

Cr orO/Ah/E/Bh/Bg/Cr and Endogleyic Arenosol O/EAh/Bhs/Bg/Cr. In the sites at Spandau and Ferch (both sites are at present time strongly influenced by groundwater lowering) on the bottom of the slope surrounding the fens (Figure 2), Epigleyic Podzol (O/Ah/Er/Chr/Cr) followed by Endogleyic Podzol (O/Ah/E/Bh/Bgh/Cr), Carbic Podzol (O/Ah/E/Bh/C) and Dystric Arenosol having relict hydromorphic properties (O/EAh/Bhs/Bg/C). The fact that a relict Bg-Horizon is found in the subsoil of the Dystric Arenosol indicates that the C-Horizon of the Dystric Arenosol must also represent a relict Horizon = Cr.

The colour of the Chr-horizon is brown to dark brown (dry: 7,5YR5/3 to 10YR4/3 and moist: 7,5YR4/3 to 10YR2/2) similar to Bw- or Bs-horizons. The thickness of horizons enriched by humic material

Table 3: Content of sesquioxides in the fine earth of four representative soil profiles surrounding oligotrophic fens

Sample Nr	Hor	Fe_o g.kg^{-1}	Al_o g.kg^{-1}	Mn_o mg.kg^{-1}	Al_o:Fe_o
Ombric Histosol (C53)					
C53.01	O	4,720	1,90	25	0,4
C53.02	H	5,320	2,00	29	0,4
C53.03	H	2,930	1,95	45	0,7
C53.04	Ah	0,329	0,85	11	2,6
C53.05	Eg	0,143	1,50	7	10,5
C53.06	Chr1	0,144	5,50	7	38,2
C53.07	Chr2	0,076	1,80	2	23,7
C53.08		0,051	1,17	1	22,9
Ombric Histosol/Epigleyic Podzol (C35)					
C35.01	H				
C35.02	Ah	0,25	0,96	0	3,9
C35.3a	AEr	0,06	0,54	1	9,0
C35.03	Er	0,05	0,44	0	8,2
C35.04	Chr	0,26	6,35	0	24,3
C35.05	Cr	0,04	0,78	0	20,6
Epigleyic Podzol(C34)					
C34.01	O	1,45	0,98	4	0,7
C34.02	O	0,98	0,52	0	0,5
C34.03	E	0,41	0,29	0	0,7
C34.04	Bhs	0,71	2,51	0	3,5
C34.05	Bg	1,86	1,62	0	0,9
C34.06	Cgr	0,33	0,63	0	1,9
Endogleyic Arenosol (C40)					
C40.01	O				
C40.02	O	1,32	0,80	8	0,6
C40.03	EAh	0,29	0,21	4	0,7
C40.04	Bhs	1,62	3,48	7	2,2
C40.05	Bg1	0,88	0,63	5	0,7
C40.06	Bg2	1,15	0,35	4	0,3
C40.07	Bg3	0,91	0,21	4	0,2
C40.08	Cgr	0,20	0,17	3	0,9
C40.09	Cr	0,14	0,15	3	1,1
Carbic Podzol (C54)					
C54.01	H	1.08	1.05	33	0,97
C54.02	EAh	0.63	0.91	17	1,44
C54.03	E	0.04	0.28	2	7,00
C54.04	Bh1	0.04	2.43	1	60,75
C54.05	Bh	0.02	2.49	0	124,50
	C*	0,02	0,98	2	49,00

* The data of the C-Horizon were taken from Alaily *et al.* (1981).

increases from the slope foot to the periphery of the fen. The E-horizon is not always present in the Epigleyic Podzol. It was also noticed that the Bg-horizons of the Epigleyic Podzol and Endogleyic Arenosol as well as the relict Bg-Horizons are strongly mottled. Podzolization (measured by how pronounced are the E-, Bh- and Bs-horizons) increases from the elevated area to the depression. The elevated areas are dominated by Dystric Arenosol. Usually the EAh- and Bhs-horizons are mixed owing to occasional ploughing of the topsoil.

Tables 2 and 3 present some analytical data for four representative soil profiles of the sites investigated. Data for the soil profiles C53, C35, C34 and C40 are described in Alaily & Brande (2002). Table 2 shows that the soils are acidic and have very low electrical conductivity, indicating that the electrolyte content of groundwater and soil are very low. The content of organic matter decreases in general with depth. A small increase is noticed in the Bh- and Chr-horizons. The amount of organic mater in both horizons lies between 1.7 and 6.0 %. The highest amount of organic mater is found in the O- and H-horizons. The C:N ratio of the Chr-horizons of the Ombric Histosol/ Epigleyic Podzol (C35), the Bhs-horizons of the Endogleyic Arenosol (C40) and the Bh-Horizon of the Carbic Podzol are high. This might result from a high content of fulvic acid in the humic material and it indicated that the humic material of the Chr- and Bh-horizons are very similar. Only the Bhs-horizon of the Epigleyic Podzol (C34) have a remarkably low C:N ratio.

The content of amorphous as well as organic bound sesquioxides, which were determined in oxalate extract are presented in Table 3. The highest amounts of Fe_o, are found in the H-Horizons of the Ombric Histosol (Profil Nr C53) followed by the Bg and Bhs-Horizons of the Epigleyic Podzol(C34) and Endogleyic Arenosol (C40). The smalles amounts of Fe_o are found in the eluvial horizons: EAh-horizon of the Endogleyic Arenosol (C40), E-horizon of the Epigleyic Podzol (C34), Er-horizon of the Ombric Histosol/Epigleyic Podzol (C35), Chr-horizon of the Ombric Histosol (C53) as well as in the illuvial horizon: Bh-Horizons of the Carbic Podzol (54).

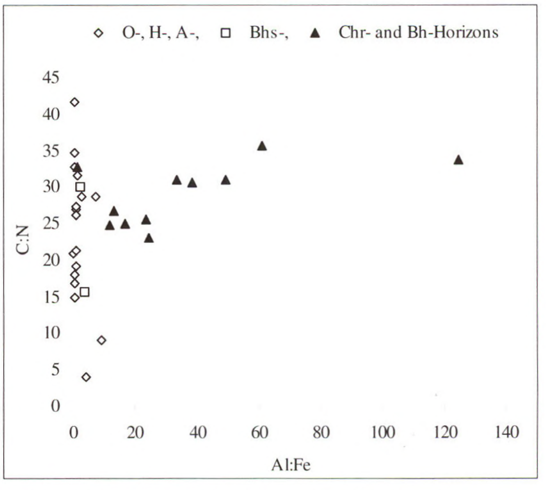

Fig. 3. C : N- and Al_o : Fe_o-ratio of soil samples containing organic substance.

The topsoils shown in Table 3 have high contents of Al_o. Table 3 also indicates that all horizons, which are enriched by humic material are also enriched by Al, mainly in the Chr1-horizon of the Ombric Histosol, the Chr-horizon of the Ombric Histosol/Epigleyic Podzol, the Bhs-horizon of the Epigleyic Podzol (C34), the Endogleyic Arenosol (C40) and in the Bh-Horizons of the Carbic Podzol. The Bg-Horizons (C34 and C40) are mainly enriched in Fe_o and are poor in Al_o. These results are best reflected by the Al_o:Fe_o-ratio.

The content of Mn_o (table 3) indicates that only the Bhs- and O-horizons of the Endogleyic Arenosol as well as the H-horizon of the Ombric Histosol are enriched with Mn. In the first case Mn is enriched via podzolisation, in the second case it is enriched via plant activity.

These results point out that only, the Bhs-Horizons are enriched with Fe, Al and Mn whereas the Bh-Horizons of the Carbic Podzol are only enriched with Al. The fact, that the Chr1- and Chr-horizons of the Ombric Histosol and Ombric Histosol/Epigleyic Podzol are enriched by organic matter (they are rich in Al but poor in Fe and Mn) indicates that the Chr-horizons were developed from drowned Bhs- and/or Bh-horizons of a normal Haplic Podzol. Under these conditions Fe^{+++} and Mn^{++++} were reduced to a water soluble form (Fe^{++}, Mn^{++}) and then migrated with the groundwater. This process is confirmed by a high Al_o:Fe_o ratio of the Chr-horizons compared to the Bhs-horizons while the C:N ratios in both horizons are similar (Figure 3). Alaily and Brande (2002) reported that the illuvial horizons are enriched by Al-Chlorite as a result of podsolization.

The results of the fens investigated in Schmöckwitz, which have a nearly constant groundwater level in the last decades, permit the following conclusions:

1. The colour as well as the C:N ratio of organic mater of the Chr-horizons is similar to the Bh-horizon of normal terrestrical Haplic Podzols.
2. Aluminium seems to be enriched with organic mater in the Chr-horizons and in the Bh-Horizon.
3. Iron, in the area occupied by the fen (Ombric Histosol/Epigleyic Podzol), was washed out under anaerobic conditions of the groundwater, which moves from the centre to the periphery of the fen. There it is enriched in the Bg-horizons of the Endogleyic Podzol and Endogleyic Arenosol (figure 4).
4. Compared to Fe, Mn was not enriched in the Bg-horizons. It must have been completely washed from the investigated area.
5. The centrifugal movement of groundwater must be caused by a higher evapotranspiration and a higher interception of the forest, surrounding the fen, compared to the vegetation of the fen (Schwiebert 1980), as well as the high water capacity of peat compared to the sandy material of the surrounding area.

The results of the fens investigated in Spandau and Ferch, which are strongly influenced by lowering groundwater level in the last few decades, permit the following conclusions:

The relief position of the Carbic Podzol (figure 2) as well as its situation between a Epigleyic Podzol and a Dystric Arenosol with relict hydromorphic properties indicates that the Carbic Podzol was developed from Ombric Histosol/Epigleyic Podzol after lowering of the groundwater level. This is also confirmed by the laboratory analysis, which shows that the Bh-Horizon of the Carbic Podzol resembles very much the Chr-Horizon of the Ombric Histosol/Epigleyic Podzol:

1) Both horizons have relative high amounts of organic matter and high amounts of $Al_{o,}$
2) They are nearly free of Fe_o and Mn_o,
3) They have very similar Al_o:Fe_o- and C:N-ratios.

The formation of the Carbic Podzol can be summarized with the following schema:

Soil unit:	Haplic Podzol	Ombric Histosol/Epigleyic Podzol,	Carbic Podzol
	---------▶	--▶	
Groundwater level:	Low	high	low

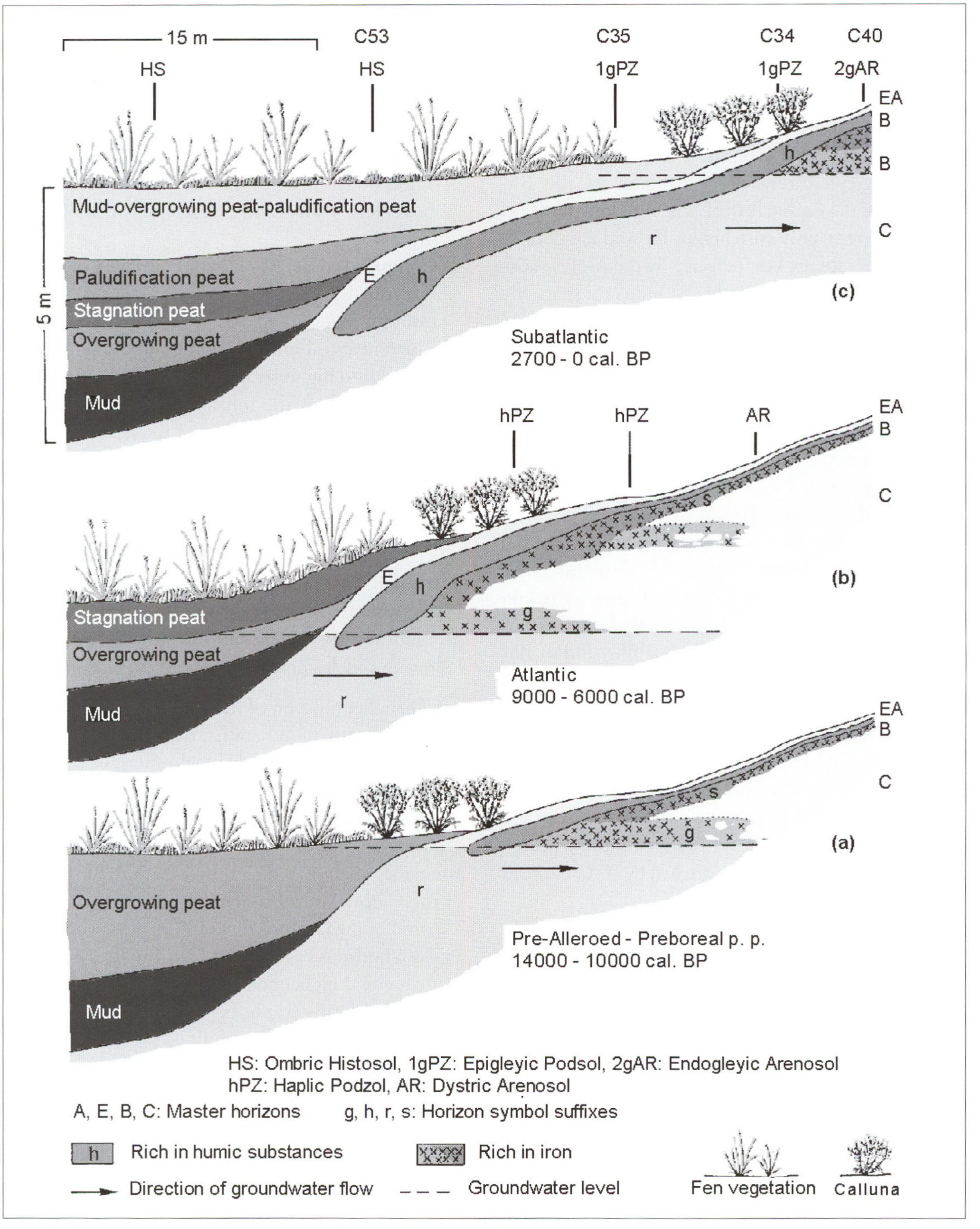

Fig. 4. Scheme of the chronopedology of the soils surrounding the fen of Langes Luch near Schmöckwitz (modified and translated from Alaily and Brande 2002) and the position of the investigated Ombric Histosol (C53), Ombric Histosol/Epigleyic Podzol (C35), Epigleyic Podzol (C34) and Endogleyic Arenosol (C40).

According to Alaily and Brande (2002) the first stages of podzolisation and formation of Epigleyic Podzol (specially the Chr-horizon) took place from the end of the Preboreal until the Sub-boreal chronozone, above all in the Atlantic chronozone (figure. 4, Phase b). Within this period of 5 - 6 millennia low groundwater levels caused humification of peat and formation of large quantities of humic material. Around the peripheries of oligotrophic fens, Fe, Mn and Al were then leached by humic material in deeper soil horizons. In the Subatlantic chronozone groundwater rose (figure 4, phase c) and peat accumulated higher and expanded horizontally. Meanwhile Fe and Mn were reduced under anaerobic conditions and then translocated with groundwater to the new borders of the fen. This process continued in the younger Subatlantic period because of groundwater level rises caused by the construction of dams in the Spree and other surrounding rivers for operating mills (Herzberg and Rieseberg 1987). Only Fe was accumulated in the Bg-horizon directly at the border of the fen where redox conditions for precipitation of Mn seemed to be unsuitable. Recently (in the last few decades) owing to lowering of groundwater level in Spandau and Ferch, Ombric Histosol/Epigleyic Podzols were transformed into Carbic Podzols (Figure 2).

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THE RESTORATION OF KIRKCONNELL FLOW: SEARCHING FOR A BOG AMONGST THE TREES

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SUMMARY

Conservation priorities for Kirkconnell Flow, a wooded raised mire in southwest Scotland, have changed radically over the last 20 years. Now, intensive management is planned to reinstate "typical" mire vegetation without trees. The nature of past disturbance to the site is such that its hydrological integrity may be sufficiently impaired to render direct restoration techniques (tree removal and ditch-blocking) ineffective in reinstating *Sphagnum* communities. A study is described which aimed to assess whole-system ecohydrology in terms of the legacy of past peat extraction and the potential influence of a new scheme to abstract drinking water from an aquifer beneath the site. The results indicate that the system is already demonstrating strong inherent capacity to adjust to new hydrological constraints, and that it currently retains potential to support the desired vegetation.

Keywords: catotelm, groundwater mound model, peatland ecohydrology, raised mire, woodland management

INTRODUCTION

Kirkconnell Flow is a National Nature Reserve situated 6 km south of Dumfries in southwest Scotland. It occupies 142 ha of the post-glacial raised beach at the western side of the Nith estuary (Figure 1). Apart from a 0.5 km belt of salt marsh fringing the estuary, the Nature Reserve contains the only remnant of the original wetland/mire catena because the intervening land has been reclaimed for agriculture. Various modifications occurred between 1845 and 1858, including removal of peat, but approximately 50 ha of uncut, primary raised mire surface still remain.

Although the site has been a National Nature Reserve since 1959, scientific and conservation interest focussed initially on the progress of its colonization by Scots pine (*Pinus sylvestris*), which proceeded vigorously and unchecked until 51,801 trees were reported to be growing there in 1995[1]. Meanwhile, commercial afforestation of more than 1100 ha of the nearby Lochar Mosses during the 1970s had radically altered conservation priorities for Kirkconnell Flow and, in 1990, a programme of active management to conserve the raised mire ecosystem was conceived. The innovative action proposed involved removal of trees from, and blocking of drains on, the uncut bog surface in conjunction with management of the peripheral area as a demonstration woodland. Revenue from sale of timber would part-finance the mire rehabilitation work.

Whilst the management plan was being developed, a new scheme was initiated to abstract drinking water from the Permian bedrock 35-55 m beneath Kirkconnell Flow. Two production boreholes were drilled within 2 km of the northern boundary of the site, in May 1994 and January 1995.

The study described here was conducted during the summer of 1995, in order to assess the potential stability of a raised mire ecosystem within the constraints imposed by existing and proposed modifications both to the site itself and to regional hydrology.

RATIONALE

The basis of a self-sustaining raised mire ecosystem is a stable groundwater mound, which is the physical expression of the dynamic equilibrium between water supply to and seepage loss from the catotelm (Ingram

[1] David & Goss Associates, unpublished report to Scottish Natural Heritage.

1978, 1982). The profile of a groundwater mound developed on an elliptic base and draining to the level of the mineral substratum is given by the equation:

$$Z^2 = \frac{U_{cat}}{K}\frac{A^2B^2}{(A^2+B^2)}\left[\frac{2X}{A} - \frac{X^2}{A^2} - \frac{Y^2}{B^2}\right]$$ Equation 1

where the hydrodynamic constant $\frac{U_{cat}}{K}$ is the ratio of flux density of lateral seepage in the catotelm to bulk hydraulic conductivity of the peat; *A*, *B* are the major and minor axes of the ellipse respectively; *Z* is the altitude of the surface of the catotelm above the substratum; and *X*, *Y* are positional co-ordinates.

Sphagnum cannot survive if the mire surface lies more than a few decimetres above the surface of the groundwater mound, and the catotelm is constrained to the same shape because plant material is preserved where microbial activity is curtailed by perennial saturation.

The flux of water, which feeds the system, is derived solely from precipitation, appearing in the water balance for a typical water year as

$$U_{cat} = P - E - U_{acr} - G$$ Equation 2

where P is precipitation, E actual evapotranspiration, U_{acr} lateral seepage in the acrotelm and G vertical leakage from the catotelm.

This leads to the idea that the profile of an undisturbed raised mire cannot exceed a climatic limit, which corresponds, at first approximation, to the excess flux of P over $(E + G)$ during dry years (U_{acr} @ 0) (Ingram 1982).

The effects of human intervention on the hydrodynamic equilibrium of raised mire ecosystems are explored by Bragg (1995). At Kirkconnell Flow, direct disturbance to the acrotelm is evident in the presence of drains, which tend to enhance U_{acr}, and in the tree cover, which promotes E, both at the expense of U_{cat} (Equation 2). The prospect of water abstraction from a deep aquifer beneath the Flow introduces the possibility of promoting leakage through the base of the system (G in Equation 2), with further reduction of U_{cat}. Since the site is a remnant of a larger mire system, the areal extent of the catotelm has already been reduced, reducing Z in Equation 1. Woodland management at the perimeter may be expected to exacerbate this effect, permanently excluding peat-forming vegetation and promoting further water loss and wastage of peat.

Removal of atypical vegetation and repair of drains should help to reinstate natural patterns of net water supply ($P - E$) and lateral seepage (U_{acr}) within the acrotelm. However, such expensive measures may still prove ineffective in re-establishing the desired *Sphagnum* communities if the physical shape of the peat body and/or vertical leakage of water from the system preclude restoration of the necessary close relationship between mire and groundwater mound surfaces. Therefore, a study to estimate the existing degree of disturbance to the system in these respects was identified as a prerequisite to implementation of the management plan.

METHODS

The density of the trees presented unusual problems in site survey, in that they obscured features on air photographs and obstructed lines of sight on the ground. Hence, the study relied heavily on the legacy of previous work at the site. Marker posts located at the intersections of a 50 m square grid (Figure 2) proved invaluable to navigation. A map of surface drains surveyed in 1961[2] and a contour map of the mire expanse drawn around 1970[3] were also available.

Fieldwork was carried out between 9 and 11 July 1995 in dry, sunny weather. Apart from general reconnaissance of the site, the work undertaken involved mapping of the cut peat edge, measurement of peat depths and assessment of the vertical hydraulic gradient within the peat.

The cut peat edge was mapped by sketching its shape relative to the squares of the location grid.

Peat depth was measured at 19 locations (Figure 3) using a screw auger with extendible handle. For each location, peat depth was subtracted from the surface altitude indicated by the contour map to yield the apparent altitude of the peat/mineral interface. The nature of peat and substratum were ascertained by examination of material retained in the auger.

The vertical hydraulic gradient was assessed using nested piezometers. These were lengths of uPVC pipe, internal diameter 17 mm, with perforations for 10 cm at their lower ends. Two piezometers, lengths 130 and 200 cm respectively, and one dip well (perforated along the full submerged length of wall) were installed near grid point L14, close to the southern summit of the mire surface. The pipes were posi-

[2] Unpublished survey by the U.K. Nature Conservancy.

[3] Unpublished work by the U.K. Institute of Terrestrial Ecology.

tioned at 30 cm horizontal spacing and sunk vertically into the peat until approximately 10 cm remained above ground, then adjusted so that their upper ends were all at the same level. The water level in each pipe was measured, relative to the upper end of the pipe, one and two days after installation.

RESULTS

Surface Features

Figure 3 shows the shape of the cut peat edge, the positions and flow directions of drains, and the Carlin Loch, a pond dug in the mid-19th century to attract wildfowl. The primary mire has an irregular outline, and is slightly kidney-shaped. A small part near grid point W18 lies outwit the present boundary of the Nature Reserve. Most of the drains are on secondary (previously cutover) surface, with the exceptions of a large ditch crossing the centre of the site and one small drain at the south-western side. The perimeter of the Nature Reserve is defined by boundary drains 0.5-2 m deep, which penetrate mostly to the mineral substratum. The pines planted around the Carlin Loch to provide cover for sport shooting are now approximately 150 years old and the tallest on the site.

Within the ground flora, hollow *Sphagnum* species (mostly *S. cuspidatum*) are restricted to stagnant drains, but there are extensive carpets of the lawn and hummock species *S. papillosum*, *S. magellanicum* and *S. capillifolium*. *S. fuscum*, *S. imbricatum* and *S. pulchrum* are also present. Only where they are heavily shaded by the trees do *Sphagna* give way to woodland ground flora, characterised by *Vaccinium myrtillus*.

Morphology

The contour map (Figure 2) shows the primary surface as a dome rising from 12 m a.s.l. to two separate summits. The measured peat depths indicated that the floor of the deposit is a flat bed of grey clay at approximately 10 m a.s.l., and the whole of the Nature Reserve is peat-covered. Thus, the only explanation that can be offered for the fact that the mire surface does not conform to the usual smooth dome is the influence of past disturbance, which is concentrated near the centre of the site. Drainage is most intense here, owing to the proximity of the two drains on primary surface, the uncut surface narrows at this point and the trees around the Carlin Loch now exert considerable pressure on the peat body[4].

Table 1: Water levels in nested piezometers near grid location L14 on Kirkconnell Flow, after two days' equilibration.

Instrument	Depth to water surface (cm)
Dip well	52.1
130 cm piezometer	46.6
200 cm piezometer	45.4

Vertical Hydraulic Gradient

Depths of water from the tops of the piezometers after two days' equilibration are shown in Table 1. The results indicate a hydraulic gradient tending to direct water movement towards the mire surface, and thus offer no evidence of vertical leakage through the base of the deposit.

Peat

The degree of humification of peat retained in the auger was H3-H5 on the von Post scale (after Heathwaite & Göttlich 1990).

Groundwater Mound Modelling

The approach adopted was to establish and scale a model groundwater mound to contain the whole of the remaining primary mire surface, and then to assess the possibility of achieving this in practice.

The plan shape of the model was an ellipse with major axis 1200 m and minor axis 800 m. Since drains at the edges of the Nature Reserve penetrate to the clay, and eventual total loss of peat from the woodland area is anticipated, the boundary was set at substratum level. The model was scaled and superimposed on the site map and transect profiles by trial and error to give the result shown in Figures 4, 5 and 6. The hydrodynamic constant applied to achieve this fit was 2.26×10^{-4}, and the central summit of the model was 5 m above the substratum. Notably, it was necessary to include part of the cutover surface within the model boundary.

[4]The potential yield of timber in the vicinity of the Carlin Loch has been estimated at more than 200 m3 ha -1.

Table 2: Possible combinations of hydraulic conductivity (K), catotelm seepage flux, (U_{cat}) and summit altitude (Z_{m}) for Kirkconnell Flow: (a) for the present situation with K similar to the value for peat at Dun Moss; (b) for a groundwater mound corresponding to the possible configuration of the site in 1976 (see Discussion); (c) as (b) but with U_{cat} =100 mm year^{-1}.

	K (μm s^{-1})	Z_m (m)	U_{cat} / $K \times 10^4$	U_{cat} (mm yr^{-1})
(a)	5	5	2.26	35.59
(b)	5	7	4.42	69.75
(c)	7.2	7	4.42	100

No data permitting an independent assessment of the hydrodynamic constant for Kirkconnell Flow were available. However, extensive investigations on Dun Moss in Perthshire yielded an estimate of hydraulic conductivity of 5 mm s^{-1} for peat of similar origin and humification to that at Kirkconnell Flow (Keatinge 1976, Ingram 1982). At the Wiggonby station of the U.K. Meteorological Office, 40 km to the southeast (Figure 1), mean annual precipitation for the 16-year period 1973 to 1988 was 819.8 mm, and the surplus of precipitation over potential evapotranspiration for the driest water year during this period, from April 1984 to March 1985, was 95.5

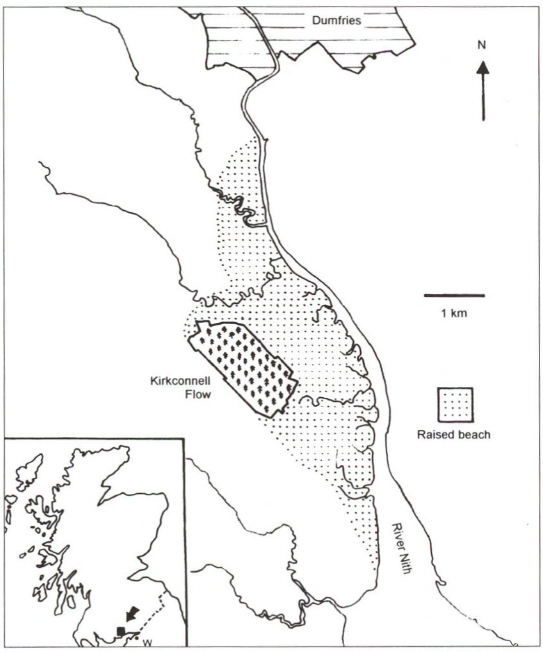

Fig. 1. Location of Kirkconnell Flow. "W" (inset

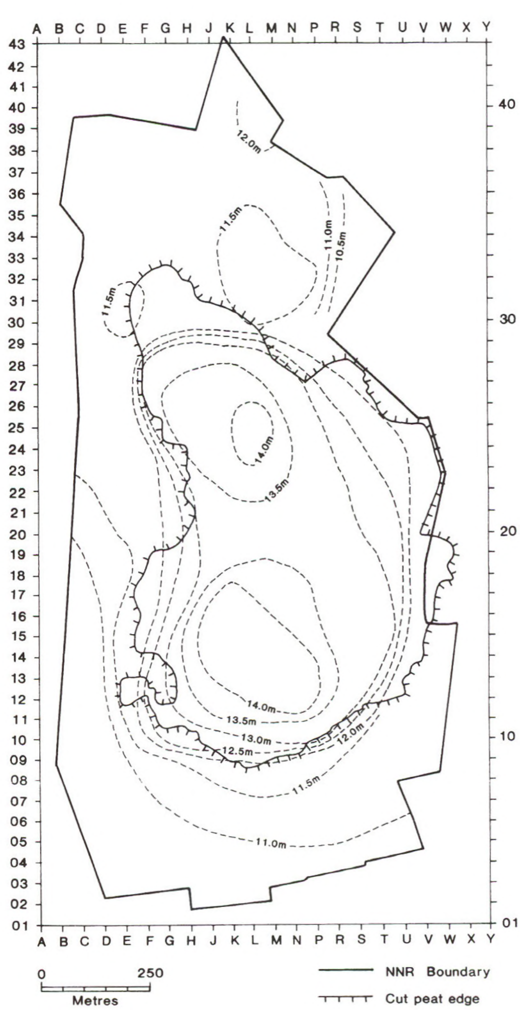

Fig. 2. Kirkconnell Flow: National Nature Reserve (NNR) boundary and surface contours. Contour heights are in metres a.s.l. and the contour interval is 0.5 m. The map border shows orientation and co-ordinate system of the location grid. Within the

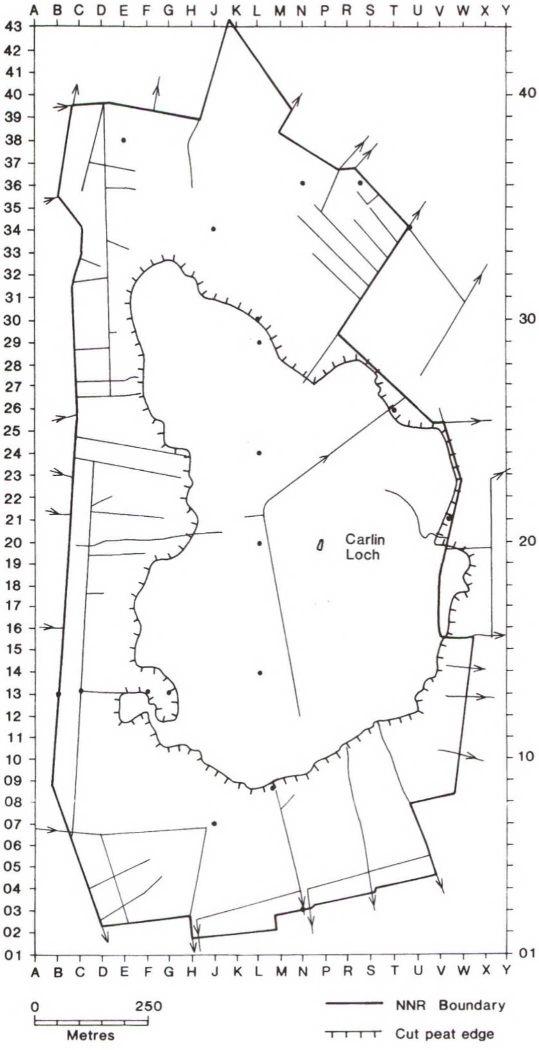

Fig. 3. Kirkconnell Flow: drains, the Carlin Loch and the limit of peat cutting. Filled circles indicate the locations of the 19 peat depth measurements made during this study.

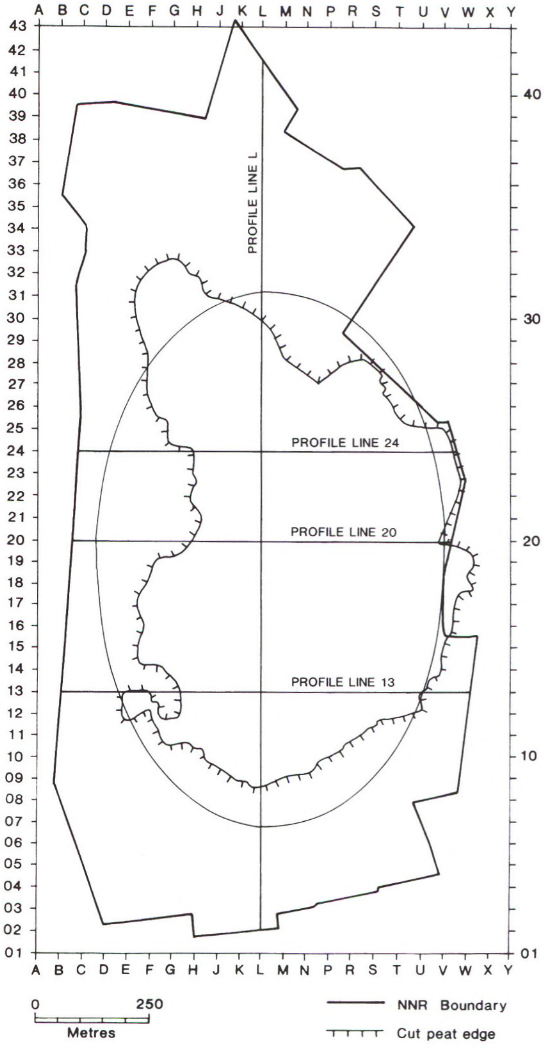

Fig. 4. Plan of the elliptic groundwater mound model chosen to represent Kirkconnell Flow, superimposed on the site map to give best fit of selected surface profiles.

mm. The 35-year (1881 - 1915) mean annual precipitation for Cargen Hill, 4 km from Kirkconnell Flow, was 1139 mm. Thus it seemed reasonable to assume that the dry-year net precipitation at Kirkconnell was at least 100 mm.

Possible calibrations for the groundwater mound model are shown in Table 2. If hydraulic conductivity were similar to that at Dun Moss, less than 36 mm net precipitation per year would be sufficient to maintain the modelled groundwater mound. If the peat were more highly permeable, or if it should become so on reduction of overburden, 100 mm of net rainfall could maintain a groundwater mound 2 m higher than the fitted model in peat with $K = 7.2$ mm s^{-1}.

Practical Interpretation

Use of the analytically tractable "exact" solutions to the groundwater mound problem can be helpful in assessing the potential for maintenance of a functional groundwater mound system where the hydrological integrity of the mire has been fundamentally modified. However, the closeness of fit to plan shape of the real mire is usually inexact (e.g. Bragg *et al.* 1991). Thus, although the results obtained for Kirkconnell Flow were positive, some interpretation was necessary to relate the model to the site itself.

The principle of division of the Nature Reserve into two compartments, one to be managed as raised

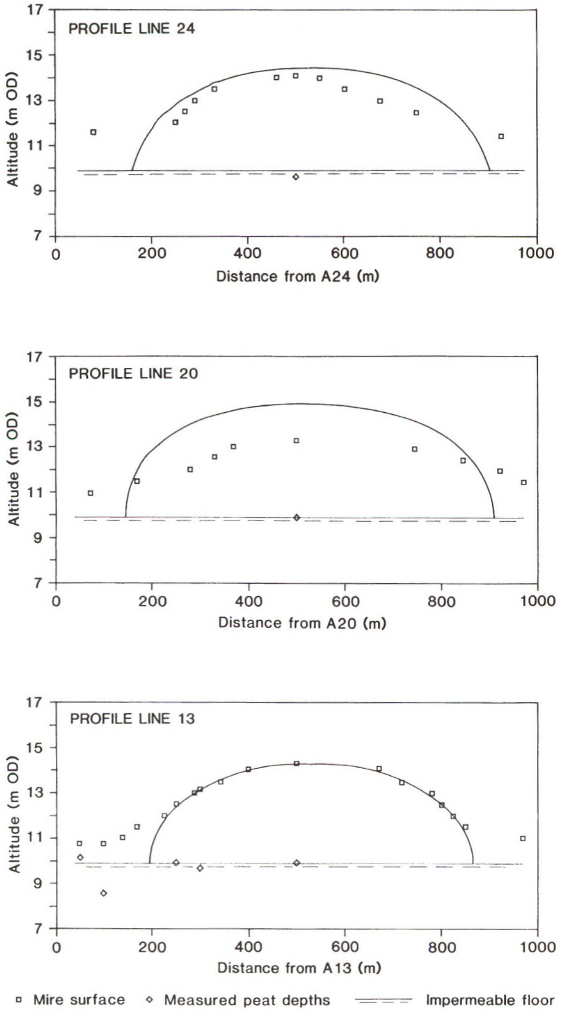

Fig. 5: Profiles of the groundwater mound model for location grid lines 24, 20 and 13 (curved lines) superimposed on corresponding profiles of the mire surface derived from the contour map shown in Fig. 2.

mire to develop the primary interest of the site and the second to be managed as woodland, appeared feasible. However, the cut peat face was an inappropriate choice for the compartment boundary for two reasons. First, its outline had a pronounced indentation at the south-western side. This appeared to be one of the factors contributing to dewatering of the centre of the Flow. Moreover, a previous attempt to establish a groundwater mound on a base of such shape resulted in catastrophic failure of the peat (Bragg *et al.* 1991). Secondly, the depth of peat beneath the cut face was substantial, so that it was necessary to extend the model beyond the edge of the primary surface to achieve groundwater mound profiles coincident with the highest parts of the mire dome (Figures 4-6), indicating that some of the cutover area still functioned as an integral part of the groundwater mound system.

On this basis, the following criteria for definition of the boundary of the mire compartment were set:

1. It should contain all remaining primary raised mire surface.
2. It should have a smooth outline, consisting of convex curves and straight lines.
3. It should include a peripheral strip of secondary surface wherever practical, and especially where indicated by the model.

A modified boundary, which largely meets these criteria and avoids inclusion of the deepest drains, is shown in Figure 7.

Discussion

The lack of evidence for vertical leakage of water from the catotelm of Kirkconnell Flow was reassuring but must be regarded as inconclusive. The upward

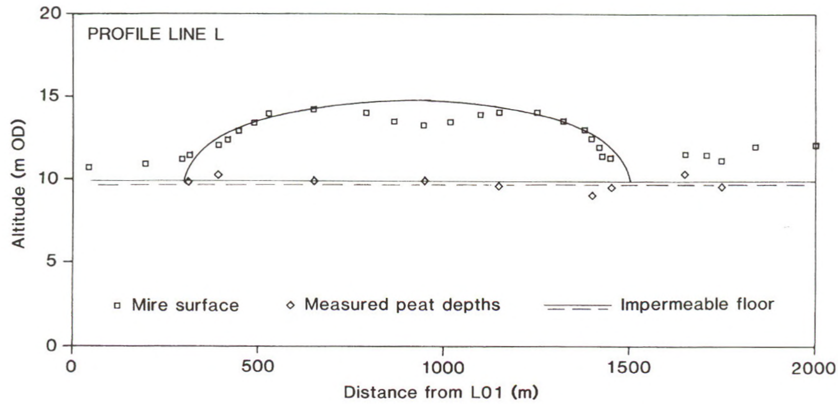

Fig. 6. Comparison of profiles of groundwater mound model and mire surface for location grid line L.

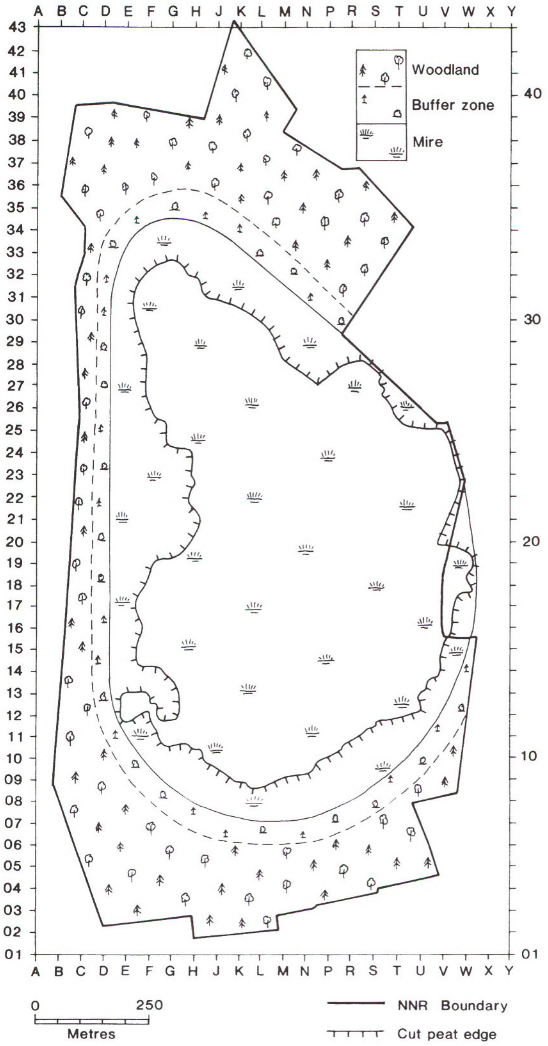

Figure 7: Map of management compartments proposed for Kirkconnell Flow on the basis of groundwater mound modelling. The "buffer zone" is a belt of young trees, managed to minimize seeding of pine from the surrounding mature woodland onto the mire area.

hydraulic gradient observed might be associated with weather conditions, seasonal variations, or regional hydrology[5]. Therefore, these measurements should be repeated under different conditions, and should be related to groundwater abstraction activity.

The ground vegetation of the central part of Kirkconnell Flow is of surprisingly high quality in view of the fact that the site must be regarded as a severely disturbed remnant of the original raised mire system. It is also initially surprising that the morphology of the site conforms so closely to that of a groundwater mound which appears to be well within climatic capability.

Keatinge (1976) located the mineral substratum at 8-9 m a.s.l. Comparison with the altitude of 10 m a.s.l. derived during the present study[6] actually suggests that the depth of the peat deposit has declined through shrinkage by 1-2 m during the last 20 years. The nature of the cut peat edge is also of interest in this context. In 1955 the height of the peat face was 3-6 feet (1-2 m)[7]. When examined during the present study, it consisted of vertical faces up to 1 m high in some places, whilst in others its presence was apparent only as a discontinuity in slope. The primary surface above the limit of cutting was dry, often cracked, and devoid of *Sphagna* except for patches of *S. capillifolium*. Below, there was a very wet strip, 0.5-1 m wide with luxuriant growth of *S. magellanicum* and *S. papillosum*. Thus it seems that repair of the discontinuity in slope introduced by peat cutting is in progress, through simultaneous slumping of primary surface and *Sphagnum* recolonisation on the adjacent secondary surface.

It has been suggested (Bragg 1995) that the complex of natural feedback mechanisms which must operate to maintain raised mire systems through long-term climate change ought also to afford capacity for adjustment to at least a limited degree of human intervention. The role of trees in this may be significant, since their growth gradually increases overburden, tending to compress the whole peat mass, reducing permeability and at the same time assisting in lowering the surface towards the water table. On this basis, Schneebeli (1989) suggested that forestry should be cleared as late as possible in mire rehabilitation programmes.

The evidence from Kirkconnell Flow suggests that readjustment of the biological system to new hydrodynamics is well advanced. Perhaps, through initial conservation of the tree cover, this site has for-

[5] A study carried out by Dumfries & Galloway Regional Council detected artesian groundwater approximately 1 km north of Kirkconnell Flow. Moreover, after completion of the project reported here it emerged that a pumping test on the groundwater production boreholes had been conducted for 90 days from 10 March 1995, apparently ending just one month before the measurements of hydraulic gradient in the peat were made.

[6] Note that this result was derived by subtracting peat depths from surface altitudes shown on the 1970s contour map (see Methods).

[7] Note in Scottish Natural Heritage files attributed to H. Salzen.

tuitously received the best possible management for its restoration to raised mire. Now that *Sphagnum* is beginning to disappear beneath the trees, the opportunity for active management may also have arrived at exactly the right historical moment. In any case, the prospect promises exciting insights for mire restoration science.

ACKNOWLEDGEMENTS

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WORLD MIRE CLASSIFICATION : AN APPROACH BASED ON THEIR ORIGIN, DEVELOPMENT AND VEGETATION

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Summary

A new vision of global mire classification is proposed, taking into acccount the mire origin. When the water balance is positive, two processes of peat formation may occur, *terrestrialization* and *paludification* that give rise to *seven kinds of mire origin*, in which may be included, as subtypes, all the classical mires types based on regional hydromorphology. Each ontogenesiac mire type may change dynamically through time, from a geotrophic stage towards an ombrotrophic one. Some mires stay at the geotrophic stage, however, owing to their young age or special, local ecological conditions. These dynamic phenomena may be observed generally at microtope level. The purely ombrotrophic stage (central stage of mire dynamic) may evolve towards a mineralized stage by natural or artificial drainage. The ombrotrophic stage may also be a little bit enriched, owing to surface running water, or the chemical features of rain (oceanic areas). At a finer scale (microform level), the classification may operate at the floristic-ecological perception level. Vegetation can indicate the different ecological gradients occurring on a mire site, for example, **water supply type** ; depending on the water origin (rain, spring, flood, lake, condensation...) and quality (*Mineralbodenwasserzeigergrenze* of Du Rietz 1954); **climatic gradient**: latitudinal, altitudinal, longitudinal (oceanic versus continental); **hydric gradient**: accompanying primary succession, disturbances and regeneration; **trophic gradient**: oligotrophic - mesotrophic - eutrophic soils (with oligotrophilous - mesotrophilous - eutrophilous vegetation); **pH factor**: basic or acidic soils (neutrophilous or acidophilous vegetation); **mire expanse - mire margin zonation**. Vegetation may also show well the small-scale pattern of a mire, with the correlation between vegetation and T-A terminology. To classify mires at a world scale, two different classifications are proposed: one, which could be named « ontogenesiac classification » is useful to understand the basic global features of mire creation on the earth, allowing comparison of mires complexes at the world scale, between very different regions. The primary units produced by this classification could be subdivided into geomorphological types and dynamic stages. A second, which could be named « floristico-ecological classification » (i.e. phytosociological classification) would be useful to understand, compare and predict ecological processes and features, at microform level but also at geographical level (vicariance of communities and species).

Keywords: mires, classification, ecosystem dynamics, ecological factors

Introduction

Many attempts to classify mires have already been proposed by different authors. After presentation of previous concepts, a new way to classify mires at world scale is proposed, from the perspective of their origin and dynamic development. In this « ontogenesiac approach » seven primary types of mire origin (limnogenous, fluviogenous, thalassogenous, condensarogenous, soligenous, topogenous, ombrogenous) are distinguished, which all may pass through three dynamic stages (geotrophic, ombrotrophic, mineralized). For a finer and local scale the use of vegetation (« phytosociological approach ») seems to be most useful to precisely describe the phenomena, into the general scheme.

Historical attempts to classify mires

Many attempts have already been made to classify mires, and from this point of view, mires are among the most studied ecosystems, apart from forests. Unfortunately, most of the approaches used are valuable only for a limited geographical range or for a given purpose.

Among these former attempts some are of historical, practical or theoretical interest.

One of the oldest attempts is the one of Cajander (1913) who distinguished four types of mires in Finland, namely, Weissmoore (» poor fens), Braunmoore (» rich fens), Reisermoore (» raised bogs) and Bruchmoore (» forested mires). Sjörs (1948) tried to distinguish mires on the basis of the origin of their water supply. He also described the surface pattern of the bogs (hummock-lawn-carpet-hollow). Kulczynski (1949) underlined the role of hydrology in mire classification. Du Rietz (1954) emphasised the role of the «mineral water supply indicators limit» as an important criterion for mire vegetation typology. Ruuhijärvi (1960) and Eurola (1962) gave regional classifications for mire types in Finland, based on mire complexes and vegetation. Tolpa, Jasnowski & Palczynski (1967) proposed a classification based on peat genesis. Malmer (1968) recognised some important variations in mire vegetation and tried to translate them into a vegetation classification. Tüxen (1969) emphasized the role of bryophytes in mire vegetation, which he used for his classification system. Moen (1973a, b) distinguished between different ombrotrophic and minerotrophic mire complexes in Norway in order to produce a strategy for mire conservation in that country. He also proposed to use phytogeography to select sites. Succow (1974, 1982, 1988) developed an ecological classification of mires, giving importance to the trophic level and pH. Ivanov (1981) described different patterns of water supply in mires and the relation to their morphology. He also emphasized the scale effect with four levels of functional hydrology (macrotope-mesotope-microtope-microform). Dierssen (1982, 1996) described the vegetation in mires of northern Europe using the classical central european approach based on sigmatist phytosociology and by emphasizing the role of *pre-defined* vascular characteristic species. Julve (1983, 1993, 1996) and De Foucault (1984) proposed a detailed phytosociological classification system for fen vegetation at European level and a preliminary scheme for bogs in France. Wheeler (1984), distinguished a whole range of fen types in Britain based on hydrology and topography. Lindsay, Riggall, & Burd (1985) gave a fine picture of the hummock - hollow system and developed a formal classification of each topographical level (A-T scale). Lindsay *et al.* (1988) described the influence of climate on blanket bog surface pattern and emphasized the importance of scale. They also described vegetation units in their area of interest (Caithness and Sutherland). Grosvernier, Matthey & Mülhauser (1992) developed a typology for the mires of Jura, designed to be used for the local management of peatlands. Steiner *et al.* (1992) published one of the best examples of a national mire catalogue for conservation purposes, including a well illustrated presentation of Austrian mire complexes and a classical phytosociological description with many tables. Brinson (1993) presented an interesting hydrogeomorphic classification of wetlands which included consideration of mires. Lindsay (1995) discussed the ways of classifying bogs at different scales, and gave a typology for Great Britain. Bridgham *et al.* (1996) studied the limiting gradients in peatlands and made suggestions for naming different kinds of mire types. Wheeler & Proctor (2000) working on ecological gradients in NW-European mires suggested a revised terminology.

Some symposia have entirely, or partly, been devoted to mire classification. Many of them have produced very interesting papers, which can only be cited selectively here:

- The IAVS Symposium in Stolzenau/Weser (1964, published in 1968): « Pflanzensoziologische Systematik ».
- The IAVS Symposium in Rinteln (1970, published in 1972): « Grundfragen und Methoden in der Pflanzensoziologie ». This one has produced a lot of interesting, sometimes conflicting, papers upon the philosophy of mire vegetation classification among classical phytosociologists.
- The IPS Symposium in Glasgow (1973): Classification of Peat and Peatlands. Many others IPS Symposia include papers dealing with peat and mire classifications.
- The AAIP Symposium in Lille (1978, published in 1980: Géhu (Ed.) 1980): « La végétation des sols tourbeux ».
- The Symposium in Hailuoto - Kuusamo (1983, published in 1985: S.A.N.O. 1985): Field symposium on classification of mire vegetation. One of the best synthesis of different approaches.
- Recent IMCG workshops in Greifswald (1998), Popelna (1999), Lagow (2000) have dealt specifically with global mire classification. The contributions have been sent through E-mail and some are to be seen on the website (http://imcg.net). Following these workshops, some specific working groups (Plant, Hydrogeology, Animal, etc) have been organized.

Many synthetic books also deal, at least partly, with mire classification at different functional levels: Botanisch-Geologische Moorkunde, edited by

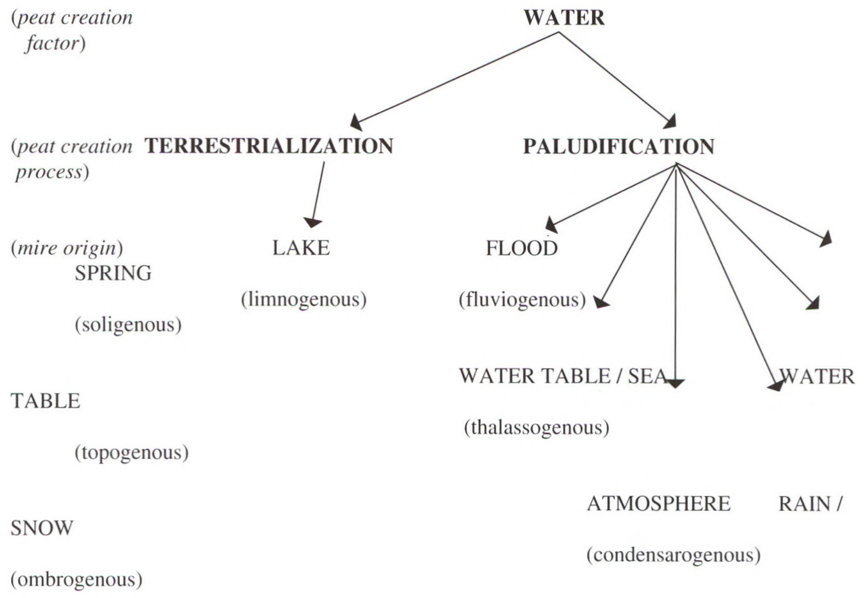

Fig. 1. The ontogenesis of mires.

Overberck (1975), Moor und Torfkunde (2nd edit.), edited by Göttlich (1980), Ecosystems of the world, volume 4a & b, edited by Gore (1983), European Mires, edited by Moore (1984), Landschaftsökologische Moorkunde, edited by Succow (1988).

Many of these attempts have brought interesting ideas but none of them allow a consistent classification of mires at the world scale.

If we synthesize all the criteria that have been used to classify mires types we obtain the following list: (onto-)genesis of the mire, (hydro-)geomorphology of the actual surface (generally at landscape level), feeding mode and mineral content (ombrotrophic-geotrophic gradient), trophic level (oligotrophic-eutrophic gradient), pH (acidic-basic gradient), micromorphology (hummock, lawn, hollow, pool), flora and vegetation (species versus communities, using different phytosociological approaches), geography (oceanic-continental, planarian- alpine, tropical-polar gradients), transition ecotones (mire expanse towards mire margin).

It is clear that all these criteria reveal part of the mire diversity, but the question is how to organize a hierarchy with them, in order to produce a global and coherent classification, valid from the world to the local scale. It seems that time has come for a new synthetic proposal, which could serve as a basis for a global agreement on Mire Classification. This proposal should make use of the actual pattern and processes of the mires, as well as recognizing the specific characteristics resulting from the ontogenesis of each mire.

Origin and early Development of Mires

If we look at a world map of mire area (Gore 1983) or even at the distribution of typical mire plants, for example, the genus *Drosera* (in Meusel *et al.* 1965) or *Sphagnum* (in Daniels & Eddy 1990), we can see that mires may occur everywhere on earth, even in tropical areas. For example, *Sphagnum* mires may be found in Malaysian Islands or in the French West Indies (Guadeloupe), neutrophilous mires may also be found along the coasts of French Guyana, at 5° northern latitude, in Indonesia, in Kalimantan, West papua and Sumatra. So it becomes clear that Geography (regional climate) is not the decisive factor, but only a favourable one. In fact, **Water supply** is the most important ecological factor for the occurrence of a mire. What is important for the development of a mire is the water balance, i.e. the ratio between **input** (rain, snow, dew, upstream flow, air condensation) and **output** (downstream flow, percolation, evaporation, transpiring of the plants). If this balance is positive, mire creation may occur everywhere on earth.

The greatest areas (and volumes ?) of mires are found in cold boreal regions or in the mountain belt of temperate mountains (Kivinen & Pakarinen, 1981). At higher latitude or higher altitude, the cold temperature decreases the production of organic matter, while at lower latitude or lower altitude, the turn-over of organic matter through mineralization is accelerated, although even in tropical areas deep peat bodies may be produced, as in Indonesia (Rieley & Page 1997).

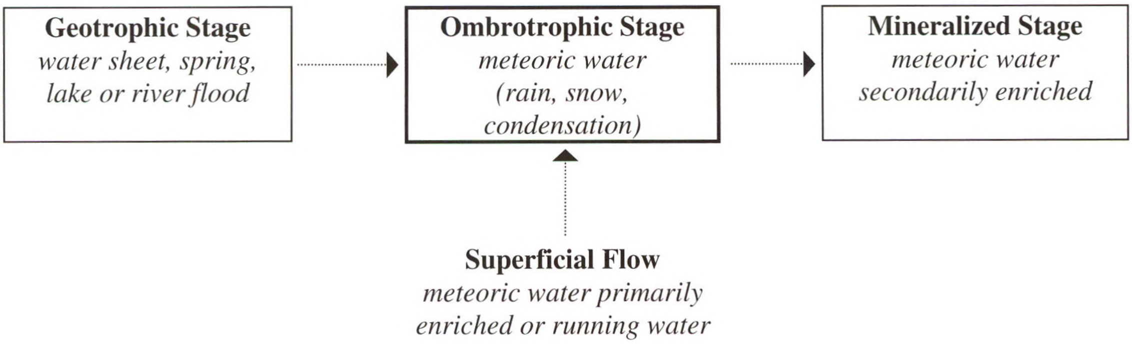

Fig. 2. The Generalized formal sturcture of the mire dynamics with resoects to the water feeding and the water mineral content (after JULVE 1996 a).

These simple observations are valid at the world scale and so it means that a global classification of mires should be firstly based on the water resource at the mire origin, then on the water supply during development. Because hydrological conditions, combined with local climate, are recognizable all around the earth, they give a good way to classify mires globally at landscape level (mesotope level), as these conditions are shown by the geomorphology of natural mire surfaces (Kulczynski, 1949; Ivanov, 1981).

With a positive water balance, two processes of peat formation may occur, *terrestrialization* and *paludification* (Sjörs 1948).

Taking into account the origin and the physical properties of the feeding water, these two processes may generate *seven types of mire origin* (Fig. 1), in which can be included, as subtypes, all the classical mire types based on regional hydromorphology (Ruuhijärvi, 1960; Eurola, 1962; Moen, 1973a, b; Succow, 1988; Diersen 1996). Here are some examples with common synonyms (*German names in brackets*) :

- **limnogenous**: ancient lake mires (*Verlandungsmoore*)
- **fluviogenous**: alluvial valley mires (*Überflutungsmoore*)
- **thalassogenous**: dune-slack mires (*Dünenmoore*), transgression mires (*Transgressionsmoore*)
- **topogenous**: swamp mires, palsa mires, polygonous mires (*Versumpfungsmoore, Grundwasseranstiegsmoore, Palsamoore, Polygonalmoore*)
- **soligenous**: sloping mires, spring mires, percolating mires, aapa mires (*Überrieselungsmoore, Quellmoore, Durchströmungsmoore, Hangmoore, Aaapamoore*)
- **condensarogenous**: condensation mires (*Kondenswassermoore*)
- **ombrogenous**: blanket mires, saddle mires (*Deckenmoore, Sattelmoore*)

The kettle hole mires (*Kesselmoore*) should be scattered throughout different primary types, depending on the waterfed process (limnogenous or topogenous).

MIRE DYNAMICS

Each ontogenesiac mire type may dynamically change with time, from a geotrophic stage towards an ombrotrophic one. Some mires stay at the geotrophic stage, however, owing to their young age or some special ecological local conditions. Even blanket mires, at the very beginning of the peat accumulation process, pass through a short geotrophic stage. These dynamic phenomena may be observed generally at microtope level (Fig. 2).

The purely ombrotrophic stage (central stage of mire dynamics) may evolve to a mineralized stage as a consequence of natural or artificial drainage. The ombrotrophic stage may also be a little bit enriched, owing to surface running waters, or by the peculiar chemical composition of rain, especially in oceanic areas (Damman & French, 1987; Damman, 1990).

So the concept of « transition mire » (*Übergangsmoore*) simply represents a dynamic stage, while « mixed mire » exhibits a complex of juxtaposed stages that may be fairly stable.

The « raised bogs » (*Hochmoore, Regenmoore*), which include eccentric bogs, concentric bogs, plateau bogs, Atlantic bogs and plane bogs, simply represent the ombrotrophic stage of mires of different origin. An eccentric bog evolves from a soligenous mire; a concentric bog evolves from a topogenous mire; an Atlantic bog undergoes some surface enrichment that may shadow the «mineral soil indicators limit» and may have all kinds of origin; plateau bogs are very large concentric bogs, where the physical shape (see Ingram

(1982)) has to adapt to the hydrological constraints; plane bogs are very early stages of ombrotrophic differentiation, which can be permanent in some areas. Furthermore, « fens » (*Niedermoore*) and « swamps » (*Flachmoore*) are only different kinds of geotrophic stages, which may be distinguished and subdivided on the basis of their edaphic conditions (trophic status and pH) and as shown by their vegetation.

MIRE VEGETATION AND ITS ECOLOGICAL SIGNIFICANCE

At a finer scale (microform level), classification purposes may reach the floristic-ecological perception level (Fig. 3). In Europe, the different stages may be characterized by the following phytosociological units (see de Foucault, 1984 ; Julve, 1996b, 1998 for a more detailed description, or Dierssen, 1982, 1996; Tüxen 1969, with a classical approach).

The aquatic margin may be occupied by aquatic communities (*Potamogetonetea pectinati*) or amphibious short herb communities (*Littorelletea uniflorae*).

The geotrophic stage is characterized by reedswamps and tall sedge communities (*Phragmiti australis - Caricetea elatae*) or fen vegetation (*Caricetea nigrae*). The latter represents short sedge communities in humid zones or floating mats with helophytes (*Menyanthes trifoliata, Potentilla palustris, Carex lasiocarpa, Carex rostrata, etc*) in more hydrophilous situations. In the sense of the synusial approach (Gillet *et al.*, 1991), these vascular vegetation communities may be combined phytocoenotically with bryophytes classes (*Aulacomnio palustris - Sphagnetea fallacis*, acidophilous, *Drepanoclado revolventis- Campylietea stellati*, neutrophilous).

The ombrotrophic stage is characterized by a special phytosociological class of peat-forming bryophytes (*Aulacomnio palustris - Sphagnetea fallacis*), by relict species of fen class (*Caricetea nigrae*) or pioneer of heathland classes (*Calluno vulgaris - Vaccinietea myrtilli, Calluno vulgaris - Ulicetea minoris*), which are optimal in the mineralized stage and also accompanied by bryophyte communities (*Lepidozietea reptantis, Dicranelletea cerviculatae*).

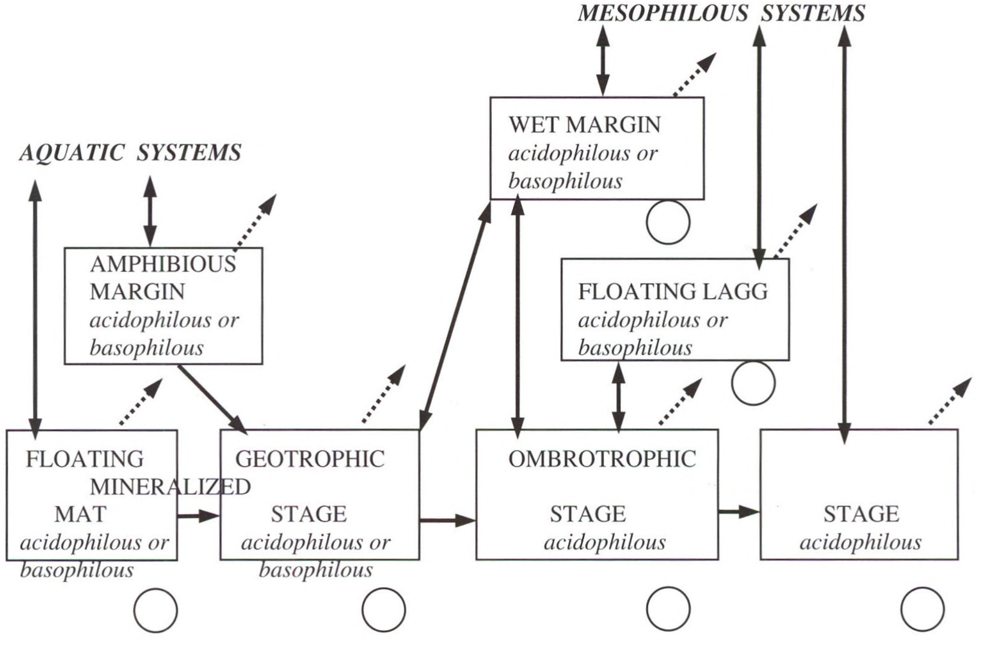

Fig. 3. Formal structure of mire vegetation at world scale (modified after JULVE 1996 a)
In each square, one or several synusiae may represent a dynamic succession or be combined in complexes (phytocoenosis, tesela, catena).
bold simple arrow : possible dynamic
bold double arrow : juxtaposition
broken arrow : possible dynamic towards wooded vegetation
circle : cicatrization dynamic (= phases)

Table 1 : Bryophyte communities of European bogs (from original data of Dierssen, Steiner and others)

column	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
number of relevés	40	20	81	18	611	4	40	32	276	13	140	28	45	285	322	255	1026	129	61	1063	204	8	71	159	335	195
acidophilous mires :																										
Warnstorfia exannulata	V	II	I	II	I		I	I	I		I		I	I	I	I				I			I			
Sphagnum subsecundum	I	V	I		I		I		I		I		I	I	I		I			I						
Sphagnum angustifolium		I	V		I				I		I				I	II	I		II	II	II		II			
Sphagnum flexuosum			II		I							I								I						
Sphagnum squarrosum				III	I								I													
Pseudobryum cinclidioides				III																						
Sphagnum fallax				III	V	I	I					III	I			I	I			II				I		
Polytrichum commune	I		II	III	II			I	I		I	II	I	I	I	I	I			I	I			II	I	
Sphagnum obtusum						IV																				
Sphagnum pylaesii								V																		
Sphagnum denticulatum	I		I		I		V	V	II	I						I	I									II
Sphagnum cuspidatum			I				I	III	V		I			I		I	I	I		I		I		I	I	III
Cladopodiella fluitans							I		II		I			I	II	I	I	I							I	I
Sphagnum pulchrum									I	V	I				I		I	I								
Sphagnum majus	I		I		I				I	I	V			I	I					I						
Sphagnum riparium				I	I							V	V	I												
Sphagnum angstroemii													I													
Oncophorus wahlenbergii														I												
Sphagnum jensenii														I												
Drepanocladus schulzei													I	II												
Sphagnum balticum					I	I			I		I		I	II	I	II			I		I					
Sphagnum lindbergii					I						II		III	V	II	III	I		I		I		I			
Gymnocolea inflata			I						I		I		I	II	III	II	I		I	I	I		I		I	I
Sphagnum compactum	I		I		I				I		I			II	IV		I			I					IV	III
Sphagnum tenellum			I					I	II		I			I	IV	II	III	II	II	I	I	IV	I	I	III	IV
Sphagnum papillosum	I		II		I	I	I	I	III	I	II		I	I	II	V	V	II	I	I	I	II	I	I	II	III
Sphagnum subnitens			I					I	I						I	II	II	I	I		I		I	I	I	III
Odontoschisma sphagni									I						I	I	II	IV	I		I	IV		I	II	IV
Kurzia pauciflora									I								I	III	I			II			I	II
Sphagnum imbricatum																	I	V								I
Sphagnum magellanicum	I	I	II		I	I	I		II		I			I	I	II	II	I	V	V	I		I	I		I
Calypogeia sphagnicola									I							I	I	I	I		II	II	I	I	I	
Sphagnum fuscum																I	I	I	II	II	V	V	I	I		
Mylia anomala			I						I						I	I	I	III	II	I	IV	IV	II	II	I	I
Sphagnum russowii					I										I	I	I			I	I		V	I		
Ptilidium ciliare			I												I	I	I		I		I		I	III	I	
Sphagnum capillifolium					I				I		I				I		II	I		III	I	II	I	V	II	I
Pleurozia purpurea									I								I					I			I	V
Campylopus atrovirens									I								I								I	IV
Breutelia chrysocoma									I								I								I	II
Calliergon stramineum	I	III	II	I	II	IV	I		I	I	I	I	III	II	II	III	I	I	III	I	II		III		I	
Sphagnum rubellum			I		I	I			I		I				I	II	III	IV	IV		II	III			I	III
Polytrichum strictum	I	I	I		I		I		I						I	I	I	I	III	III	III		II	I	I	
Aulacomnium palustre	I	II	II		I		I		I						I	I	I	I	I	II	I		I	II	I	
Sphagnum palustre		II	I		I			I	I								I									I
Sphagnum inundatum			I		I			I	I		I					I	I									I
Sphagnum warnstorfii			I		I				I											I						

Warnstorfia fluitans					I				I		I	I		I	I	I										
Cephalozia bicuspidata									I					I	I		I							I	I	I
Lophozia ventricosa									I					I			I	I			I			II	I	
Cephalozia connivens									I								I	I				II		I	I	I
Cephalozia loitlesbergeri															I		I	I			I				I	
Dicranum bergeri															I	I			I	I	I		I			
Sphagnum molle									I						I		I	I	I						I	
Sphagnum strictum															I										I	I
Paludella squarrosa												I		I												
Calypogeia trichomanis																	I							I		I
Sphagnum teres					I																					
Sphagnum centrale																				I						
Sphagnum girgensohnii																				I						
neutrophilous mires :																										
Bryum pseudotriquetrum	I			I	I																					
Drepanocladus revolvens			I		I					I																
Calliergon cordifolium			I		I																					
Drepanocladus vernicosus					I																					
Campylium stellatum				I			I																			
Sphagnum contortum					I		I																I			
Calliergon giganteum					I		I																			
Scorpidium scorpioides							I			I																
Riccardia pinguis							I																			I
Sphagnum platyphyllum									I											I						
Calliergon sarmentosum													I	I	I	I	I									I
Drepanocladus badius														I	I		I									
Barbilophozia kunzeana														I												
Drepanocladus procerus														I												
companions :																										
Dicranella palustris	II																									
Philonotis seriata	II				I										I											
Plagiomnium affine	I	I																								
Climacium dendroides	I	I			I																					
Calliergonella cuspidata	I	I			I											I										
Philonotis fontana	I	I	I													I										
Dicranum leioneuron															I	I	I		I		I					
Pohlia nutans s.l.			I						I							I	I	I	I		II		II	I	I	
Pleurozium schreberi			I												I	I	I	I	I	II	III		II	V	III	I
Racomitrium lanuginosum									I							I	I	I	I		I			III	III	IV
Hypnum jutlandicum									I						I		II	I			I	I		IV	IV	III
Rhytidiadelphus loreus									I								I				I			IV	I	I
Dicranum scoparium															I		I			I				III	II	I
Hylocomium splendens									I							I	I		I	I	I		I	III	I	I
Diplophyllum albicans									I								I	I						I	II	III
Campylopus flexuosus									I								I	I						I	I	II
Plagiothecium undulatum																	I							II	I	I
Calypogeia muelleriana																	I	I						I	I	I
Mylia taylori									I								I	I						I		I
Cephalozia macrostachya									I								I	I				I			I	I
Riccardia latifrons									I								I	I				II				I
Calypogeia fissa									I								I							I		
Leucobryum glaucum									I								I								I	I
Scapania gracilis																	I								I	I
Nowellia curvifolia																	I								I	I
Rhytidiadelphus squarrosus	I																I								I	
Kurzia trichoclados																	I								I	
Pellia epiphylla																I										I

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Campylopus brevipilus											I									I
Lophocolea cuspidata											I									I
Polytrichum longisetum								I												I
Anthelia juratzkana									I											I
Mnium hornum																			I	I
Cephalozia leucantha																			I	I
Dicranum bonjeani				I																
Scapania irrigua							I	I	I											
Scapania paludicola						I		I												
Oncophorus virens								I												
Lophozia wenzelii											I									
Lophozia incisa											I									
Lophozia porphyroleuca											I									
Bazzania trilobata														I						
Dicranodontium denudatum														I						
Dicranum polysetum														I						
Barbilophozia lycopodioides														I						
Anastrepta orcadensis																		I		
Barbilophozia floerkii																		I		
Cephaloziella hampeana																		I		
Polytrichum alpinum																		I		
Dicranum fuscescens																		I		
Cladopodiella francisci																			I	
Odontoschisma denudatum																			I	
Cephalozia elachista																			I	
Hypnum imponens																			I	
Barbilophozia atlantica																			I	
Mastigophora woodsii																				I
Dicranella heteromalla																				I
Campylopus setiformis																				I
Campylopus shawii																				I
Scapania undulata																				I
Frullania tamarisci																				I
Lophozia wenzelii																				I
Campylopus swartzii																				I
Marsupella emarginata																				I

Philonotido seriatae - Warnstorfietum exannulatae ass. nov. 1
Sphagnetum subsecundi ass. nov. 2
Calliergono straminei - Sphagnetum angustifolii Julve 93 prov. ex hoc loco 3
Pseudobryum cinclidioides - Sphagnum squarrosum comm. 4
Polytricho communis - Sphagnetum fallacis (Hueck 25) Julve 96 prov. ex hoc loco 5
Sphagnum obtusum comm. 6
Sphagnetum denticulati ass. nov. 7
Sphagnetum denticulati ass. nov., hyperoceanic race 8
Cladopodiello fluitantis - Sphagnetum cuspidati (Osvald 23) Julve 96 prov. ex hoc loco 9
Sphagnetum pulchri ass. nov. 10
Sphagnetum maji ass. nov. 11
Sphagnetum riparii (Dahl 56) Chipon, Deny, Estrade, Nardin & Vadam 88, southern race 12
Sphagnetum riparii (Dahl 56) Chipon, Deny, Estrade, Nardin & Vadam 88, northern race 13
Drepanoclado schulzei - Sphagnetum lindbergii (Dahl 56) ass. nov. 14
Gymnocoleo inflatae - Sphagnetum tenelli (Jensen 61) Julve 93 prov. ex hoc loco 15
Sphagnetum subnitento - papillosi (Cajander 13) Julve 96 prov. nom. inv. ex hoc loco, northern race 16
Sphagnetum subnitento - papillosi (Cajander 13) Julve 96 prov. nom. inv. ex hoc loco, southern race 17
Kurzio pauciflorae - Sphagnetum imbricati (Osvald 23) ass. nov. 18
Sphagnetum rubello - magellanici (Osvald 23) Julve 96 prov. ex hoc loco, northern race 19
Sphagnetum rubello - magellanici (Osvald 23) Julve 96 prov. ex hoc loco, southern race 20

Mylio anomalae - Sphagnetum fusci (Cajander 13) Julve 93 prov. ex hoc loco, northern race 21
Mylio anomalae - Sphagnetum fusci (Cajander 13) Julve 93 prov. ex hoc loco, southern race 22
Sphagnetum russowii ass. nov. 23
Ptilidio ciliaris - Sphagnetum capillifolii (Koch 28) Julve 93 prov. ex hoc loco 24
Sphagnetum stricto - compacti (Oberdorfer 38) Julve 96 prov. ex hoc loco 25
Campylopo atrovirentis - Pleurozietum purpureae (Braun-Blanquet & Tüxen 52) ass. nov. 26

Tab. 2. Main herbaceous and scrub synusial as sociations on European acidophilous and ombrotrophic mires (ddata from Dierssen, Steiner and Others).

column	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
number of relevés	13	61	527	93	153	9	42	533	11	54	84	294	186	9	44	27	80	21	53	213	29	[illegible]
Chamaephytes (Calluno vulgaris - Vaccinietea myrtilli)																						
Vaccinium microcarpum	IV	III	III	I	I	I	III	I		I	II											
Empetrum nigrum subsp. hermaphroditum	III	V	III	V	II	V	III	I		II	II					II	II	III				
Rubus chamaemorus	II	V	IV	V	V	V				II	II					I	I	II	I			
Betula nana	V	IV	III	III	II		I			I	II					I	II	I	I			
Cornus suecica			I	I	I	II										I	I	II				
Diapensia lapponica				I																		
Chamaedaphne calyculata	V																					
Ledum palustre	IV	V							V													
Vaccinium uliginosum subsp. uliginosum	I	III	III	IV	I	IV	IV	IV	III	I	I	II			I	II	II	V	I			
Vaccinium vitis-idaea	I	V	I	III	II	IV	IV	IV	IV			I						I	I			I
Vaccinium myrtillus		II	I	II	IV	V	III	V	III			I			II	I	I	I	I			I
Empetrum nigrum subsp. nigrum			I	I	IV										II	I	I	III	I		I	I
Calluna vulgaris		I	III	II	V	IV	IV	III	III	II	II	II	III	III	III	III	IV	V	V	V	V	V
Andromeda polifolia	IV	III	V	III	I		II	III		V	IV	IV	IV	II		V	IV	IV	II			I
Vaccinium oxycoccos	III	I	II	I	I		II	IV	IV			III	III	II					I			
Loiseleuria procumbens				I																		
Arctostaphylos alpina					I	II																
Rhododendron ferrugineum							I	I														
Vaccinium uliginosum subsp. microphyllum												I										
Chamaephytes (Calluno vulgaris - Ulicetea minoris)																						
Erica tetralix					II							I							V	V	V	V
Erica cinerea																				I	I	I
Erica mackaiana																				I		
Hemicryptophytes (Scheuchzerio palustris - Caricetea nigrae)																						
Carex pauciflora	II	I	II	I			II	II				III	I	I		II	II	I	II			I
Drosera rotundifolia	IV	I	II	I			II	I	I	I	I	III	III	II		II	II	II	II	IV	V	II
Eriophorum vaginatum	V	II	IV	II	V	V	V	V	V	II	II	IV	IV	I	II	II	II	II	III	III	III	II
Eriophorum polystachion		II	II	I	II	IV		I		III	III	II	III	III	V	V	IV	II	III	V	V	V
Trichophorum cespitosum subsp. cespitosum		I	III	I	I	?	I	I		V	V	V			III	V	V	V	IV	I	I	I
Molinia caerulea			I	I			II	III	III			III	III	IV	I	V	III	IV	III	V	V	IV
Potentilla erecta					I	II	II	I				II	II	V	IV	IV	II	III	III	III	III	IV
Narthecium ossifragum					I							I			V	V	V	V	IV	V	IV	IV
Trichophorum cespitosum subsp. germanicum					I	III									II				II	II	II	V
Juncus squarrosus					II	II									III				I		I	II
Carex rariflora			I	II						IV		I										
Carex limosa			I							II	II	I	I	I								
Carex rostrata			I	I			III	I		II	I	II	II	II								
Carex nigra							III	II				I	III	IV	I							I
Carex echinata							I	I	I			I	II	IV	III	II	II	I	II	I	I	I

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Carex panicea						I	I				I	I	III	IV					II	II	II
Viola palustris							I				I	I	II	II	II	I					
Agrostis canina				I			I					I	I	II							I
Menyanthes trifoliata							I				I	I	I						I	I	I
Carex lasiocarpa							I				I	I	II								
Juncus filiformis							I				I	I	II								
Trichophorum alpinum							I				I	I	II								
Tofieldia calyculata							I				I	I	II								
Scheuchzeria palustris							I				I	II									
Carex magellanica											I										
Euphrasia frigida															IV						
Selaginella selaginoides														II	V						
Dactylorhiza maculata														II	I						
Pinguicula vulgaris				I	I									II	II	I	I		I	I	I
Succisa pratensis														I	II	I	I	I	I		I
Drosera anglica		I							II	II					II	I	I		III	I	II
Rhynchospora alba											I	II							IV	II	I
Schoenus nigricans																			V	I	I
Pedicularis sylvatica																		I	II	I	II
Drosera intermedia																			II	I	I
Anagallis tenella																			I	I	I
Ranunculus flammula														I							
Carex viridula subsp. oedocarpa														I							
Carex pulicaris														I							
Pinguicula villosa	I																				
companions																					
Carex bigelowii				I	V									II							
Anthoxanthum odoratum							I				I	I	IV	I							
Equisetum palustre						I	I				I	I	III	I							
Nardus stricta					II	II	I				I	I	III	IV	I	I	I				I
Juncus bulbosus														III							
Euphrasia scottica														II							
Festuca vivipara														II							
Deschampsia flexuosa				II	II	I	I	I				I		I							I
Galium saxatile					II									I							
Festuca gr. ovina					II																I
Luzula multiflora					II																
Melampyrum pratense (incl subsp. paludosum)				I		II	II					I									
Homogyne alpina						II	I				I	I									
Leontodon hispidus							I				I	I	II								
Equisetum fluviatile							I					I	I								
Polygala serpyllifolia														I				I	III	II	II
Huperzia selago														I				I			I
Trientalis europaea															I	I	I				
Eleocharis multicaulis																			I	I	I
Listera cordata				I																	I

col 1 : Chamaedaphno calyculatae - Ledetum palustris subsp. palustris Korotkov 1986

col 2 : Vaccinio microcarpi - Empetretum nigri subsp. hermaphroditi Nordhagen 1928, ledetosum palustris

col 3 : Vaccinio microcarpi - Empetretum nigri subsp. hermaphroditi Nordhagen 1928, eriophoretosum vaginati

col 4 : Vaccinio microcarpi - Empetretum nigri subsp. hermaphroditi Nordhagen 1928, vaccinietosum uliginosi
col 5 : Rubo chamaemori - Vaccinietum myrtilli ass. nov., empetretosum nigri subsp. nigri
col 6 : Rubo chamaemori - Vaccinietum myrtilli ass. nov., empetretosum nigri subsp. hermaphroditi
col 7 : Vaccinio oxycocci - Callunetum vulgaris Schubert 1960, empetretosum nigri subsp. hermaphroditi
col 8 : Vaccinio oxycocci - Callunetum vulgaris Schubert 1960, typicum
col 9 : Vaccinio oxycocci - Callunetum vulgaris Schubert 1960, ledetosum palustris
col 10 : Caricetum rariflorae Fries 1913
col 11 : BC [Caricetum rariflorae Fries 1913]
col 12 : Trichophoro cespitosi subsp. cespitosi - Eriophoretum vaginati (Zlatnik 1928) Julve 1996
col 13 : Eriophorum vaginatum - Eriophorum polystachion comm.
col 14 : Molinio caeruleae - Caricetum paniceae ass. nov.
col 15 : Narthecio ossifragi - Caricetum paniceae (Dierssen 1980) ass. nov.
col 16 : Narthecio ossifragi - Trichophoretum cespitosi subsp. cespitosi ass. nov., selaginelletosum selaginoidis
col 17 : Narthecio ossifragi - Trichophoretum cespitosi subsp. cespitosi ass. nov., typicum
col 18 : Narthecio ossifragi - Trichophoretum cespitosi subsp. cespitosi ass. nov., empetretosum nigri subsp. nigri
col 19 : Narthecio ossifragi - Ericetum tetralicis Moore 1968, trichophoretosum cespitosi subsp. cespitosi
col 20 : Narthecio ossifragi - Ericetum tetralicis Moore 1968, schoenetosum nigricantis
col 21 : Narthecio ossifragi - Ericetum tetralicis Moore 1968, typicum
col 22 : Narthecio ossifragi - Ericetum tetralicis Moore 1968, trichophoretosum cespitosi subsp. germanici
col 23 : Narthecio ossifragi - Ericetum tetralicis Moore 1968, eriophoretosum vaginati
col 24 : Empetro nigri subsp. nigri - Ericetum tetralicis (Moore 1962) ass. nov., vaccinietosum myrtilli
col 25 : Empetro nigri subsp. nigri - Ericetum tetralicis (Moore 1962) ass. nov., vaccinietosum uliginosi
col 26 : Junco squarrosi - Trichophoretum cespitosi subsp. germanici (Jouanne 1926) ass. nov.

The wet margin is generally a stable equivalent of the geotrophic stage, which shows a stable zonation towards the mineral surroundings. A good example is the « lagg » of some mires. One should be careful not to mix the primary dynamics of a mire, which often exhibits a zonation, and the margin effect which is accompanied by a stable zonation.

The dry margin is often occupied by mesophilous grasslands (acidophilous: *Nardetea strictae*, neutrophilous: *Festuco valesiacae - Brometea erecti*) or mesophilous meadows (*Arrhenatheretea elatioris*).

Some stages may be more or less wooded (Fig. 3).

As has been shown in various phytosociological studies using differing methodology (Succow, 1974; Dierssen, 1982, 1996; Moen, 1990; Steiner, 1992; Julve, 1996 b, 1998) the vegetation brings some clues to various ecological gradients occuring on a mire site:

- trophic gradient: oligotrophic - mesotrophic - eutrophic soils (with respect to nutrients N,P,K and translated by oligotrophilous - mesotrophilous - eutrophilous vegetation);
- pH: basic or acidic soils (in relation to cation concentrations and accompanied by neutrophilous or acidophilous vegetation);
- hydric gradient: accompanying primary succession, disturbances and regeneration;
- water supply: depending on the water origin (rain, spring, flood, lake, condensation) and quality (*Mineralbodenwasserzeigergrenze* of Du Rietz 1954);
- mire expanse - mire margin zonation;
- climatic gradient: latitudinal, altitudinal, longitudinal (i. e. oceanic versus continental);

Vegetation also shows the small-scale pattern of a mire, for example with the correlation between vegetation and T-A terminology (Lindsay *et al.*, 1985). Table 1 provides an original example with the use of synusial phytosociology to describe the bryophyte communities of European bogs.

CONCLUSIONS

The « morphogenetic » or « hydrogenetic » classifications currently in use are considered inconsistent for a global world typology, at least at higher hierarchical levels, because they mix at the same taxonomical level very different criteria and features, for example, origin of the mire, actual geomorphological shape, actual water supply, actual process of peat accumulation, geographical location and actual vegetation.

Therefore, two separate classifications are suggested:

- The first one, which could be named « ontogenesiac classification », portrays the basic global features of mire ontogenesis on the earth, and allows comparisons of mire complexes at the world scale. The primary units produced by this classification could be subdivided into geomorphological types and dynamic stages.
- The second one, which could be named « floristico-ecological classification », (i.e. phytosociological classification) to promote understanding, comparison and prediction of ecological processes and features, at microform and geographical levels (vicariance of communities and species). For this second one, the integrated synusial approach of phytosociology (Gillet, De Foucault & Julve, 1991) seems to be the best tool to translate ecology and dynamics of the plants communities into a coherent global classification scheme (see also Tables 1 and 2).

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APPROACHES TO SWISS MIRE MONITORING

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SUMMARY

Following a referendum in 1987, the Swiss Federal Government introduced regulations that set strict terms and targets for the protection and rehabilitation of mires. Three national inventories have been established, each designating sites of national importance embracing 550 bogs, 1200 fens and 90 mire landscapes. It is now the duty of the 26 Swiss cantons to implement compulsory mire conservation measures in order to obey the federal law, which states that mires of outstanding beauty and national importance are to be preserved in their entirety. Where feasible, regeneration operations should be implemented on mires already suffering disturbance. According to this legislation mire protection in Switzerland comprises both quantitative and qualitative aspects and, consequently, the size of mire sites of national importance must not be reduced and their diversity with respect to structure, types, vegetation, and species richness has to be maintained or improved. There are different ways to achieve the protection required by legislation and there is an on-going discussion about the best way to reach both the legislation targets and a general acceptance by landowners and users. Considering the high cost of public and private efforts involved in the national mire conservation scheme it is important to detect advantages and disadvantages of the different implementation procedures as early as possible. A step-wise procedure has been recommended to achieve this, starting with evaluation of the implementation of the regulations and measures by the cantons and ending up with monitoring of their effects on mire habitats. Therefore, in 1993, the Advisory Service for Mire Conservation was commissioned by the Federal Office of Environment, Forests and Landscape to develop a sensitive nationwide long-term mire monitoring strategy in order to reveal discrepancies between targets and reality. It was also directed to provide scientific results that would enable the authorities to evaluate and revise their protection policies. The basic problem of any nature conservation monitoring scheme is to answer the following questions: "How is it possible to get precise information from vague estimates?" and "Which is the most efficient method to detect changes in space and time?" Thus, to develop a successful monitoring approach it is absolutely vital to set clear objectives, have an appropriate sampling design and conduct a professional baseline assessment of the target sites. The Advisory Service for Mire Conservation has developed and tested several methods to assess both the quantitative and qualitative aspects of mire change. The pilot survey of "Gross Moos" in Schwändital (canton of Glaris) is presented as an example.

Keywords: mire conservation, habitat evaluation, mire monitoring, vegetation change, indicator values, remote sensing, sampling design

INTRODUCTION

There are on-going debates about the difference between monitoring and research. We think there is no clear distinction, although some would have us believe otherwise. Much basic research depends on repeated survey and observation. This is especially the case with mires, where only sound monitoring programmes can produce evidence of long-term effects, e.g. of a given management regime or climatic change. To emphasise this, we present some results of an international cooperative project to develop a national monitoring programme for the mires of Switzerland.

Since the 1987 Referendum, when the Swiss voted in favour of the Rothenthurm amendment to the Federal Constitution, strict terms and targets for the protection and rehabilitation of mire sites have been laid down by legislation and the responsible Federal Authorities. According to this "Mires and mire landscapes of outstanding beauty and national importance are protected areas. The construction of any kind of building or installation whatsoever and any operations changing soil structure are strictly prohibited."

A set of three national inventories has been established to comply with the demands for interpretation and definitions in the field of mire conservation: a bog, a fen, and a mire landscape inventory (Table 1). Based on these surveys, about 550 bogs, more than 1150 fens and 90 mire landscapes have been designated as being of national importance (and some are still waiting to be classified).

The whole ratification system appears to be a rather tedious and time-consuming exercise (Grünig *et al.*, 1986), considering that systematic mire conservation started as early as 1978 with the raised bog survey (Table 2) and that 15 years ago it was hoped that the whole procedure could be concluded, at least on the federal level, in 1997 for bogs and 2004 for fens, respectively. In reality, however, the implementation of the whole mire conservation project was (and still remains) several years behind schedule (Grünig, 1994; OFEFP, 2002).

It is the responsibility of the 26 cantons to devise and implement compulsory mire conservation measures, for which they have several options.

In view of the high level of public spending and private efforts involved, the obvious question inevitably arises as to which cantonal measures best meet the objectives of mire conservation and legislation. A national scheme to monitor the designated mire habitats is required to answer this question. Consequently, the Advisory Service for Mire Conservation was commissioned by the Federal Office of Environment, Forests and Landscape in 1993 to develop a sensitive long-term and nationwide mire monitoring strategy. This should reveal as early as possible any discrepancies between conservation targets and actual developments. It should also become a practical instrument providing the people responsible for conservation with feedback about their measures and scientific results and enable them to evaluate their policies and adapt them to the actual situation.

Table 1: Synopsis of the different mire inventories of Switzerland

Mire inventories	Number of sites	Total mire site area [ha]	Average size [ha]	% of the country's surface
Raised bogs	549	1,524	2.8	0.037
Fenlands	1,163	19,186	16.5	0.465
Total mire habitats	1,314	20,710	15.8	0.502
Mire landscapes	89	87,334	981.3	2.115

Table 2: Development of federal mire protection in Switzerland since 1978

Year	Raised Bogs	Fens	Mire landscapes	Events / Monitoring
1978	Start of survey			
1979	↓			
1980	↓			
1981	↓			
1982	↓			
1983	↓			Submission Mire Conservation Referendum
1984	End of survey			
1985				
1986		Start of survey		
1987		↓		Referendum accepted by the Swiss people
1988		↓	Start of survey	
1989	Consultation phase	↓	↓	
1990	Negotiations	End of survey	↓	
1991	Enactment of Bog Decree	Consultation phase	End of survey	
1992		Negotiations	Consultation phase	
1993		Negotiations	Negotiations	Studies for nationwide mire monitoring
1994		Partial enactment of Fen Decree, 1st series	Negotiations	↓
1995		Negotiations	Negotiations	↓
1996	Start of 2nd survey	Partial enactment of Fen Decree, 2nd series	Enactment of Mire Landscape Decree	Implementation of a national mire monitoring scheme

GENERAL APPROACHES TO MONITORING OF HABITATS

The basic problem of any nature conservation monitoring concept can be summed up with the following questions:

1. What are the objectives of the monitoring scheme?
2. What target surfaces and key factors are to be monitored?
3. Which is the most appropriate procedure (sampling design) to monitor the effectiveness of conservation measures and to detect as early as possible significant changes in space and time?
4. What will it cost?

The answers to these questions as applied to the monitoring programme of Swiss mires can be summarised in the the main objectives of Swiss mire conservation stated in the Federal Decree on the Protection of Mire Habitats: "The mires of outstanding beauty and national importance are to be preserved in their entirety. In mire areas already suffering disturbance, regeneration operations should be implemented where feasible."

Preservation of mires "in their entirety" does not only mean that reduction of the size of the protected area cannot be accepted; it also means that deterioration of the quality cannot be tolerated. Hence, to assess the effectiveness of conservation, monitoring should examine both the quantitative and the qualitative aspects of mire conservation.

We propose identifying an appropriate and representative set of reference sites that will be investigated with the necessary precision to arrive at conclusions applicable to all protected mire habitats.

A step-wise procedure is employed to comply with the targets set by the federal decrees (i.e. preservation of both quantity and quality of mires). This should both monitor the implementation of the regulations and measures by the cantons and determine their effects on the conservation of mire habitats (Fig. 1).

In Switzerland, there are 1500 bogs and fens scattered all over the country, covering about 20,000 ha in total (Table 1; Fig. 2; Grünig *et al.*, 1986; Broggi, 1990; Hintermann, 1992; Grünig, 1994; http://www.wsl.ch/land/inventory/mireprot/besmos/projekte/versuchsanordnung-en.ehtml). The aim of a national mire monitoring scheme is to obtain unbiased information on the site conditions on the whole surface of the peatlands under investigation. Therefore, a procedure providing meaningful (representative) and statistically verified information on any changes in area or quality is needed. But, the optimal monitoring design can only be selected when cost-efficiency is involved (Köhl *et al.*, 2000). Consequently, choosing a representative sample of sites is both a first and absolutely vital step for long-term monitoring. However, the selection of the mires must not be completely random. To ensure representativeness, the database of both the bog and fen survey had to be stratified according to various criteria:

- to give more weight to landscape types (i.e. biogeographic regions) with few mires;
- to give preference to mires at low and high altitudes over those at medium altitudes;
- to give raised bogs more weight than fen, which are twelve times as frequent (Tab. 1);
- to give preference to the few large mire areas over small ones, which are much more frequent.

The resulting sample of 124 representative mire sites, shown in Figure 2, will be surveyed at regular intervals to monitor possible changes in the mire habitats. In addition to developing an optimal sampling design on the national level, there was a need to identify appropriate indicators and methods to assess the quality of site conditions in the field.

HOW TO DETECT CHANGES IN MIRE HABITATS?

To find an answer to the question "Which method or which combination of methods is the most appropriate for describing mires and their changes in space and time?", it is necessary to focus on the reality of observing and measuring.

Both a survey of the literature and a study report suggest that a national monitoring scheme to detect even small changes in mire systems as early as possible is a very ambitious project that must be particularly sophisticated in the following objectives (Grünig, 1998):

- *definition of clear aims and targets;*
- selection of representative sites (biotopes, habitats) to allow inter-regional comparisons;
- selection of sensitive variables (i.e. indicators) and appropriate criteria of significance;
- choice of the methods which should be cheap and robust for both data gathering and data analysis;
- recording of raw data and to avoid the collection of derived or interpreted data;
- flexibility, so as to allow modification

In 1993, when the Advisory Service for Mire Conservation was commissioned to develop a nationwide mire monitoring strategy (Grünig *et al.*, 1996), an in-

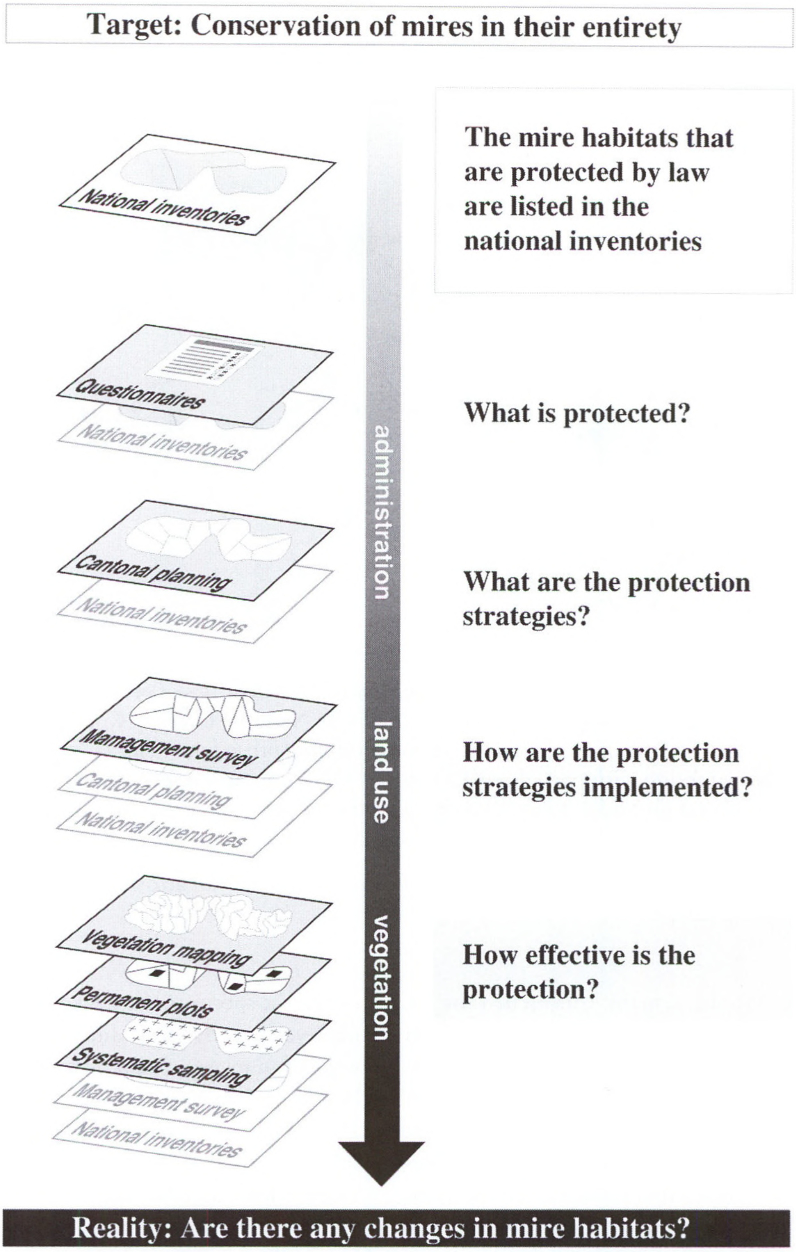

Fig. 1. Conservation of mires in their entirety (modified from Longatti 1994).

ternational co-operative project was started between the Universities of Vienna and Berne and the Swiss Federal Institute for Forest, Snow and Landscape Research. This project focussed on rehabilition of the Canton of Glaris's largest, most damaged and highly diverse bog complex, Gross Moos, covering almost 20 ha at an altitude of about 1250 m. Gross Moos is a sloping percolation mire, which was drained about 100 years ago and subsequently grazed heavily by cattle.

The data gathered during the baseline assessment for the Gross Moos rehabilitation study (Grünig & Steiner, 1994) proved to be very valuable for the evaluation of both the quantitative and qualitative aspect of the Swiss mire monitoring programme. Several indicators and methods - e.g. vegetation cover and its floristic composition, hydrology, the trophic status, remote sensing techniques, etc. - have been tested to assess both the qualitative and qualitative change of mire

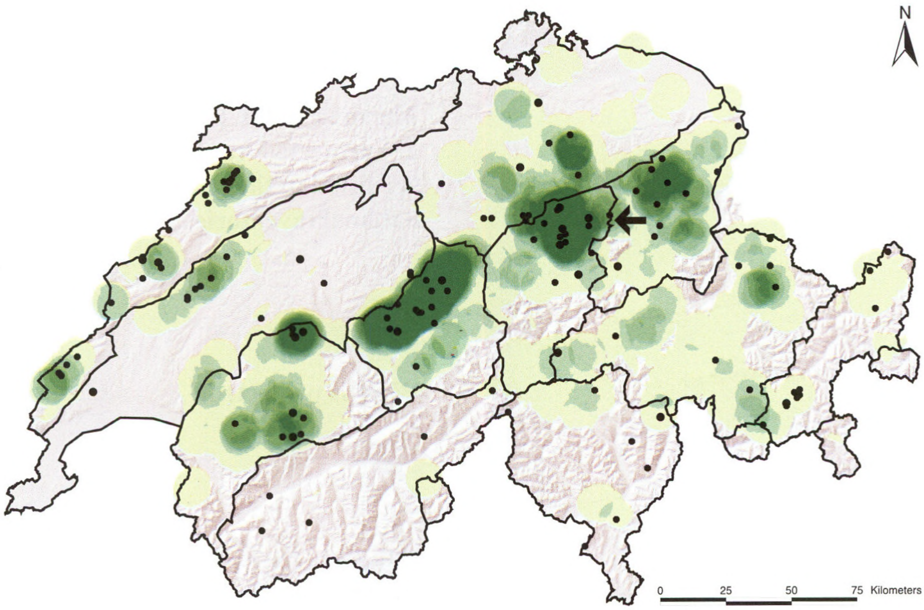

Fig. 2. Distribution of bogs and fens showing (by green colour) the densities of occurrence of mire habitats of national importance summarised by 1 km squares of the Swiss National Grid. 124 black dots mark the monitoring sites selected according to a stratified random sampling procedure. (The 1st 5 year cycle comprises 103 sites. To enable sampling with partial replacement in the 2nd 5 year cycle, an additional sample comprising 21 mire sites is set aside). to the 103 ordinary sites of the 1st 5 year cycle). Also shown are the individual bio-geographical mire regions of Switzerland.

The Case Study Area of Gross Moos in the canton of Glaris is located by an arrow and is not an element of the Swiss mire monitoring sample

habitats which should remain untouched or be returned to a state as natural as possible. As vegetation cover and especially its indicator values derived from floristic composition provide much useful information on the ecological conditions pertaining at a site (Hill *et al.*, 1999), hence on habitat quality too, it also enables monitoring of environmental changes. In addition, vegetation can be investigated rather easily at relatively low cost. Therefore, selecting vegetation as a key indicator is not only sound in scientific terms but is also an economical solution. This approach to mire monitoring fits very well into a long-term and nationwide monitoring concept.

Alternatives for Recording and Analysing Changes in Vegetation

Vegetation recording methods

Complete versus reduced plant species list

It is often argued that for monitoring, a reduced plant species list is optimal, as this can make it easier to recognize the species in the field and therefore reduces the observer bias between different surveyors recording vegetation relevés. Reduced field-work time is said to be another benefit of this method (Marti & Tschander, 1995) However, a test of a complete versus a reduced species (specifically without mosses) list carried out in Gross Moos in 1995 showed that the reduction of species results in a big shift of the distribution curve (see Fig. 3). The use of a reduced species list produces, not only in a change of both the mean and the shape of the distribution curve, but also in a considerable loss of information. In fact, this is not consistent with the general monitoring objectives claiming to collect whenever raw data.

Relevé size

It is well known that an increasing vegetation relevé size is correlated to some extent with increasing plant species numbers. The reason for this is that usually the site homogeneity of the vegetation plots decreases with increasing size, hence the diversity of microsites within

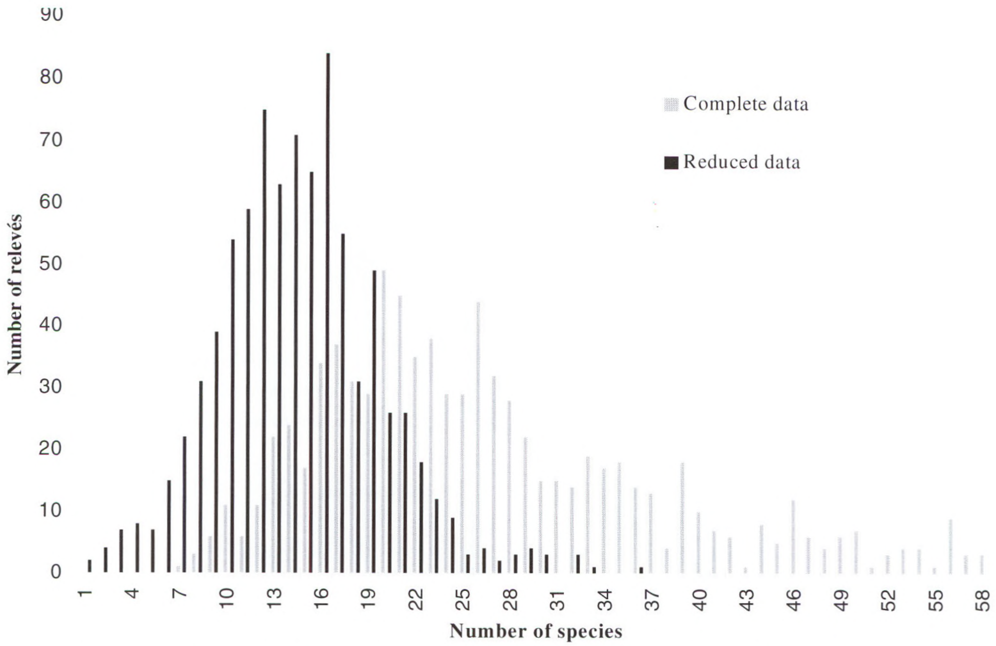

Fig. 3. Distribution histogram of 856 relevés of about 15 m² from Gross Moos with all species (grey) and a reduced species list (black).

the habitat may permit more species to occupy specialised microenvironments within the community (Harper, 1977). This hypothesis is also supported by the findings from a representative sample of 53 nested vegetation plots recorded in the open mire area of Gross Moos (Fig. 4; to locate the plots see the triangles in Fig. 12)

On the one hand, the findings from the nested plot data of Gross Moos support Dierssen (1982) who recommended 1 m² as being the most appropriate size to describe hummock-hollow complexes of raised bogs, but on the other hand, there is a discrepancy between the Gross Moos data and textbooks (e.g. Dierschke, 1994) that suggest an ideal plot size of 25 m² for recording fens and other wetland vegetation types. To overcome these problems, the use of spatial units of both variable size (of about 200 to 500 m²) and the greatest site homogeneity possible seems to be the appropriate method for both a reliable record of raw data sets in the field and a sensitive description of (mire) habitats and their plant species diversity. For the identification of such spatial units or homogenous habitat patches, high resolution aerial photographs can be a very useful tool (see Fig. 8).

Ecological indicator values

"The basis of indicator values is the realised ecological niche. Plants have a certain range of tolerance of temperature, light, soil pH, and so on. If we wish to make inferences about the ecological conditions pertaining at a site, much useful information can be obtained from the flora. Indeed, the flora may indicate quite a narrow range of conditions" (Hill *et al.*, 1999). Ecological indicator values represent the habitat conditions in which species occur under normal (natural or near natural) competition. In most cases, the values are estimates, prepared by well-trained vegetation ecologists in Germany (Ellenberg *et al.*, 1992), Switzerland (Landolt, 1977), and Great Britain (Hill *et al.*, 1999). The following values are available for Switzerland and Central Europe: nutrient, soil reaction, humidity, light, temperature and continentality; and only for Switzerland, humus and dispersity values (soil porosity). The Ellenberg-values for Central Europe are ranked into 9 classes (humidity into 12), the Landolt-values for Switzerland into 5 classes. The mean values together with their deviations are normally used for the characterization of a vegetation sample (plot, patch, spatial unit) or a habitat (see Fig. 11). For monitoring purposes, mean indicator values for vegetation samples are calculated at intervals over time, and changes are interpreted by reference to the indicator in question.

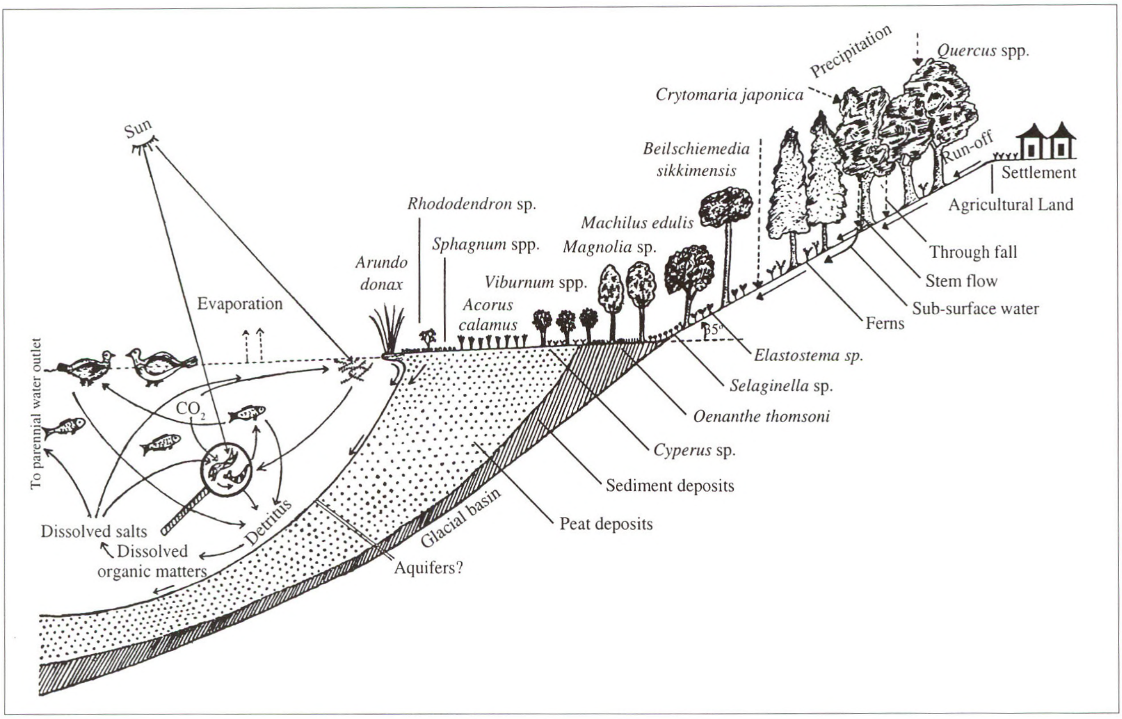

Fig. 4. Plant species diversity of Gross Moos recorded in a representative stratified random sample of 53 nested vegetation plots of 1 m² size and 100 m² size, respectively, in relation to the plant species diversity of 7 mire vegetation units. The vegetation units are arranged according to a trophic gradient ranging from very poor to quite rich site conditions.

The solid horizontal line in the box plots is located at the median of the species number data, and the upper and lower ends of the boxes are located at the upper quartile and lower quartile of the data, respectively. Hence, the box, i.e. the interquartile range (IQR) comprises 50% of the data and provides a useful criterion for identifying outliers. Any observation which is beyond the whiskers, i. e. more than 1.5 x IQR above the third quartile or below the first quartile is a suspected outlier marked by a horizontal line.

For example, increasing nutrient values are likely to indicate eutrophication.

Using indicator values is also quite an effective means to reduce problems stemming from the subjective observer bias inherent in each vegetation relevé. Another advantage of indicator values is that they may be more sensitive to the requirements of the plants than is a selected physical variable such as depth to the water table.

For special vegetation types (e.g. mire vegetation), it is possible to calibrate the indicator values using suitable reference data. Before the Swiss mire monitoring programme was launched in 1996, a reference data set of Austrian mires was available containing more than 4500 relevés (Steiner, 1992). The reference data enabled indicator values to be both based on particular combinations of species and tuned to specific project requirements.

Remote sensing methods

Aerial photographs

It is possible to document changes over longer periods by means of repeated aerial photographs since each one records a part of the terrain at a given time and is the medium providing the densest package of information available. The use of stereoscopic CIR (false-Colour InfraRed) aerial photographs is especially recommended for monitoring wetland vegetation (Devillez & De Sloover, 1978; Bierhals, 1988). The scale of the photographs has to be chosen with respect to the resolution demanded for the project.

To provide basic data on vegetation pattern and the spatial distribution of plant communities in the Gross Moos pilot study area (and in the Swiss mire monitoring sample at a later period), high resolution

CIR aerial photographs at a scale of 1:5000 were taken in 1994 (see Fig. 8). It is noteworthy, that in terms of image resolution even recent satellite images did not cope with the requirements of the Swiss mire monitoring programme.

A priori segmentation of aerial photographs

All land cover features have their signature on aerial photography. These signatures are defined by pattern, colour, structure, texture, and tone. By observing the context and extent of the photo signatures, e.g. peatland boundaries and other mire features, for example, vegetation types, forest edges, drainage ditches, etc., can be delineated by hand by a photo interpreter using a stereoscope to view the CIR stereo-paired diapositives. A possible outcome of such an *a priori* segementation is shown in Figure 8 (see the black outlines). Usually, when the work is done by an experienced and trained photo interpreter, most of the delineated spatial units reach certain homogeneity standards with respect to colour composition, structure, and texture (see Scherrer *et al.*, 1996, for details).

Analytical photogrammetry

Aerial photographs have a central perspective which means that they are more or less distorted towards the margin. Thus, analytical photogrammetry is needed for the geometrical reconstitution of both the terrain surface (e.g. by means of contour lines) and other features in the terrain and to provide basic data for further analysis with geographical information systems (GIS). A more recent method to get a geometrically correct model of the area under investigation is the production of orthophotographs using digital terrain models (DTM) and image processing methods.

Digital photogrammetry and image processing methods

At the beginning of the Swiss mire monitoring programme, several procedures for automated image segmentation (Woodcock & Harward, 1992) were tested but, too often the calculated patches did not comply with the vegetation pattern and the delineation quality needed for field work was not met. Swiss mire monitoring still relies, therefore, partly on traditional *a priori* delineation of aerial photographs although, automated image processing can be very useful for the analysis of *a priori* delineated orthophotographs. In order to assign patches to strata, similarities of colour, structure and texture are used to form a series of two or three dozen strata, which can be regarded to reflect distinct vegetation units. Thus the establishment of the strata is not founded on the occurrence of vegetation types or plant communities observed on the ground, but exclusively on attributes (e.g. colour composition, structure, texture) interpreted and/or assessed in aerial photographs.

The Gross Moos aerial photographs were scanned and digitized for the production of orthophotographs and these were analyzed by means of digital photogrammetry using a HELAVA DPW 770 station (see Küchler *et al.*, 2004, for details).

Sampling design

One-phase sampling designs

A traditional approach in vegetation monitoring is to rely on one-phase sampling designs and assess a set of systematically or non-systematically distributed sampling units and remeasure it on successive occasions. However, in long-term monitoring applications it has often been shown that cost-efficency can be improved by combining information gathered, for example, from remote sensing and field assessment. In the Gross Moos pilot study 3 one-phase sampling designs have been tested.

1. Systematic sampling of regular vegetation plots

In principle, vegetation surveys relying on systematic sampling (i.e. on systematically distributed sample plots) are strictly field-based assessments. In the office, the data recorded for a single plot are extrapolated to the area represented by the plot (i.e. the surrounding area and/or the surrounding plots) and used to produce e.g. pixel maps.

In the case of Gross Moos, two people and a theodolite (or a DGPS = differential Global Positioning System) were needed to establish about 300 sample points at given co-ordinates and at regular intervals of twenty metres. After two weeks of field work the result looked like Figure 5.

Afterwards, a trained vegetation scientist assessed vegetation relevés (of 15 m^2 size each) in the field at the 300 grid points to obtain the relevant information about the state of the vegetation. Together with the data processing, it took another 6 weeks to get a picture of the mire vegetation in Gross Moos. Using the data from this systematic sampling combined with the mean indicator values calculated from the species

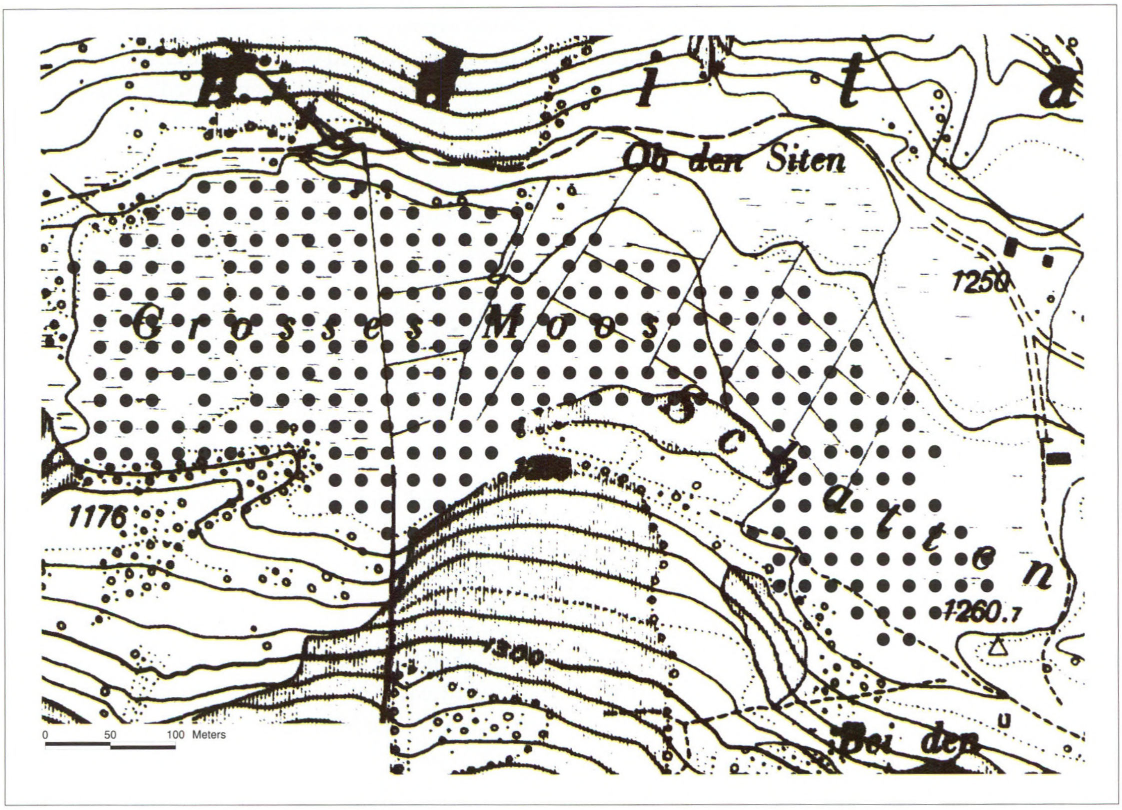

Fig. 5. Location of the 300 vegetation plots of the systematic survey on the Swiss Ordnance Survey map of the Gross Moos Case Study Area. Each plot has a size of 15 m²; the equidistance of the contour lines is 10 m. The missing grid points inside the mire boundary in Figure 5 and Figure 6, respectively, result from dense tree stands. The establishment of the grid points in these areas would have been difficult and too expensive for both a test and a regular survey.

recorded at the grid points, a variety of information can be garnered, e.g. the trophic status of the site can be derived using nutrient indicator values (Fig. 6).

Although, systematic surveys are said to be objective, they are in fact only authentic. This means that it is possible to reconstruct the geometric features of the grid and the plots later on, but many subjective decisions still have to be made. For example, the origin of the grid has to be chosen as well as the shape of its perimeter, its orientation and mesh-width. Comparable decisions on size, shape and orientation are needed to establish the plots. In addition, several studies have shown that vegetation recording on sample plots using area cover by species is prone to observer bias which cannot really be reduced by sample size (see Gertner & Köhl, 1992, for details).

Also, the grid density of systematic sampling designs has to be fairly large to give a realistic situation of the spatial distribution and frequency of vegetation types, species, and indicator values in the area under concern. Especially, the necessary sample size to detect sensitive and meanigful changes of spatial patterns should not be underestimated (Köhl *et al.*, 2000).

2. Complete vegetation record by means of mapping vegetation over normal CIR aerial photography enlargements

In order to draw a vegetation map by means of traditional field verification, an experienced phytosociologist (being also a peatland specialist) had to spend one week of field work in the Gross Moos Case Study Area. The vegetation patches were originally drawn by hand in the field over normal, i.e. unrectified, CIR aerial photography enlargements at a scale of about 1:2000. In order to reduce ambiguities of identifying individual vegetation units, a map key, especially developed for mapping mire vegetation, was used.

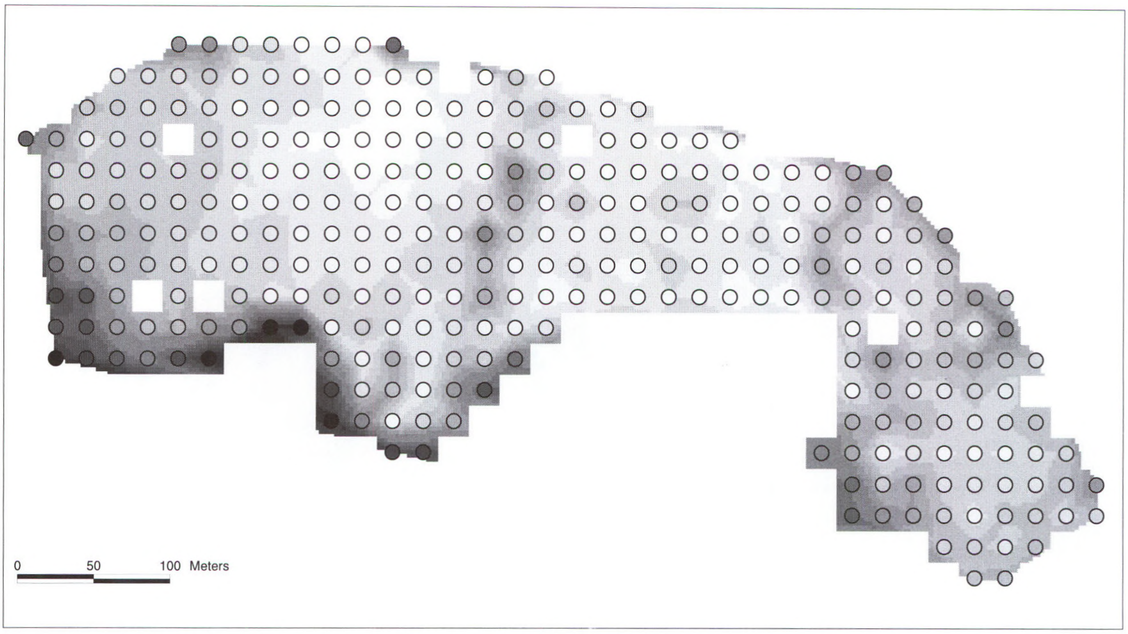

Fig. 6. Kriged distribution of soil fertility at the Gross Moos mire site in 1994. Soil fertility has been derived from 300 mean indicator values for nutrients (or nitrogen) which have been calculated from the vegetation data set presented in Figure5.

However, the lack of information on the third dimension, inherent in every normal (i.e. non-stereoscopic) aerial photograph, made it often very difficult to identify and delineate vegetation patches and to attribute them clearly to a vegetation unit directly in the field. This was especially true in cases where the vegetation cover did not seem to be homogeneous and clear boundaries between different vegetation types did not exist.

As a result of the inherent distortion, vegetation maps drawn on unrectified aerial photographs are geometrically inaccurate. Therefore, orthorectification was needed to transform the central projection of the aerial photograph into an orthogonal view and to produce the map shown in Figure 7 which can be used to make measurements and comparisons with other maps or (ortho-) photographs that have the geometric properties of a map.

Another problem arises from the fact that a traditional vegetation map based on a phytosociological map key contains no real raw data about the species composition of the described units but only interpreted data with an unknown inherent bias. Therefore, the detection of both floristic and vegetation changes will be very difficult, even when they seem to be significant. To overcome this problem it is better to use the (preliminary) units of this vegetation map e.g. as the basis for both an improved stratified random sampling and the preparation of a map key enforcing the mapper into establishing a consistent definition of what the operator has to portray. This procedure was applied in 1994 using vegetation relevés made at the locations marked by black dots in Figure 7. Some of the resulting vegetation units are shown in Table 3.

3. Complete vegetation record based on stereoscopically pre-delineated CIR aerial photographs

In the case of Gross Moos with its complex mire vegetation pattern covering an area of 20 ha, the analysis of the aerial photographs was carried out in two and a half days by an experienced photo-interpreter using a stereoscope to view the CIR stereo-paired diapositives. The delineations of the vegetation boundaries represent about 1000 vegetation patches which are homogenous in terms of photo signature, i.e. colour, structure and texture on the photograph (see the black outlines in Fig. 8 and Fig. 10, respectively).

With this interpreted orthophotograph in hand, a skilled vegetation-scientist assessed in 1994 traditional

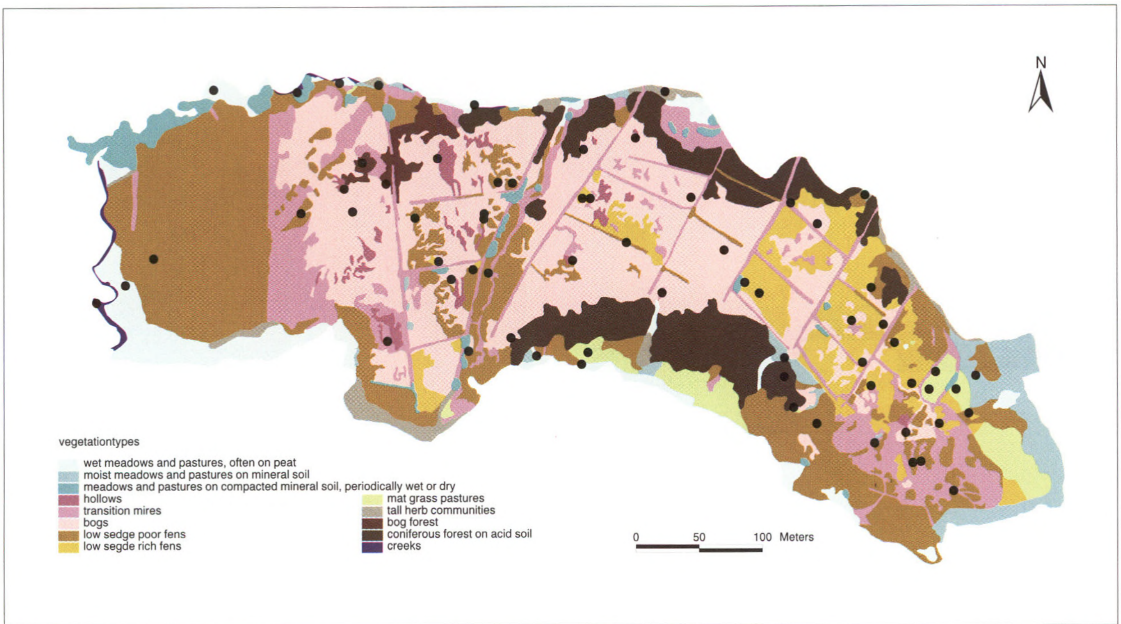

Fig. 7. Overlay of stratified random sampling plots (localised by black dots) from 1994 and the vegetation pattern of Gross Moos mapped in 1993 by a trained phytosociologist using unrectified CIR aerial photography enlargements at a scale of about 1:2000.

Braun-Blanquet vegetation relevés within each delineated surface or patch. The aim was to get as complete a list of the species as possible, including the mosses. The abundance was estimated by a logarithmic scale. The data were processed by means of multivariate statistics. An outcome received after 12 weeks of work is a quite fine-scale vegetation map as shown in Figure 9.

Based on this exhaustive dataset, it is possible to produce distribution maps of individual species or to calculate the potential for a certain species to occur in a given patch. The results of the two processes can be combined (see Fig.10 and Küchler, 2004, for details).

It is also possible to calculate an average indicator value for each vegetation relevé or patch from these data and, thus, a rather detailed map of the trophic status of the Gross Moos can be derived (Fig. 11).

Compared, for example, with a vegetation survey based on systematic sampling (see Fig. 6), the complete vegetation record method using delineated aerial photographs provides, for roughly double the cost, a much more realistic picture of the spatial distribution of, for example, soil fertility in the whole Gross Moos Case Study Area. However, in a mire such as Gross Moos, a site that contains at least 1000 different vegetation patches, the effort to assess the vegetation of the whole area in detail is very great (and expensive). Therefore, there is an evident and urgent need to overcome this temporal and financial bottleneck by more resilient sampling design.

Two-phase sampling designs (Stratified random sampling)

As a financially more realistic alternative, there are two-phase sampling designs using image-processing methods based on orthophotographs combined with ground truthing on a limited number of ecologically homogenous vegetation patches. Principally, two-phase sampling designs rely on both

1) the stratified (hence representative) and reliable selection of the sample units providing a statistically sound raw data-base from the survey, and
2) the combination of data of different resolution and quality gathered from different resource, e.g. digital terrain models, remote sensing technique, field assessment, interpreted or derived data, etc.

Fig. 8. Rectified CIR aerial photograph of the Gross Moos area taken in 1994 at a scale 1:5000. The black outlines confine about 1000 spatial units reflecting homogenous vegetation patches which have been delineated a priori *in the aerial photograph by a photo-interpreter using a stereoscope. In each of the 1000 patches a vegetation relevé was recorded in 1995 and 1996, respectively.*

The yellow outlines confine a sample consisting of 167 spatial units which have been selected representatively for prediction. A soil fertility map of the entire Gross Moos area resulting from such a prediction is shown in Fig. 13

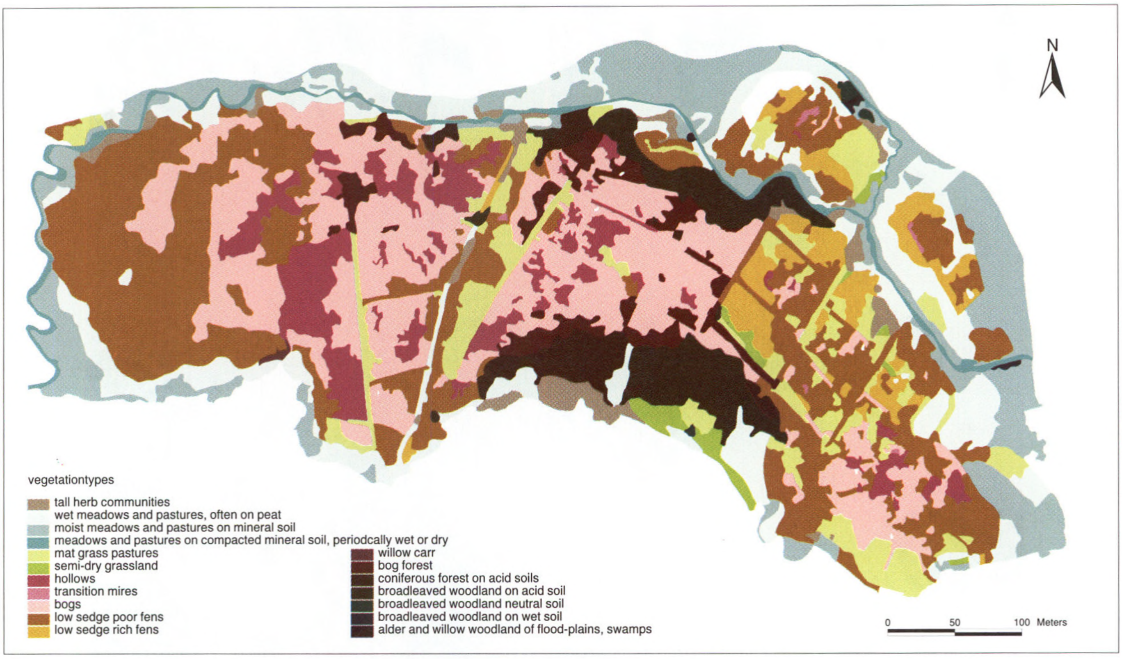

Fig. 9. Vegetation units of Gross Moos derived from both 1000 delineated spatial units and the relevant complete vegetation data set recorded in 1995 and 1996, respectively

This is in contrast to one-phase sampling designs which do not rely on stratified sampling approaches.

The principle of stratification is that before the sampling points are selected, the population or the area under study is divided up into groups or strata on the basis of major and usually obvious features and traits including their variations. Thus, the resulting strata are more or less homogeneous in relation to the criteria in question. In each stratum the sampling points are distributed randomly.

Fig. 10. Distribution of Primula farinosa *in Gross Moos showing both the recorded occurrence of the species (black dots) and their predicted distribution (gray shading) as derived from the complete vegetation data base. Comparison with Figure 9 and Figure 11, respectively, reveals that* Primula farinosa *and its predicted distribution pattern are fairly good indicators for low sedge rich fens*

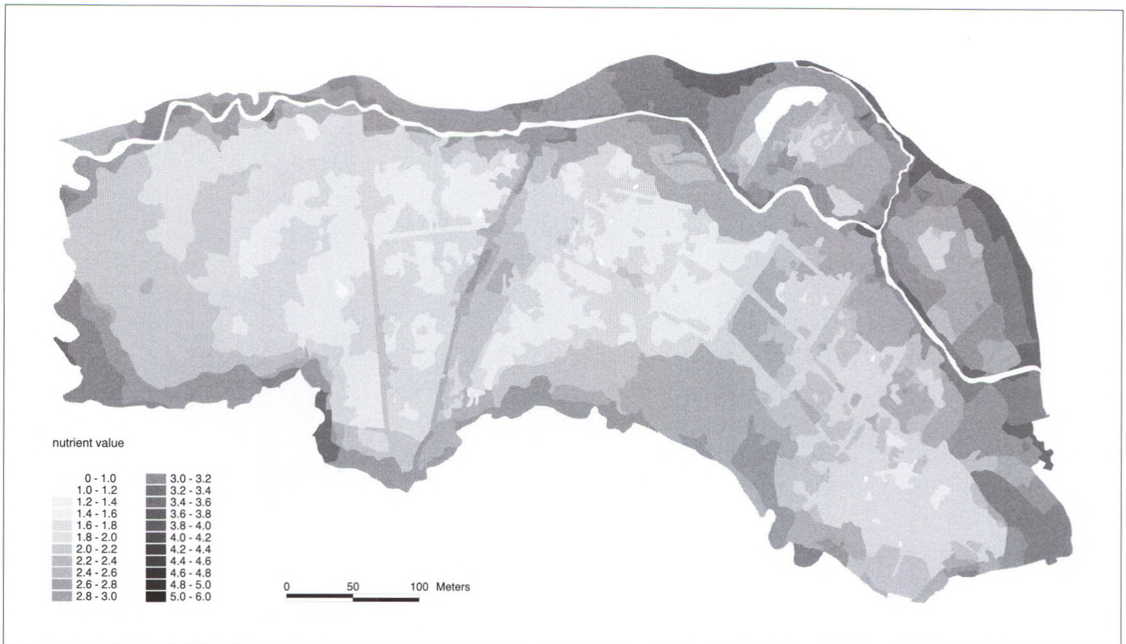

Fig. 11. Soil fertility or trophic status of the Gross Moos area derived from a combination of 1000 delineated spatial units and the mean nitrogen indicator value calculated from the respective vegetation relevé

In the case of Gross Moos, two different stratification criteria have been used to test two-phase sampling approaches:

1. Selection of a representative set of sampling locations by means of stratification according to topography and geomorphology

To define strata based on topography and geomorphology, patches with similar altitude, inclination and exposition derived from the DTM were overlayed onto a sketch map showing the peatland boundaries and drainage ditches of the Gross Moos area (see Fig. 12). Based on these geomorphological and topographical strata, sampling points have been derived from stratified random sampling. For a preliminary survey, the vegetation was recorded in 1993 and 1994 at the given sampling points in nested plots (cf. Wildi & Krüsi, 1992) of 1 m² and 100 m², respectively, and classified using TWINSPAN (Hill, 1979), MULVA-5 (Wildi, 1993), and VEGEDAZ (Küchler, 2004). Results are shown in Table 3, Figure 4 and Figure 12, respectively. Preliminary maps derived from this approach can be used as additional information for the next approach.

2. Selection of a representative set of sampling locations by means of stratification in combination with traditional aerial photograph interpretation, remotely sensed data, and digital surface models

The idea underlying this sampling approach is simple: "What looks similar on an aerial photograph is assumed to be similar in nature, too." (Küchler *et al.*, 2004). By relying on both different homogenous patches showing similar colour composition on the aerial photograph, and field inspection, therefore proving that these patches have more or less the same vegetation cover, it is very possible to make predictions about the distribution of different vegetation types within the site under consideration. It is also feasible to gain additional ecological information about the whole site by extrapolation from the vegetation data recorded from selected patches in the field.

To reduce costs, a stratification supported by both traditional interpretation of aerial photographs and image processing methods is applied to sample randomly a limited but representative number of patches for vegetation recording. The performance of several selection procedures and prediction methods as well as combinations of them was tested using the vegetation and terrain (DTM) data of the Gross Moos pilot study. In many cases, the variation of most site factors could

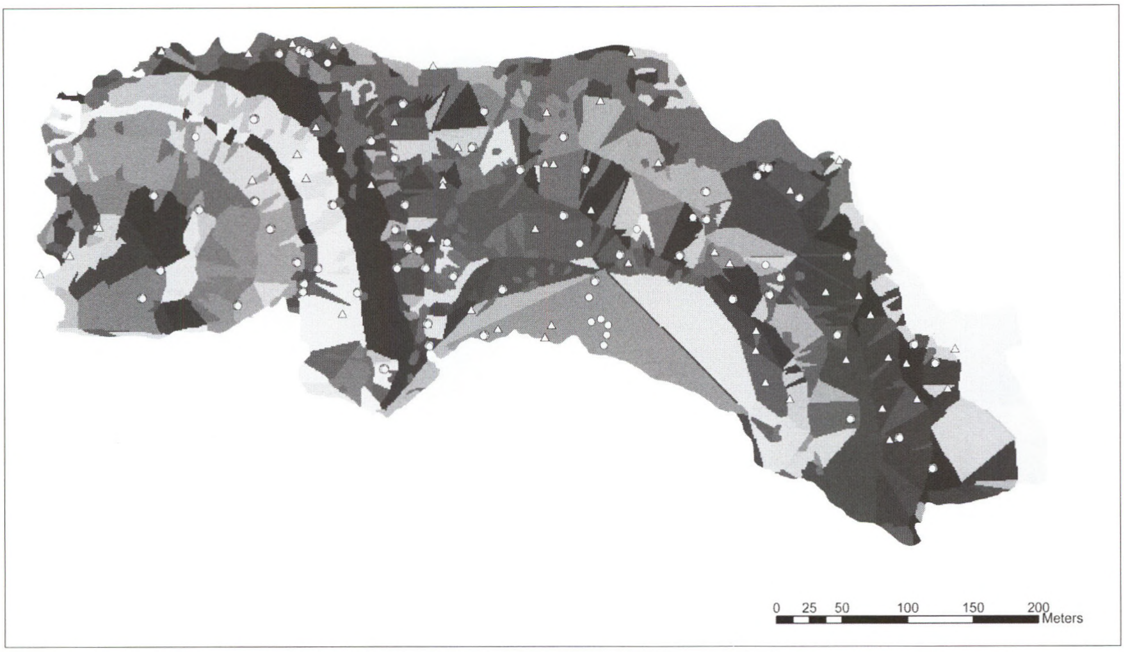

Fig. 12. Topographical strata derived from the Digital Terrain Model (DTM) of Gross Moos area overlaid with stratified random vegetation sampling plots from 1993 (marked with triangels) and 1994 (marked with circles), respectively

be explained satisfactorily by 100 to 200 vegetation relevés (see Küchler *et al.*, 2004, for details).

In order to give an idea of the method's performance, Figure 13 shows the pattern of soil fertility in the Gross Moos pilot study area, predicted as mean nitrogen values on the basis of a sample of 167 vegetation relevés, which stand for 167 spatial units selected both representatively and randomly of a population exceeding 1000 individual vegetation patches (see Fig. 8 and 10, respectively, black and yellow outlines). A comparison with Figure 11 reveals that the two maps have a quite similar pattern reflecting quite well the main features of Gross Moos. For example, on either map there are more or less infertile bog centres, usually surrounded by vegetation types indicating sites ranging from intermediate fertility to richly fertile. The huge drainage ditches are displayed, too, as well as a small stream winding from South to Northeast and separating hydrologically the Western part of the Gross Moos mire complex from its Central and Eastern parts. However, a closer inspection of details reveals differences between predicted and observed fertility. According to the limited data set, for instance all ditches are predicted to be nutrient-rich (Fig. 13), whereas, according to all observed data, some of them in reality are not (Fig. 11).

Concernig cost-efficiency of different methods and alternatives, the total cost of obtaining aerial photographs, aerial photo interpretation, and amortization of the technical equipment as well as the field assessment has to be considered. The present method relying on stratified two-phase sampling, remote sensing, and recording 167 vegetation relevés in the field, provides, for roughly both half the cost of systematic sampling (see Fig. 6) and a quarter the cost of a complete vegetation record (see Fig. 9 and 11, respectively), a reasonably realistic picture of the site qualities and their spatial distribution in the whole Gross Moos Case Study Area. Similar tests in other mire sites led also to a considerable increase in efficiency, especially for extensive mire sites. This is evidence that the costs of a monitoring programme can be reduced substantially using stratified random sampling in combination with sophisticated remote sensing technique and reliable ground verification focused on recording unbiased raw data (i.e. complete vegetation relevés).

CONCLUSIONS FOR APPLICATION TO THE !ST CYCLE OF SWISS MIRE MONITORING

Experience from both Gross Moos pilot study and other studies has shown that two-phase stratified random sampling designs combining remotely sensed

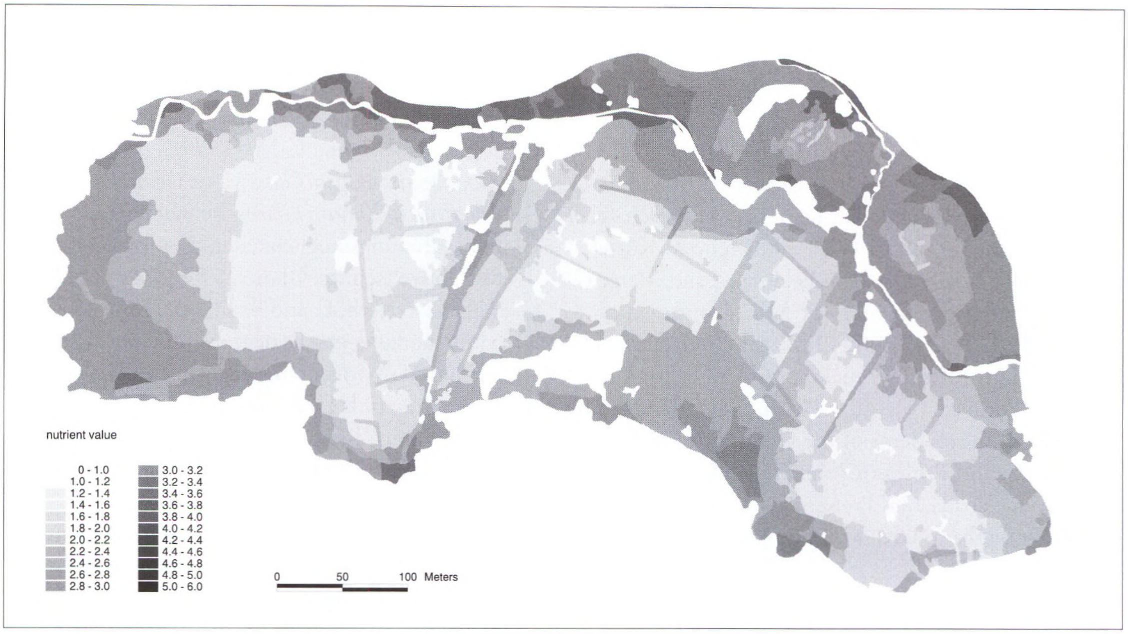

Fig. 13. Predicting soil fertility of the Gross Moos area based on mean nitrogen indicator values derived from a sample comprising 167 vegetation relevés and spatial units, respectively (see the yellow outlines in Fig. 8, for localisation). The sample has been selected both representatively and randomly in combination with traditional aerial photo interpretation, remotely sensed data, and digital surface models. Prediction is mainly due to both spectral and topographical similarities among the sample set and the 1000 delineated spatial units.

Blank polygons stand for spatial units "where the corresponding predicted nutrient values have been filtered out because they are extreme with respect to the range of the calibration data. The polygons affected mostly represent forest where the ground is completely hidden" (Küchler et al., *2004).*

data, digital surface models, and traditional interpretation of aerial photographs with selected ground truthing, i.e. recording a limited number of vegetation relevés, are most likely to be superior in terms of cost-efficency (Köhl *et al.*, 2000). Taking into account other side-effects of aerial photographs such as the documentation of a historical situation, providing a piece of evidence for later investigations, and allowing retrospective analysis at a later date, the superiority of two-phase approaches is even more evident.

Although further verification in the field was very satisfactory, we realised that the methodology has not yet been fully elaborated and further research was necessary (see Küchler *et al.*, 2004, for details).

However, based on all this evidence, the initial questions "How is it possible to get precise information from vague estimates?" and "Which is the most efficient method to detect changes in space and time?" could be answered quite satisfactorily, and in 1996, the Swiss mire monitoring programme was initiated at WSL in partnership with the Swiss Agency for the Environment, Forest and Landscape.

To provide valid data for the whole country, a stratified random sample has been drawn from the mires listed in both federal bog and fen inventories. The resulting sample comprises 103 mire sites (see Fig. 2.) These 103 mire sites have been assessed during the first 5 year cycle of the Swiss mire monitoring scheme which was launched in 1998 and finished in 2002. The field work essentially consisted of listing as fully as possible all the vascular plants and mosses occuring within each of the 20,000 homogeneous patches selected in the 103 mire sites. The cover of each species was estimated on a rough logarithmic scale. Together with the aerial ortho-photographs, the terrestrial data form a sound baseline databank which will allow, after an ongoing second 5 year cycle of monitoring and recording, to detect quantitative and qualitative changes of the mire resource in Switzerland.

There is a homepage on the internet that provides further outcomes in detail from every mire site which has been investigated: http://www.wsl.ch/land/inventory/mireprot/besmos/projekte/ersterhebung-de.ehtml

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KIRITAPPU MIRE IN EASTERN HOKKAIDO, JAPAN - A REVIEW OF ITS DEVELOPMENT, HYDROLOGY AND VEGETATION

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SUMMARY

Mire ecosystems can only be understood sufficiently if their development process, current environmental conditions and vegetation are considered together. A review is presented of the data available on stratigraphy, hydrology and vegetation of Kiritappu Mire in eastern Hokkaido, Japan together with discussion of the influence of past and present environmental factors on vegetation patterns. Kiritappu Mire, which is located in a low-lying basin exposed to the Pacific Ocean, developed after the Holocene transgression had crossed its peak ca. 5000 years BP. Since peat formation started, several tsunamis (earthquake-induced giant oceanic waves) have affected different parts of the mire to a different degree, and at least five layers of tephra (aerially transported volcanic ejecta) have been deposited. Minor sea-level oscillations may have influenced parts of the mire. Some observations suggest that there is groundwater flow in the mire affecting water levels and water chemistry, but central areas are probably supplied mainly by atmospheric water. Lower reaches of the rivers in the mire are brackish and show tidal water level changes. Ionic composition of groundwater at some sites is influenced by seawater. Different plant communities occur, ranging from submerged aquatic to upland types and from brackish water to partly ombrotrophic ones. The distinct hummock and hollow microtopography adds to the environmental diversity of some communities. In some cases the distribution of vegetation types is related to events or processes in the past but in others current conditions seem to be more important. Sites with different stratigraphy can support the same plant communities.

Keywords: Coastal mire, stratigraphy, hydrology, vegetation, Eastern Hokkaido

INTRODUCTION

Kiritappu Mire is one of the largest remaining natural wetlands in Japan. Owing to harsh climatic conditions it was unsuitable for agricultural development that has destroyed most of the mires in warmer parts of Japan. It is, however, not untouched and, for example, a road cuts through the centre of the mire and marginal areas in the east and west have been reclaimed for pasture, housing, seaweed-drying lots and small-scale vegetable production. It is only in the north and south that large areas are still in a natural state. A review of the information on its stratigraphy, hydrology and vegetation has never been published before, although its value for nature conservation and research was recognized as long ago as the 1920s, and it has been intensively studied since its designation as a wetland of international importance under the Ramsar Convention in 1993.

Kiritappu Mire is located in the town of Hamanaka, Kushiro District, in the eastern part of Hokkaido, Japan, at 43°05' N and 145°06' E. It covers the bottom of a flat coastal basin that is delimited by the Pacific Ocean to the east and wooded hills, that reach up to 70 m above sea level, to the north, west and south (Fig. 1). The mire stretches about 9 km from north to south and 3-4 km from east to west; its total area is about 30 to 40 km^2, depending on the source cited (Tanaka, 1959, Fujita *et al.,* 1997). The elevation of the mire surface ranges from 8 m a.s.l. in the northwest to ca. 0.5 m a.s.l. in the southeast, but most of it lies between 1 and 3 m a.s.l. In the northern half there is a distinct pattern of ridges separated by slightly lower basins that run parallel to the shoreline. In the south, there are also areas, which are elevated above the surrounding land with a slightly sloping mire surface, but these are not arranged in parallel rows as in the north.

The courses of the five rivers that run through the mire follow the general topography: Shinkawa River and Dorogawa River in the north are parallel to the shoreline, Biwasegawa River, Nibangawa River and Ichibangawa River in the south flow into a common estuary from three different directions. Their total catchment area is comparatively small and is only about twice that of the mire itself. There are about 30 shallow ponds of different size and shape, mostly in the northern half of the mire. Many of these are elongated and situated in rows parallel to Shinkawa and Dorogawa Rivers.

The geological formations of Kiritappu and its surroundings belong mainly to the Upper Cretaceous and consist of sandstone, shale, mudstone, conglomerate, tuff and, in some layers, quartz intrusions (Nagao *et al.*, 1966). These rocks are called the "Nemuro Group" and are widely distributed in eastern Hokkaido. Comparatively small areas are covered by Tertiary (Tenneru formation of the Oligocene) or Quaternary deposits. The latter are found in river flood plains and along the coast (sand, gravel, clay, beach sand and peat) as well as on the Cretaceous terraces (sand and "mud" probably of volcanic origin). Most of the Quaternary deposits have been eroded from the terraces.

Eastern Hokkaido is the coldest lowland region in Japan and belongs to the cool temperate zone (Maejima, 1980). In the biogeoclimatic classification of Kojima (1979), locations below 100 m a.s.l. belong to the nemoral *Acer mono* zone, whereas those between 100 m and 700 m a.s.l. are in the montane *Abies sachalinensis* zone. The vegetation around Kiritappu Mire seems to have more in common with the latter. The mean annual air temperature at Sakakimachi at the northern tip of Kiritappu Mire is 5.0°C, the coldest month is January with a mean of -6.9°C, while the warmest is August with 16.9°C. Precipitation is about 954 mm yr^{-1}, most of which falls between June and October (Sapporo Kanku Kishodai, 1993). Snowfall is low compared to the western side of Hokkaido but freezing of soil water has been observed to a depth of 40 cm in Kiritappu Mire (Miyazaki, 1995). Ice was found between 10 and 20 cm depth until mid-June during stratigraphical investigations in 1996. Sea fog occurs frequently in the summer months causing relatively low temperatures and high humidity. There are no detailed records of fog frequency and duration for Kiritappu, but an average of about 100 days with fog during the summer months are said to be normal.

Scientific investigations of Kiritappu Mire started in the 1920s when the first description of its vegetation was provided by Yoshii & Kudo (1926). At that time the first stratigraphical data were also collected under the survey program of the Hokkaido Agricultural Experiment Station, but they were not published until more than 40 years later (Iizuka & Seo, 1966). Another early account of the vegetation was published by Miyoshi (1938). From the 1950s on, reports on the vegetation, topography and development process were prepared by Tanaka (1956, 1957, 1959, 1976), followed by reports on geological, floristic and faunistic as well as historical aspects (Kushiro City Museum, 1982; Tsujii *et al.* 1986; Fujita, 1992). The

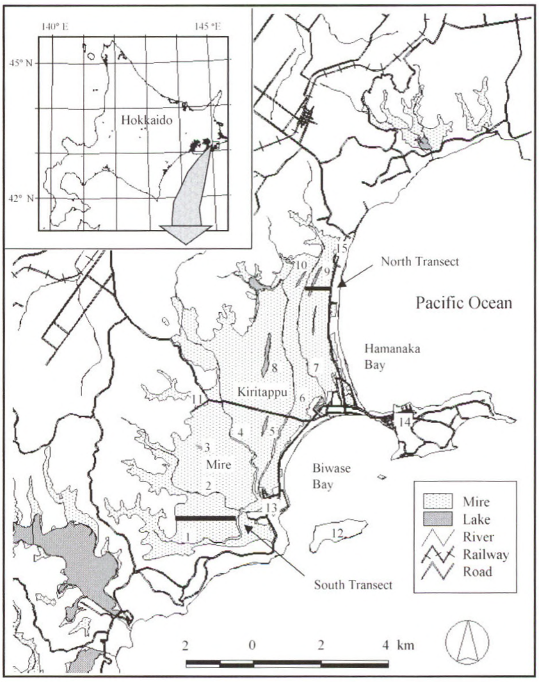

Fig. 1. Map of Kiritappu Mire. Small insertion map: Location of Kiritappu Mire

1 Ichibangawa River 2 Nibangawa River 3 Biwasegawa River 4 Koorikiri-numa Pond 5 Dorogawa River 6 Shinkawa River 7 Junsai-numa Pond 8 Wakayama-numa Pond 9 Naganuma Pond 10 Kiritappu Mire Centre 11 Kenbokki Island 12 Biwase Village 13 Kiritappu Village 14 Sakakimachi Village

(original map by Hokkaido Institute of Environmental Science)

administration of the town of Hamanaka, in which Kiritappu Mire is located, has been supporting scientific research on the mire since 1994 and, as a result, a number of papers on different aspects of the mire have been prepared every year by different working groups and individual scientists (*e.g.* Tachibana *et al.*, 1997).

FORMATION OF THE GEOGRAPHICAL SETTING

The lowland in which Kiritappu Mire is located was formed as a result of erosion of the marine terraces that make up the surrounding uplands. Sea-level changes during the Pleistocene and Holocene have greatly contributed to this process. Ancient shorelines of the last interglacial (120,000 years BP) can be found at 30 m a.s.l. on the sides of hills adjacent to Kiritappu mire (Okumura, 1996). River valleys can be traced out into Hamanaka and Biwase Bays, indicating fluvial erosion during periods of lower sea-levels. The cliffs along the coastline consist of comparatively soft rocks (Okazaki, 1982). Erosion progresses quickly at an estimated speed of 0.6 m yr^{-1} . The islands of Kiritappu and Kenbokki (see Fig. 1) were still connected with the mainland during the last (Ulm) ice age about 20,000 years BP when the sea-level was 55 - 60 m lower than at present and the shoreline was located up to 11 km further east. The sea-level rose again after this period, causing the Jomon transgression. When this transgression reached its peak about 6,000 – 5,000 years BP, the floor of the basin was inundated by seawater. The softer rocks of the coastal terraces were subsequently eroded and Biwase Bay was opened, giving the landscape its present appearance.

MIRE DEVELOPMENT

The first comments on mire development at Kiritappu can be found in a report on natural monuments of the Japanese Ministry of Education (Yoshii & Kudo, 1926) that provides a description of the microtopography and a distribution map of substrate types including sand, fen peat, transition mire peat, transition mire peat

Table 1. Frequency of deposit types1 in cores from Kiritappu Mire

Deposit type	Number of samples	% of all samples
Sand	313	46.9
Tephra	81	12.1
Clay/silt	14	2.1
Silt	3	0.5
Sedge peat	109	16.3
Moss-sedge/moss-reed peat	97	14.5
Moliniopsis/Poaceae peat	21	3.2
Sphagnum peat	10	1.5
Fern peat	6	0.9
Polytrichum peat	4	0.6
Eriophorum peat	3	0.5
Myrica peat	3	0.5
Wood peat	2	0.3
Dicranum peat	1	0.1
Total	667	100

[1] Samples with less than 70% ash content were classified as peat, those with more than 70% ash content as mineral. However, if mineral particles were dominant during the visual investigation with a stereomicroscope, samples with ash contents between 60% and 70% were included in the "mineral" group.

covered by sand and bog peat. The importance of climatic conditions for the genesis of *Sphagnum* hummocks, namely the occurrence of fog during the summer, was stressed.

Six cores were taken at Kiritappu Mire between 1921 and 1923 as part of the soil survey program of the Hokkaido Agricultural Experiment Station but the results were not published until more than fourty years later (Iizuka & Seo, 1966). The map based upon this study indicates fen peat, transition mire peat and bog peat, although the distribution of these differs slightly from that given by Yoshii & Kudo (1926). The profile descriptions of the six sites that were studied included depth, classification of a layer as bog peat (four samples at three sites), transition mire peat (three samples at two sites), fen peat or (22 samples from six sites) "sandy soil" (20 samples at six sites), colour and an indication of main macrofossils, the occurrence of tephra (ten samples at six sites) and an estimate of the degree of decomposition. The "sandy soil" layers in most cases were identified as tephra, but sometimes information on their origin was not given. The maximum number of tephra layers in one core was four. The macrofossils distinguished comprised "peatmoss", "reed", "sedge" (sometimes given in more detail as *Eriophorum vaginatum*, *E. gracile*, *Carex lasiocarpa*(?), *Carex augustinowiczi*), "wood" and "horsetail". All peat layers comprising *Sphagnum* remains were classified as "bog peat". They were confined to the upper 12 - 15 cm in two cores but an additional "bog peat" layer was located between 33 and 84 cm in the third one. This was overlain by a grey, sandy, soil layer on which a fen peat layer was evident. Tephra was deposited on top of this fen peat. The surface bog peat layer had accumulated directly on top of this tephra. The depth of the profiles ranged from 72 to 144 cm; the base of five of the six cores was a "sandy soil" layer, one core did not reach a basal mineral layer.

The next papers containing information on the development of Kiritappu Mire were by Tanaka (1956, 1957, 1959). Tanaka detected nine sand bars stretching from the northern end of the basin southward to its centre and he claimed that these elevated ridges were formed as the sea retreated from the basin, and that elongated lagoons were left between them that became large ponds when the connection to the sea was interrupted. These ponds were divided subsequently into several smaller ones as a result of terrestrialization and, in some cases, these have been completely overgrown by vegetation. By comparing the map of Yoshii and Kudo (1926) with aerial photographs taken in 1947 he concluded that the terrestrialization process, which involved the growth of floating vegetation mats, must have been very fast. According to his own map, the loss of open water area amounted to ca. 50% in 25 years, although the largest of the remaining ponds were up to 450 m long and 60 m wide. Tanaka remarked upon the difference in appearance of the shore of large and small ponds. The former, in general, had steep banks whereas in the latter floating vegetation mats occupied the zone between shore and open water. He speculated that waves were generated in large ponds but not in small ones during strong winds. He observed also that large ponds have mostly sandy bottoms, whereas small ones usually have layers of fine organic sediment on top of a sand layer. Tanaka (1959) also pointed out the influence of grazing and trampling, caused by about 20 horses that were allowed to move around freely in an area along the coast between Sakakimachi and Kiritappu, preventing peat from accumulating.

Okazaki (1982) also mentioned the elevated ridges, but he recognized eight, two of which were forked at their southern ends. These ridges were generally higher than 2.5 m a.s.l., whereas the depressions between them were lower than 2.5 m a.s.l. He interpreted the ridges as rows of "sand dunes", which originated from beach ridges and were later transformed into "dunes". Thus, they indicate the location of the former shoreline, which moved from the western margin of the basin towards the current shoreline in the course of the sea-level fall that took place after the postglacial maximum. The width of the ridges is generally about 320 m but, in some places, is up to 550 m. Eight ponds and streams occurred in lines between the ridges but the one closest to the shore has been filled in for land reclamation purposes. Since a similar pattern is not found in the southern half of the mire it has been concluded that the ridges and depressions must have been buried by peat. According to Okazaki conditions for peat formation were created by subsidence after the sea retreated from the basin, a phenonomenon that was more pronounced in the south than in the north. The depressions would have been filled in first, after which the ridges would also have been covered by peat. Okazaki also provided the first estimates of the time scales over which these changes have taken place. He cites Yoshii and Kudo (1926) who reported maximum peat depths of 2.6 m (in fact they do not give any information on the thickness of the peat layer, so the original source of this value is not clear) and infers that peat formation must have started 2,000 – 3,000 years BP (obviously assuming a mean peat accumulation rate of 1 mm yr^{-1}).

The first systematic stratigraphical investigation, including measurement of ground heights and macrofossil analysis, was carried out more recently (Hotes, 1998; Hotes *et al.*, 2001) along two transects. The southern transect spanned 1700 m from the break of slope at the western mire margin to the confluence of the Ichibangawa and Nibangawa Rivers through an area that has not been altered by human activities. The northern transect (760 m long) cut through the site of an unsuccessful reclamation attempt made in the 1970s around the Junsai-numa pond (Fig. 1).

A total of 31 cores were obtained using two types of peat samplers (a "Russian type" peat sampler and a "Hiller type" peat sampler, respectively) after monoliths of the upper 30 cm were cut out with a spade. The core length varied between 30 cm and 230 cm. Twenty cores were taken along the southern transect and 11 at the northern one. A total of 667 samples was investigated for ash content and macrofossils in the laboratory. Five representative cores and an overview of peat and sediment types are given in Figure 2 and Table 1, respectively. From this study it became clear that there are several mineral layers of non-volcanic origin in addition to the previously described tephra layers. These deposits have been paid more attention over recent years (Nanayama *et al.*, 1999, 2000; Nishimura *et al.*, 2000) and it is now widely accepted that they were brought into the mire by tsunamis. Influence of long-term sea-level changes may, however, also play a role at least in the lowest parts of the mire, as Sawai and Kashima (1996) have postulated a minor marine transgression for 1,000 years BP at Bekanbeushi Mire 30 km west of Kiritappu Mire. The presence of salt crystals on dried peat samples of most cores confirms that sea water has covered much of the mire in the past. A preliminary investigation of subfossil diatoms in one core from the transect between Ichibangawa and Nibangawa showed that limnic and marine taxa were mixed, suggesting that there were alternate phases of freshwater and saltwater influence. The tephra layers in Kiritappu Mire peat were investigated by Nanayama *et al.* (2000) whose results are reproduced in Table 2.

Vegetation changes following tephra deposition have been reported by several authors (*e.g.* Tokito, 1915, Lees & Neall, 1993, Giles *et al.*, 1999) and vegetation shifts following tsunami impact (Minoura *et al.*, 1996, Clague & Bobrowsky, 1999, Nanayama *et al.*, 1999, 2000) have also been found. The macrofossil analysis carried out by the author, however, did not reveal a deterministic pattern of vegetation changes after mineral deposition in Kiritappu Mire. A total of 88 changes in macrofossil composition were detected in 31 cores, 33 of which occurred at mineral layers. The remaining 55 peat composition changes were not related to mineral deposition. In 39 cases, there was no distinct shift of peat composition although mineral deposition had taken place. The presence of remains of mosses (Sphagna acutifolia and cymbifolia, *Aulacomnium palustre*, *Polytrichum juniperinum* var. *strictum*) in addition to sedge, reed and fern macrofossils down to the basal peat deposits suggests that the peat forming vegetation has stayed the same since mire development began. This is a matrix of sedges and reeds interspersed with patches dominated by *Sphagnum*/dwarf shrub communities (dryer, more acid, nutrient-poorer sites?), with belts of alder forest along the margins and on parts of the mire expanse (wetter, less acid, nutrient-richer sites?).

The speed of terrestrialization that was reported by Tanaka (1959) could not be confirmed in this study. None of the ponds seems to have become overgrown by vegetation since 1947 and only one (core N 3, see Fig. 3) of the 31 cores contained peat that was formed during a terrestrialization process.

It is a mystery why mires in Japan have rarely developed a vegetation that would be called "ombrotrophic" in other parts of Eurasia or North America, although the plant species which can form bogs are present. Damman (1988) suggested this was owing to repeated tephra deposition and favoured the term "tephratrophic mire", which had been proposed previously by Wolejko & Itoh (1986). In the case of Kiritappu Mire, the potential influence of tephra is obscured by the heavy tsunami impact in the eastern part. Observations in other mires in Hokkaido indicate that tephra is not the only important factor: Bekanbeushi Mire and Shibetsu Mire in eastern Hokkaido have a more "bog-like appearance" although they have been covered by tephra during their development, and mires in northern Hokkaido (Sarobetsu Mire, Sarufutsu Mire) appear to be fens or at least not purely ombrotrophic types, although they have not been affected by tephra and their age and topographical location is similar to the mires in eastern Hokkaido. Yabe (1993) has pointed out that climatic conditions vary significantly between different parts of Hokkaido, and this is likely to have had an influence on mire development. In their study of Bibi Mire in southern Hokkaido, Yabe & Onimaru (1997) stressed the importance of mean water level, water level fluctuation and water flow rates, which would ultimately determine the chemical environment

Table 2. Tephra layers at Kiritappu Mire (from Nanayama 2000).

Code	Source	Age	Depth	Author
Ta-a	Tarumae-san	1739 AD	10 cm - 30 cm	Furukawa et al. (1997)
Ko-c2	Komagatake	1694 AD	10 cm - 30 cm	Furukawa et al. (1997)
Ta-b	Tarumae-san	1667 AD	10 cm - 30 cm	Furukawa et al. (1997)
Ma-b	Mashu	ca. 900 AD	30 cm - 40 cm	Machida (1996)
B-Tm	Hakuto-san	820 - 895 AD	30 cm - 40 cm	Okumura et al. (1999)
Ta-c2	Tarumae-san	2000 BP	50 cm - 200 cm	Tokui (1989)

(availability of oxygen and minerals/nutrients, pH) for mire plants.

It seems that climatic/hydrological factors and tephra deposition/tsunami impacts all play a role in mire development in Hokkaido. Further comparative studies on stratigraphy and current environmental conditions in mires in Hokkaido are necessary in order to make a judgement on their relative importance. Kiritappu Mire with its different types of mire environments, several tephra layers and the distinct gradient of tsunami impact intensity will be a key site in this context.

Human influence on mire development at Kiritappu is not well documented. The oldest settlements on the uplands surrounding the mire have been dated to 6,000 years BP (Sawa *et al.,* 1982). Consequently, people have been living in the area before peat formation started, but information on their activities is lacking. Over the last century, anthropogenic impact has been most intense in a belt along the coast, as Tanaka (1959) has pointed out. The coastal area and the upper reaches of the river valleys have only thin peat layers or no peat at all and thus were more suitable for conversion to pastures and, housing settlements than the central parts of the mire. There are drainage ditches along the road that crosses the mire, east of Kiritappu Mire Information Centre and in the area of Junsai-numa Pond. Remnants of fences, indicating former pastures, can be found along the coast, locally in the western part of the mire and south of the road through the mire, between Biwasegawa River and Dorogawa River. Since 2000, horses have been released again onto a former pasture between Biwase Bay and Dorogawa River during the summer for vegetation management and tourism purposes. Most pastures, however, have been abandoned and are left to undergo spontaneous vegetation succession. Collecting berries, harvesting *Brasenia schreberi* (eaten by the local people) in Junsai-numa Pond and reed (probably mostly in restricted areas at the western mire margin) seems to have been common until rather recently and may have influenced the mire vegetation. Accidental or deliberate burning (one case is reported for 1962 (Itoh, 1995)) is another factor that threatens the mire. Further studies of the "human impact" and its importance for the vegetation pattern are needed.

HYDROLOGY

Early comments on hydrological factors were made by Tanaka (1956) who described a high groundwater level and flow directions of the rivers from north to south. Measurements of water levels were first conducted in the course of a study by Umeda *et al.* (1985), which aimed at assessing the hydrological influence of the road that cuts through the centre of the mire. They found higher water levels on the northern than on the southern side of the road and concluded that water movement was hampered by the dam on which the road was built owing to compaction of the peat layer and subsequent lowering of its water permeability. Water level amplitudes ranged from 20 cm to 40 cm and were higher at a low-lying site closer to Biwasegawa River than at a transect further east that was 1 m higher. The authors attributed this to a groundwater flow that follows the surface contours towards the south-west in this area.

Investigations by Hotes (1998) showed that the mean water level in an undisturbed area (between the rivers Ichibangawa and Nibangawa, south transect) was 1.5 cm below the ground surface (measured at hollow bottom level), with amplitudes generally smaller

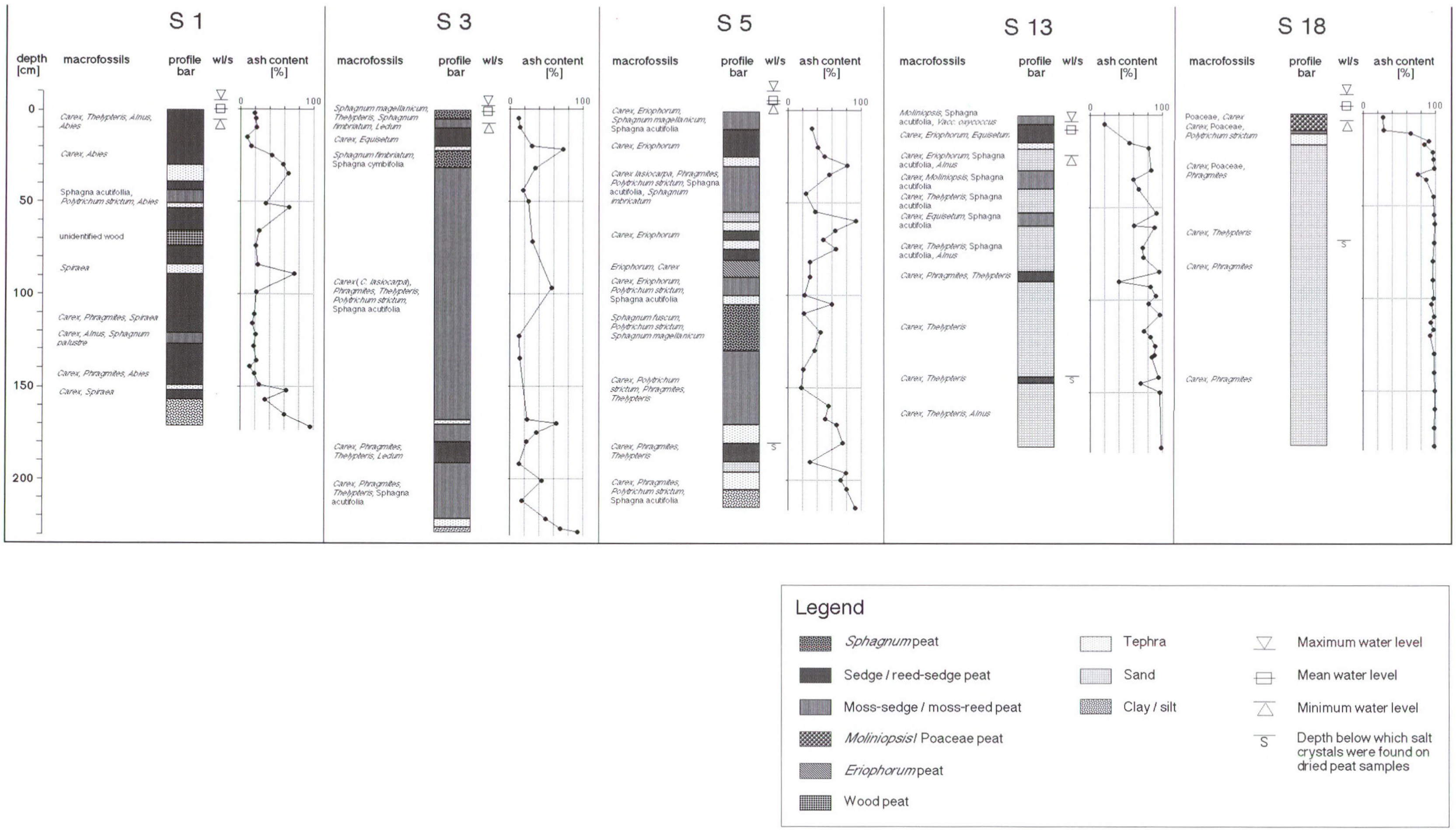

Fig. 2. Stratigraphy of the cores S 1, S 3, S 5, S 13 and S 18 from the south transect, Kiritappu Mire. Dominant macrofossils, deposit types (profile bar, see legend), maximum, mean and minimum water levels relative to the hollow bottom level, depth below which salt crystals were found on dried samples and ash contents are indicated.

Table 3. Hydrological site factors in three vegetation types at Kiritappu Mire. pH, EC and ion contents of surface water and groundwater samples measured in the laboratory (data set "lab") and pH and EC of surface water, water levels, and water level amplitudes measured in the field (data set "field") are shown. The unit for EC is [µS cm^{-1}], the ion concentrations are given as [mg l^{-1}], water level and water level amplitude are in [cm]. Negative water levels are below the ground surface at hollow bottom level, positive ones are above it.

		Alnus japonica - Spiraea salicifolia community					*Sasa chartacea* community					*Myrica gale - Sphagnum fuscum* community				
parameter	depth [cm]	min	max	mean	SD	n	min	max	mean	SD	n	min	max	mean	SD	n
Data set "lab", surface water and groundwater																
pH	0	4.2	6.3	5.3	0.5	16	5.2	5.9	5.4	0.3	4	4.5	6.3	5.4	0.5	28
	50	5.5	6.5	5.9	0.4	16	5.5	5.7	5.6	0.1	4	3.2	6.4	5.7	0.6	28
	100	5.5	6.7	6.0	0.4	16	5.5	6.0	5.6	0.2	4	3.9	6.8	5.9	0.5	28
EC	0	43	553	174	182	16	42	48	45	3	4	34	1780	191	386	28
	50	39	370	143	116	16	55	78	63	10	4	58	3280	435	798	28
	100	27	715	262	266	16	58	74	65	7	4	85	1437	445	495	28
NH_4	0	0.0	2.3	0.3	0.7	16	0.0	1.0	0.4	0.5	4	0.0	1.6	0.3	0.4	28
	50	0.0	2.8	0.4	0.8	16	0.0	0.0	0.0	0.0	4	0.0	2.0	0.2	0.5	28
	100	0.0	1.6	0.2	0.5	16	0.0	0.0	0.0	0.0	4	0.0	2.1	0.1	0.4	28
NO_3	0	0.0	19.0	2.5	4.8	16	0.0	0.8	0.4	0.4	4	0.0	5.4	0.5	1.1	28
	50	0.0	2.6	0.6	0.7	16	0.0	0.9	0.3	0.4	4	0.0	1.3	0.3	0.4	28
	100	0.0	1.5	0.4	0.4	16	0.0	0.7	0.2	0.3	4	0.0	1.7	0.2	0.4	28
SiO_2	0	2.1	31.8	6.5	7.6	16	12.7	19.9	17.0	3.3	4	4.6	26.7	12.9	5.4	28
	50	13.1	37.8	26.6	7.3	16	20.8	28.4	23.5	3.4	4	13.5	39.0	23.3	7.2	28
	100	16.8	45.9	31.4	6.6	16	21.3	32.1	25.6	5.1	4	17.5	44.2	31.9	6.9	28
Cl^-	0	4.9	146.7	38.4	47.7	16	5.8	8.8	7.2	1.3	4	3.9	1172.4	72.2	228.9	28
	50	4.1	110.0	30.7	32.0	16	6.5	8.7	7.1	1.1	4	7.8	1750.0	197.9	473.6	28
	100	7.5	182.2	48.9	64.8	16	7.5	9.7	8.3	1.0	4	7.9	619.9	128.0	186.5	28
SO_4^{2-}	0	0.4	4.4	1.6	1.3	16	0.3	1.0	0.7	0.3	4	0.2	8.4	1.2	1.6	28
	50	0.3	2.3	1.2	0.7	16	1.4	1.7	1.5	0.1	4	0.2	50.6	4.5	11.0	28
	100	0.3	5.9	1.3	1.4	16	0.5	0.7	0.6	0.1	4	0.1	60.5	3.3	11.3	28
Na^+	0	2.6	66.4	13.7	16.5	16	2.4	6.9	3.6	2.2	4	1.9	131.4	15.5	29.1	28

															22	
	50	3.1	57.8	15.0	14.5	16	3.3	11.3	5.4	3.9	4	3.5	627.9	46.8	120.9	28
	100	4.0	117.9	25.8	29.9	16	3.3	10.9	5.3	3.8	4	3.7	215.0	34.8	46.3	28
K^+	0	0.4	3.6	1.3	1.0	16	0.3	0.8	0.5	0.3	4	0.1	5.7	1.1	1.3	28
	50	0.2	2.1	0.5	0.5	16	0.1	0.4	0.2	0.1	4	0.1	2.5	0.6	0.7	28
	100	0.2	3.1	1.0	1.1	16	0.1	0.6	0.3	0.2	4	0.1	7.8	2.0	2.6	28
Ca^{2+}	0	0.7	10.6	3.5	2.8	16	0.8	5.3	2.0	2.2	4	0.2	17.5	3.0	3.3	28
	50	0.4	17.1	3.2	4.4	16	0.9	8.7	3.0	3.8	4	0.9	274.0	18.1	52.2	28
	100	0.4	34.7	5.0	8.5	16	1.3	9.3	3.5	3.9	4	0.6	79.0	11.8	19.0	28
Mg^{2+}	0	1.5	9.1	3.6	2.8	16	0.4	1.4	0.8	0.4	4	0.5	31.3	4.1	6.8	28
	50	0.6	7.8	2.8	2.7	16	0.6	1.8	1.0	0.5	4	1.5	98.7	10.8	21.2	28
	100	0.2	28.5	7.7	10.8	16	0.6	1.8	1.1	0.5	4	2.3	38.1	11.7	13.7	28
Fe^{3+}	0	0.1	34.0	6.5	9.7	16	0.5	1.9	1.2	0.7	4	0.6	28.0	5.3	6.4	28
	50	0.3	14.0	4.0	5.2	16	0.2	0.6	0.4	0.2	4	0.5	90.0	9.2	19.4	28
	100	0.2	5.0	2.2	1.7	16	0.1	0.6	0.3	0.2	4	0.1	7.0	1.8	1.6	28
Data set "field", surface water																
pH		4.3	6.0	5.3	0.4	26	4.7	5.6	5.1	0.3	5	3.6	6.3	4.9	0.6	56
EC		68	2040	367	505	26	98	227	144	49	5	47	10030	630	1673	56
Water Level (WL)		-31	13	1.4	8.3	87	-57	-1	-25.0	17.0	39	-39	57	-2.3	15.0	233
WL Amplitude 5		39	14.0	11.0	7	22	57	40.0	17.0	3	7	74	21.0	18.0	21	

–

than 20 cm. The only exception was a sandy ridge where the amplitudes could be as high as 70 cm (and the mean water levels of the three gauges there were 15, 25 and 36 cm below the surface, respectively). The mean water level was 10 cm below the ground surface in a disturbed site with dirt roads on artificial dams and adjacent drainage ditches (vicinity of Junsai-numa Pond, north transect), and most water level amplitudes were greater than 30 cm. The two sites closest to Shinkawa River were flooded once during the monitoring period, but most of the mire area was not affected by river water.

In addition to the gauges in which the above values were measured, four automatic water level recorders (WLR) were installed at the transect between Ichibangawa and Nibangawa by T. Inoue (Hotes, 1998) (Fig. 3). These recorders monitored the water level in open pits every hour. The water level rose quickly after rainfall and dropped slowly during dry periods. One exceptionally heavy rain event of 105 mm in 24 hours gave some insight into water movement through the mire. Analysis of the response of the water level recorders suggested that influx from the hill slope at the western mire margin takes place (WLR 1: increase of water level 7 cm in 12 hours), but the amount is less than that which falls on the mire expanse (Fig. 3) and flows through shallow depressions towards the rivers (WLR 2: increase of water level 12 cm in 15 hours, WLR 3: increase of water level 9 cm in 12 hours). The water level increase at an isolated, slightly raised site close to Ichibangawa River was the smallest (WLR 4: increase of water level 6 cm in 12 hours). The stronger increase and delayed drop of the water levels at WLRs 2 and 3 probably was caused by inflow of surplus water that could not be stored in the substrate of the adjacent, slightly higher parts of the mire. This assumption is backed by the mean, minimum and maximum values at the four sites. The two locations in the central part of the mire had minimum water levels close to the mean levels (which were slightly above the hollow bottom level). This suggests there was water inflow from surrounding areas, which compensated for losses during dry periods. In contrast, the water levels dropped significantly at the mire margins; at the site close to Ichibangawa River this was probably caused by runoff at or close to the surface, perhaps combined with infiltration into the sandy substrate. At the hill foot, water loss through evapotranspiration of the alder forest might have played an important role (Takahashi *et al.*, 1984). All maxima were about 10 cm above the ground surface; surface flow was observed after the heavy rainfall at site S 6 in a shallow depression, which had standing water at the surface even in dry periods.

Automatic water level recorders installed at three sites from the mouth to the middle reaches of Biwase River showed tidal fluctuations up to the bridge where the road through the mire centre crosses the river. Further upstream cyclic fluctuations were lacking. The tidal amplitude reached 1.2 m at the river mouth and 0.7 m at the road bridge. Flow retardation and flow reversion during high tide could be observed from the river mouth up to the bridge. The tidal cycles had no effect on the water levels recorded in the mire, although the distance from WLR 4 to the mudflat of Ichibangawa River with pronounced tidal fluctuations was less than 70 m.

Water Chemistry

Investigations of the water quality of Kiritappu Mire started only in the 1980s. Physical and chemical properties of the water of Wakayama-numa and Junsai-numa ponds in the northern part of the mire were studied by Itoh (1982) who measured pH, dissolved oxygen (DO), chemical oxygen demand (COD), chloride, calcium carbonate, iron, evaporation residue and humic acid concentration. Wakayama-numa is located at the northwestern margin of Kiritappu Mire and receives water from the adjacent hills through a small stream, whereas Junsai-numa Pond in the centre of the northern part of the mire has no obvious in- or outflow. Wakayama-numa Pond had a pH of 6.5, whereas Junsai-numa was slightly more acidic with pH 6.1. Oxygen saturation of the surface waters was between 70% and 80%, while close to the bottom of Wakayama-numa 55% was measured. Chloride concentrations were somewhat higher in Junsai-numa than in Wakayama-numa, iron concentrations did not differ, and residue as well as humic acid concentrations were lower in Junsai-numa.

Haraguchi (1995) summarized his findings on water quality of rivers and pore water in different plant communities of Kiritappu Mire as follows: "The water of rivers flowing into the mire was near-neutral, relatively rich in minerals and oxygen-saturated. Standing water in shallow pools in the floodplain of the rivers had higher electric conductivity (EC) and lower redox potential, indicating enrichment of salts and decomposition of organic material. Near the river mouth, water quality was almost identical with that of sea water. In Biwasegawa River, pH, EC and redox potential were elevated as far upstream as the road, which crosses the centre of the mire, indicating

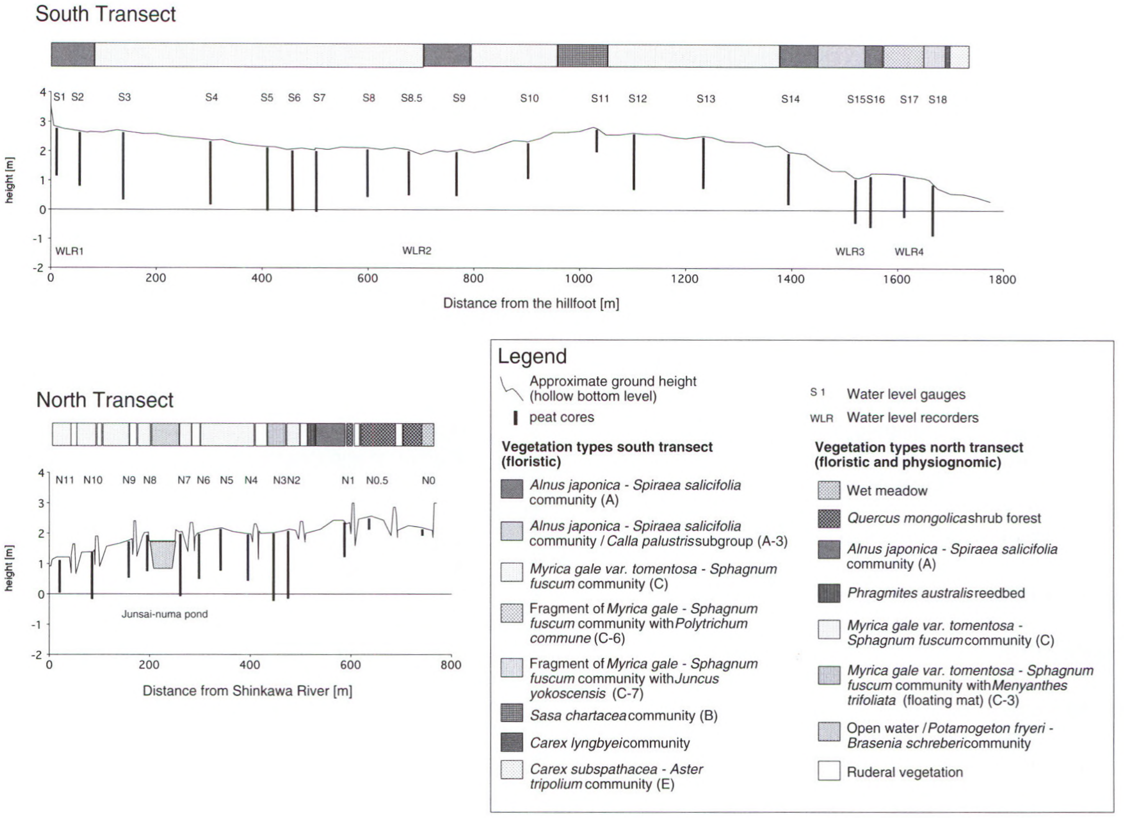

Fig. 3. Vegetation types, ground height (at hollow bottom level), location and depth of cores taken along south and north transect, Kiritappu Mire.

influence of sea water up to this point. Surface water in the alder forest at the western mire margin had higher pH and EC than the open reed community, suggesting inflow of salts from the catchment area into the forest. At another transect spanning from the floodplain of Biwase River through reed community and alder community to peat moss community, a decrease of pH and EC and an increase of redox potential was observed. On both sides of the road through the mire centre, elevated values of pH and EC were measured, which were attributed to polluted runoff water from the road. In Naganuma Pond in the centre of the mire as well as in the surface water of sites around this pond, relatively high pH and EC were measured, but *Sphagnum*-dominated sites in the same area showed the expected low values."

A report by Kunii *et al.* (1995) contains data on the water quality of four ponds that were investigated for their aquatic vegetation. Wakayama-numa Pond and Junsai-numa Pond were among these, which allows a comparison of pH and dissolved oxygen values with those of Itoh (1982). It should be noted that the water temperature during the measurements of Kunii *et al.* was 10°C higher (27-28°C compared to 17-18°C) than during the measurements of Itoh (1982). Nevertheless, dissolved oxygen in surface water of Wakayama-numa was only slightly lower (7.4 mg l^{-1} compared to 8.1 mg l^{-1}); the pH was somewhat higher (6.8 compared to 6.5). In Junsai-numa, Kunii *et al.* obtained a distinctly lower dissolved oxygen concentration (5.2 mg l^{-1} compared to 8.2 mg l^{-1}) and a higher pH (7.1 compared to 6.1). Interestingly, Junsai-numa Pond had a much higher EC than Wakayama-numa Pond (147.8 µS cm^{-1} compared to 87.1 µS cm^{-1}).

Saito *et al.* (1997) published data on the water chemistry of five ponds (Wakayama-numa, Junsai-numa, Naganuma, Koorikiri-numa, "Stefan"-numa), the five rivers and two groundwater sampling sites at Kiritappu Mire. These data were compared with the water chemistry of Biwase Bay. In ponds in the northern part of the mire, the pH was higher (5.4 - 6.7) than in the south (4.7, 4.8). EC and Na+ concentration were twice as high in Junsai-numa (100µS cm^{-1};

Table 4. Preliminary plant species list for Kiritappu Mire. The list is based on the plant species found along the south and north transects with some additions from the following papers: Yoshii and Kudo (1926), Tanaka (1956, 1957, 1959), Shinsho (1982), Tsujii et al. *(1986), Sato (1989), Fujita (1992), Fujita* et al. *(1995) Kunii* et al. *(1995), Uchiyama (1996) and Tachibana* et al. *(1997). For the vascular plants, the order of families and the nomenclature follows the list of the Japanese Environment Agency (Kankyocho 1987) in most cases, but sometimes different names that seem to be more in common usage were chosen. The name from the official Kankyocho list was then added in brackets.*

LICHENS

Cladoniaceae
- *Cladonia arbuscula* ssp. *beringiana*
- Cladonia rangiferina
- *Cladonia ciliata* f. *tenuis*
- Cladonia scabriuscula
- Cladonia pseudoevansii
- *Cladonia* cf. *squamosa*

BRYOPHYTA

HEPATICAE

Aneuraceae
- *Aneura pinguis* (?)

Scapaniaceae
- *Diplophyllum albicans*

Lepidoziaceae
- *Kurzia makinoana*
- *Telaranea nematodes*

Calypogeiaceae
- *Calypogeia neesiana*

MUSCI

Sphagnaceae
- Sphagnum palustre
- Sphagnum papillosum
- Sphagnum imbricatum
- Sphagnum magellanicum
- Sphagnum subnitens
- Sphagnum subfulvum
- Sphagnum fuscum
- Sphagnum capillifolium
- Sphagnum girgensohnii
- Sphagnum fimbriatum
- Sphagnum squarrosum
- Sphagnum subsecundum
- Sphagnum flexuosum
- *Sphagnum recurvum* var. *mucronatum*

Polytrichaceae
- Polytrichum commune
- Polytrichum formosum
- *Polytrichum juniperinum* ssp. *strictum*

Dicranaceae
- *Campylopus* sp.
- Dicranum elatum
- Dicranum flagellare
- Dicranum scoparium
- *Dicranum undulatum*

Mniaceae
- Mnium heterophyllum
- *Mnium hornum*

Aulacomniaceae
- *Aulacomnium palustre*

Climaciaceae
- *Climacium dendroides*

Amblystegiaceae
- Calliergonella cuspidata
- *Campylium sommerfeldtii* (?)
- *Drepanocladus* cf. *vernicosus*
- *Pleurozium schreberi*

Plagiotheciaceae
- *Plagiothecium* cf. *curvifolium*

Hypnaceae
- Callicladium haldanianum
- Hypnum tristo-viride
- *Rhytidiadelphus japonicus*

PTERIDOPHYTA

Lycopodiaceae
- *Lycopodium chinense*
- *Lycopodium obscurum* (?)

Equisetaceae
- Equisetum arvense
- Equisetum fluviatile
- *Equisetum palustre*

Osmundaceae
- Osmunda asiatica
- *Osmundastrum cinnamomeum (Osmunda cinnamomea* var. *fokiensis*)

Pteridiaceae
Pteridium aquilinum var. *latiusculum*

Dryopteridaceae
Dryopteris expansa (*D. austriaca*)

Thelypteridaceae
Thelypteris nipponica
Thelypteris palustris

Athyriaceae
Athyrium pycnosorum
Athyrium brevifrons
Athyrium yokoscense
Onoclea sensibilis var. *interrupta*

SPERMATOPHYTA

GYMNOSPERMAE

Pinaceae
Abies sachalinensis
Larix kaempferi
Picea glehnii

ANGIOSPERMAE

Myricaceae
Myrica gale var. *tomentosa*

Salicaceae
Salix sachalinensis
Salix sieboldiana
Salix taraikensis

Betulaceae
Alnus hirsuta
Alnus japonica
Betula platyphylla

Fagaceae
Quercus mongolica

Caryophyllaceae
Moehringia lateriflora
Spergula arvensis var. *sativa*
Spergularia marina
Stellaria humifusa
Stellaria longifolia
Stellaria radicans

Ranunculaceae
Anemone debilis
Aconitum sachalinense
Aconitum yezoense
Caltha palustris
Coptis trifolia
Ranunculus acris var. *nipponicus*
Thalictrum aquilegifolium
Thalictrum minus

Nymphaeaceae
Brasenia schreberi
Nuphar pumilum
Nymphaea tetragona

Actinidiaceae
Actinidia kolomikta

Hypericaceae
Hypericum erectum
Hypericum yesoense
Triadenum japonicum

Droseraceae
Drosera anglica (?)
Drosera rotundifolia

Brassicaceae
Cardamine pratensis

Saxifragaceae
Chrysosplenium alternifolium var. *sibiricum*
Hydrangaea paniculata
Parnassia palustris var. *multiseta*

Rosaceae
Filipendula kamtschatica
Filipendula yezoensis
Fragaria yezoensis
Malus baccata
Potentilla egedei var. *grandis*
Potentilla palustris
Potentilla stolonifera (?)
Rubus idaeus
Rubus pseudo-japonicus
Sanguisorba tenuifolia
Sorbus commixta
Spiraea salicifolia

Fabaceae
Lathyrus palustris var. *pilosus*
Thermopsis lupinopides
Trifolium repens
Trifolium pratense

Geraniaceae
Geranium yesoense

Anacardiaceae
Rhus ambigua

Violaceae
Viola blandaeformis
Viola patrini
Viola langsdorffii

Onagraceae
Epilobium palustre var. *lavandulaefolium*
Oenothera erythrosepala

Hippuridaceae
Hippuris vulgaris

Cornaceae
Cornus suecica

Araliaceae
Kalopanax pictus

Apiaceae
Cicuta virosa
Coelopleurum lucidum
Ligusticum scoticum (Ligusticum hultenii)

Ericaceae
Chamaedaphne calyculata
Ledum palustre var. *diversipilosum*
Vaccinium microcarpum
Vaccinium oxycoccus
Vaccinium vitis-idea
Andromeda polyfolia

Empetraceae
Empetrum nigrum

Primulaceae
Trientalis europaea
Glaux maritima
Lysimachia thyrsiflora
Lysimachia vulgaris

Oleaceae
Fraxinus mandshurica var. *japonica*

Gentianaceae
Gentiana trifllora
Halenia corniculata

Menyanthaceae
Menyanthes trifoliata

Rubiaceae
Galium trifidum var. *brevipedunculatum*
Galium verum
Rubia yesoensis
Galium trachyspermum var. *trachyspermum*

Polemoniaceae
Polemonium acutiflorum (Polemonium coeruleum)

Lamiaceae
Clinopodium sp.
Lycopus maackianus
Lycopus uniflorus
Prunella vulgaris ssp. *asiatica*
Scutellaria dependens
Scutellaria strigillosa
Stachys japonicum (Stachys riederi)

Solanaceae
Solanum megacarpum

Scrophulariaceae
Pedicularis resupinata

Lentibulariaceae
Utricularia intermedia
Utricularia minor
Utricularia vulgaris var. *japonica (Utricularia australis*)

Caprifoliaceae
Lonicera caerulea var. emphyllocalyx

Campanulaceae
Adenophora triphylla
Codonopsis ussuriensis
Lobelia sessilifolia

Asteraceae
Achillea alpina
Achillea ptarmica
Achillea millefolium
Artemisia montana
Aster tripolium
Cacalia auriculata
Cirsium kamtschaticum
Cirsium pectinellum
Hieracium umbellatum (?)
Ixeris dentata
Ligularia hodgsonii
Ligularia stenocephala
Petasites japonicus
Saussurea amurensis
Senecio cannabifolius
Solidago virgaurea var. *asiatica*
Sonchus brachyotus
Stenactis annuus
Taraxacum officinale

Scheuchzeriaceae
Scheuchzeria palustris
Triglochin maritimum
Triglochin palustre

Potamogetonaceae
Potamogeton alpinus
Potamogeton fryeri
Potamogeton natans
Potamogeton obtusifolius
Potamogeton pusillus
Potamogeton praelongus

Zosteraceae
Zostera nana
Zostera marina

Liliaceae
- Fritillaria camtschatcensis
- *Hemerocallis middendorfi* var. *esculenta*
- *Hosta rectifolia (Hosta sieboldii* var. *rectifolia)*
- Maianthemum bifolium
- Maianthemum dilatatum
- *Veratrum .album (Veratrum grandiflorum*)

Iridaceae
- Iris ensata
- Iris setosa

Juncaceae
- Juncus effusus
- Juncus ensifolius
- Juncus krameri
- Juncus yokoscensis
- Luzula capitata
- *Luzula multiflora*

Eriocaulaceae
- *Eriocaulon* sp.

Poaceae
- Agrostis alba
- Calamagrostis epigeios
- Calamagrostis langsdorffi
- Calamagrostis neglecta (C. stricta)
- Festuca rubra
- Miscanthus sinensis
- Moliniopsis japonica
- Phalaris arundinacea
- Phleum pratense
- Phragmites australis
- Poa macrocalyx
- Poa palustris
- Poa pratensis
- Puccinellia kurilensis
- Sasa chartacea
- *Trisetum sibiricum*

Araceae
- Calla palustris
- *Lysichiton camtschatcensis*

Lemnaceae
- *Lemna trisulca*

Sparganiaceae
- *Sparganium glomeratum*

Typhaceae
- *Typha latifolia*

Cyperaceae
- Carex aphanolepis
- Carex augustinowiczii
- Carex caespitosa
- Carex capillacea
- Carex echinata
- Carex flavocuspis
- Carex hakonensis
- *Carex lasiocarpa* var. *occultans*
- Carex limosa
- Carex lyngbyei
- Carex middendorffii
- Carex nemurensis
- Carex oligosperma
- Carex omiana
- Carex onoei
- Carex pilosa
- Carex pseudocuraica
- *Carex rhynchophysa*
- *Carex* cf. *sabynensis*
- Carex subspathacea
- Carex tenuiflora
- Carex thunbergi
- *Carex vaginata*
- *Eleocharis acicularis* var. *longiseta*
- *Eleocharis kamtschatica* f. *reducta*
- Eleocharis mamillata
- Eleocharis margaritacea
- Eleocharis wichurae
- Eriophorum gracile
- Eriphorum vaginatum
- Rhynchospora alba
- Scirpus tabernaemontani
- *Trichophorum alpinum (Scirpus hudsonianus)*

Orchidaceae
- Habenaria yezoensis
- Orchis aristata
- Platanthera mandarinorum
- Platanthera sachalinensis
- Platanthera tipuloides
- Pogonia japonica
- *Spiranthes sinensis*

12.0 mg l^{-1}) as in the other ponds (34 - 63 µS cm^{-1}; 4.5 - 6.7 mg l^{-1}). From the ion concentrations the authors concluded that ponds in the mire receive only rainwater and are thus ombrotrophic. Humic acid concentration in "Stefan"-numa was similar to that of mire surface water and 20 - 50 times higher than in the other ponds. Total nitrogen and phosphorus in the rivers showed high concentrations in the middle reaches and lower values upstream and downstream. This suggests that organic compounds and nutrients leach from the mire into the rivers that are thus enriched in these solutes. At the lower reaches, influx of seawater was evident (pH 8.0; EC 40000 µS cm^{-1}). A principal component analysis of the water chemistry data grouped the lower reaches of the rivers with seawater and "Stefan"-numa with groundwater. The other ponds were positioned between these groups.

A report on the chemistry of the pore water, ponds and rivers at Kiritappu Mire concludes that water conditions are typical for transition mires (Tani *et al.*, 1997). EC, Na^+ and Cl^- showed influence of seawater on the mire water chemistry.

Tomizawa *et al.* (1997) investigated chemical changes of stem flow and throughfall in *Alnus japonica* stands at Kiritappu Mire and found significantly increased pH, EC and ion concentrations compared to rain water in most cases.

Water chemistry of surface water and groundwater in 50 cm and 100 cm depth was investigated along two transects (Hotes, 2001) and an overview of the conditions in three plant communities is given in Table 3. In general, the statements of Haraguchi's report (1995) concerning the characteristics of surface water have been confirmed. Samples from the alder forest at the western mire margin had higher pH and electric conductivity than those from sites with dominant *Sphagnum* in the mire centre. Isolated stands of *Alnus japonica* scattered among the treeless communities also showed elevated pH and electric conductivity; in the case of low shrub stands in the mire centre this tendency was only weak, but in a higher stand close to the confluence of Ichibangawa and Nibangawa, the increase of electric conductivity was very steep. In the area between this alder stand and the river, the positive correlation between pH and electric conductivity disappeared. Low pH and high electric conductivity coincided here, which might be owing to biogeochemical processes in the soil that acidify the pore water. In general, pH and electric conductivity increased with depth, with some exceptions in the area adjacent to the river.

Influence of seawater was evident in the high content of chloride and sodium, which were dominant in samples from all depths. The concentrations of calcium, magnesium and sulphate were correlated with these. Potassium concentrations fluctuated strongly and showed less clear correlations with other ions. Nitrate was much lower in *Sphagnum*-dominated communities than in communities with alder. Ammonium fluctuated and was zero at many sampling sites; nitrite and phosphate were not detected with the analytical equipment used. Silicon dioxide showed only weak horizontal variation but increased with depth.

The findings of Kunii *et al.* (1995) and Saito *et al.* (1997) (see above) that Junsai-numa Pond has relatively high EC and Na+ concentrations were verified by Hotes (1998) and these peaks might be related to the Chile-tsunami that affected Junsai-numa Pond in 1960 (Nanayama *et al.* 2000).

Vegetation

A comprehensive flora has not been published for Kiritappu Mire so far, but a preliminary species list compiled on the basis of investigations along the south and north transects with additions from a number of publications (see table caption) is given in Table 4. It includes species from all habitats in the mire and its surroundings, *e.g.* the brackish reaches of the rivers. The nomenclature follows Ahti (1984) for lichens, Smith (1990) for liverworts, Daniels and Eddy (1985) for Sphagna and Noguchi (1987 - 94) for musci. For the vascular plants, the order of families and the nomenclature follows the list of the Japanese Environment Agency (Kankyocho 1987) in most cases, but sometimes different names that seem to be more in common usage were chosen. The name from the official Kankyocho list was then added in brackets. The list comprises 6 lichens, 5 liverworts, 34 mosses, 15 ferns and fern allies and 209 spermatophytes. It includes at least 6 doubtful species (species probably misidentified or for which Japanese or scientific names have been used wrongly) that need to be checked. A number of species occur only occasionally in disturbed areas or were obviously introduced. The list is not yet complete (especially the lichen and moss flora are not well known) and needs to be revised further.

The vegetation was the first feature of Kiritappu Mire to attract the interest of scientists. Yoshii & Kudo (1926) and Miyoshi (1938) described the "peat forming plant community", which was the reason to declare an area in the centre of the mire as a national natural monument in 1922, and listed a number of typical plant species. Tanaka (1956, 1957) divided the northern part of the mire into six areas from east to west that were separated by streams or rows of ponds, and described the vegetation of each of these. In his 1959 publication he presented vegetation tables for nine plant communities (Table 5) and additional five tables for the species composition of certain sites/levels in the microtopography. He seems to have followed the central European approach to vegetation classification, but he did not clarify this and used uncommon codes in the tables that were not explained in the text. Shinsho (1982) described four plant communities in the vicinity of Wakayama-numa Pond at the north-western mire margin (Table 5).

Three areas in the mire (Wakayama-numa Pond,

Table 5. Plant communities at Kiritappu Mire according to different authors

Author Plant communities / vegetation types

Tanaka 1959 Northern and Central Mire Area

1 *Hosta rectifolia* - *Carex thunbergi* community
2 *Carex onoei* - *Sphagnum* sp. community
3 *Eriophorum vaginatum* - *Myrica gale* var. *tomentosa* community
4 *Carex limosa* var. *fusco-cuprea* - *Carex lasiocarpa* var. *occultans* community
5 *Thelypteris palustris* - *Hosta rectifolia* community (Under *Alnus japonica*)
6 *Carex limosa* var. *fusco-cuprea* - *Eleocharis kamtschatica* community
7 *Eriophorum vaginatum* - *Sphagnum* sp. community
8 *Moliniopsis japonica* - *Myrica gale* var. *tomentosa* community
9 *Phragmites australis* - *Moliniopsis japonica* community

Shinsho 1982 Area around Wakayama-numa Pond

1 *Menyanthes trifoliata* - *Equisetum fluviatile* community
2 *Hydrangaea paniculata* - *Ledum palustre* var. *diversipilosum* community
3 *Alnus japonica* - *Calamagrostis langsdorffi* community
4 *Spiraea salicifolia* - *Carex augustinowiczii* community

Tsujii et al. 1986 Selected Areas in the North, Centre and South of the Mire

1 *Eriophorum vaginatum* - *Myrica gale* var. *tomentosa* community
2 *Hydrangaea paniculata* - *Ledum palustre* var. *diversipilosum* community
3 *Moliniopsis japonica* - *Phragmites australis* community
4 *Alnus japonica* - *Phragmites australis* - *Calamagrostis langsdorffi* community
5 *Spiraea salicifolia* - *Carex augustinowiczii* community
6 *Menyanthes trifoliata* - *Equisetum fluviatile* community
7 *Phragmites australis* - *Calamagrostis langsdorffi* - *Carex* sp. community

Central Mire Area

1 *Alnus japonica* forest
2 *Moliniopsis japonica* community
3 *Phragmites australis* - *Moliniopsis japonica* community
4 *Eriophorum vaginatum* community
5 *Myrica gale* var. *tomentosa* community
6 *Phragmites australis* community
7 *Rhynchospora alba* community
8 *Menyanthes trifoliata* community
9 Herbaceaous vegetation on the road embankment

Fujita 1992 Central Mire Area

1 *Moliniopsis japonica* - *Myrica gale* var. *tomentosa* community
2 *Moliniopsis japonica* - *Phragmites australis* community
3 *Carex lasiocarpa* var. *occultans* - *Moliniopsis japonica* community
4 *Phragmites australis* - *Moliniopsis japonica* community
5 *Eriophorum vaginatum* community
6 *Myrica gale* var. *tomentosa* community

Biwase Village Area

1 *Sphagnum* spp. community
2 *Eriophorum vaginatum* community

3 *Eriophorum gracile* community
4 *Myrica gale* var. *tomentosa* community (*Hemerocallis middendorffii* community)
5 *Hosta rectifolia* community
6 *Iris ensata* community
7 *Hydrangaea paniculata* community
8 *Phragmites australis* community
9 *Triglochin maritimum* community

Tachibana 1997 Whole Mire Area

1. Aquatic vegetation
1-1. Potamogetonetea
 1 *Potamogeton fryeri* community
 2 *Nymphaea teragona* community
 3 *Nuphar pumilum* community
 4 *Trapa japonica* association (Trapetum japonicae)
 5 *Menyanthes trifoliata* community
2. Fen vegetation
2-1. Phragmitetea
 6 *Phragmites australis* association (Phragmitetum australis)
 7 *Calamagrostis langsdorffi* - *Phragmites australis* association (Calamagrosto-Phragmitetum australis)
 8 *Carex lyngbei* association (Caricetum lyngbei)
 9 *Scirpus tabernaemontani* association
 10 *Zizania latifolia* association
 11 *Equisetum fluviatile* association
2-2. Microcaricetea
 12 *Carex limosa* association
 13 *Carex pseudo-curaica* association
 14 *Myrica gale* - *Carex lasiocarpa* association (*Carex lasiocarpa* association)
3. Transition mire vegetation
3-1. Oxycocco-Sphagnetea
 15 *Carex lasiocarpa* - *Moliniopsis japonica* association
4. Transition mire / bog vegetation
4-1. Hollow vegetation (Scheuchzerietea)
 16 *Scheuchzeria palustris* - *Rhynchospora alba* association
4-2. Lawn vegetation (Oxycocco-Sphagnetea)
 17 *Moliniopsis japonica* - *Sphagnum papillosum* association
4-3. Hummock vegetation (Oxycocco-Sphagnetea)
 18 *Ledum palustre* - *Sphagnum fuscum* association
5. Forest vegetation
 19 *Alnus japonica* community

Tachibana et al. 1997 Central Mire Area

1 *Moliniopsis japonica* - *Sphagnum fuscum* community
2 *Moliniopsis japonica* - *Sphagnum papillosum* community
3 *Alnus japonica* - *Moliniopsis japonica* community
4 *Carex lasiocarpa* var. *occultans* - *Sphagnum subsecundum* community
5 *Phragmites australis* - *Calamagrostis langsdorffi* community

Hotes 1998 South and North Transect (Fig. 1)

A *Alnus japonica* - *Spiraea salicifolia* community
(mire margin adjacent to hillfoot, patches on the mire expanse)
A-1 *Alnus japonica* - *Calamagrostis langsdorffi* subgroup
A-2 *Polemonium acutiflorum* subgroup
A-3 *Calla palustris* subgroup

A-4 *Carex nemurensis* subgroup
A-5 *Quercus mongolica* subgroup

B *Sasa chartacea* community
(sandy ridge elevated above the surrounding mire area; central part of the south transect)

C *Myrica gale* var. *tomentosa* - *Sphagnum fuscum* community
(mire expanse)
C-1 *Myrica gale* var. *tomentosa* - *Sphagnum fuscum* typ. subgroup
C-2 *Myrica gale* var. *tomentosa* - *Alnus japonica* subgroup
C-3 *Sphagnum subsecundum* - *Eriophorum gracile* subgroup
C-4 *Sphagnum recurvum* var. *mucronatum* subgroup
C-5 *Cladonia* spp. subgroup
C-6 Fragment without *M. gale / S. fuscum*, with *Polytrichum commune*
C-7 Fragment without *M. gale / S. fuscum*, with *Juncus yokoscensis*

D *Carex lyngbyei* community
(narrow belt at the margin of mire expanse and saltmarsh; between communities C and E)

E *Carex subspathacea* - *Aster tripolium* community
(saltmarsh in the tidal zone of Ichibangawa River)

mire centre north and south of the road, area between Ichibangawa and Nibangawa) were investigated by Tsujii *et al.* 1986 who reported seven different plant communities (Table 5). They also presented the results of another survey, which focused on the vegetation on both sides of the road across the mire centre where they distinguished eight mire plant communities , which resembled the communities of their previous investigation but were given slightly different names. The vegetation along the road embankment was placed in a category of its own. A detailed vegetation map showing the distribution of all nine communities along the road was included in addition to a smaller-scale map (on the basis of a slightly enlarged 1:50000 topographical map) indicating the distribution of five communities over the whole mire.

The 1:50000 actual vegetation map of the Environment Agency (Kankyocho 1988) shows the largest part of the mire as Moliniopsietalia japonicae, with Phragmitetalia confined to river courses and roadsides and the *Alnus japonica* community along the western mire margin or between the two above-mentioned vegetation types.

Fujita (1992) surveyed two transects in the central part of the mire perpendicular to the road and an area north of Biwase Village between the coastal road and Dorogawa River (Table 5). In the discussion of the results from the transects in the central part of the mire, she pointed out that the vegetation she found corresponded to the *Moliniopsis japonica* - *Myrica gale* var. *tomentosa* community of Tanaka (1959) and to the *Moliniopsis japonica* - *Phragmites australis* community of Tsujii *et al.* (1986). She also found parallels to the *Carex lasiocarpa* var. *occultans* - *Moliniopsis japonica* community of the alliance *Molinion* described in Miyawaki (1988). But, owing to the fact that *Sphagnum* is abundant and forms distinct hummocks, she concluded that the vegetation falls between the categories "transition mire (chukan shitsugen)" and "bog (koso shitsugen)" of the traditional Japanese system (that was originally adopted from the classical German scheme). She treated the second study area near Biwase Village differently for which she described nine communities and presented their distribution on a detailed map.

Tachibana (1997) in her review of mire vegetation in Hokkaido listed 19 plant communities for Kiritappu, ranging from aquatic to forest vegetation (Table 5).

Tachibana *et al.* (1997) undertook another survey of the central part of Kiritappu Mire and distinguished five plant communities (Table 5), three of which they subdivided further into subgroups according to the Scandinavian classification method (sociation-consociation system of DuRietz).

Hotes (1998) classified the vegetation along the north and south transects according to the floristic composition of 81 relevées. Five different plant communities were derived, two of which could be divided into subgroups (Table 5, fig. 3). At the northern transect, additional vegetation types occurred that were not represented in the relevées and these were described on the basis of their physiognomy. Two of the communities (*Sasa chartacea* community, *Carex*

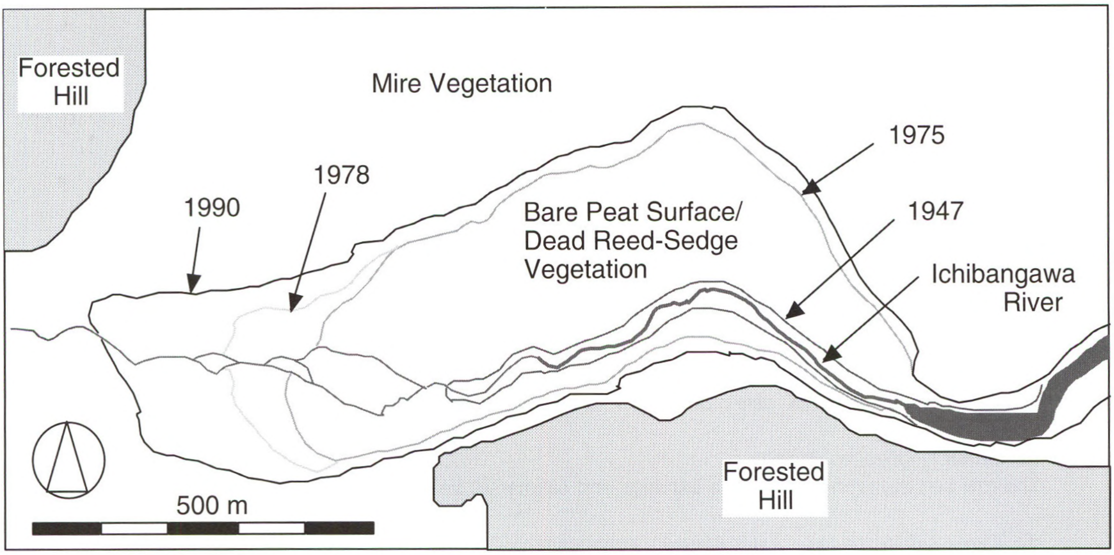

Fig. 4 . Vegetation change along the middle reach of Ichibangawa River between 1947 and 1990. Lines indicate the outer margin of the area in which reed-sedge vegetation had disappeared in the respective year. Note that patches of vegetation remained on slightly elevated locations, especially on the river banks.

subspathacea - Aster tripolium community), all subgroups of the *Alnus japonica - Spiraea salicifolia* community and the *Quercus mongolica* shrub forest are not included in the list of Tachibana (1997). This may be for several reasons: Firstly, the two communities are not normally recognized as mire vegetation types. *Sasa chartacea* occurs mostly in upland sites; accordingly, this species and a couple of other upland taxa (*e.g. Quercus mongolica*) were confined to slightly elevated sites in the mire with sandy substrates or only very shallow peat, which probably indicate ancient sand bars or beach ridges. One might argue that these areas do not belong to the mire and should be treated separately. However, there are zones where mire communities on peaty substrates and these "sandy substrate indicators" grade into one another. *Sasa chartacea* was found growing on *Sphagnum capillifolium* hummocks, and *Moliniopsis japonica, Ledum palustre* var. *diversipilosum, Eriophorum vaginatum* and others occurred in plots with considerable *Sasa* cover. For the *Carex subspathacea - Aster tripolium* salt marsh community, the separation from vegetation types that normally receive only freshwater was quite sharp. Only small individuals of *Phragmites australis* and *Carex lynbyei* were found in addition to the assemblage of salt-tolerant specialists, which grow along the lower reaches of the rivers in Kiritappu Mire. This community can produce thin layers of organic material, but these would hardly be called peat. Thus it will depend on the definition adopted of the term "mire" whether or not the two vegetation types are accepted as "mire plant communities". *Alnus japonica* forests were not further subdivided in the table of Tachibana (1997). In the study of Hotes (1998), however, at least a dry subtype with *Polemonium acutiflorum, Fraxinus mandshurica* and *Thalictrum aquilegifolium* could be distinguished from a wet subtype with standing water at the surface and *Calla palustris, Cicuta virosa* and *Equisetum fluviatile* growing on the forest floor. A subtype with *Carex nemurensis* was found on both sides of the wet forest type with *Calla* and associated species. Further investigations will be necessary to clarify if this is really an ecologically defined unit with an intermediate water level regime. Equally, for the mixed *Alnus japonica - Quercus mongolica* forest, further studies are needed to judge on its value as a vegetation unit.

There is now a fairly good knowledge of the plant communities occurring at Kiritappu Mire. Some areas, however, which are not easily accessible have not been surveyed on the ground so far, especially in the northern part of the mire west of Shinkawa River, between Biwase River and Nibangawa River, and in the extreme southwest. Furthermore, the communities described should be compared and unified as far as possible. If a set of vegetation units could be agreed on, a more detailed vegetation map could be drawn, and this would be a valuable tool for conservation and management purposes as well as for any further scientific investigation in the mire.

A preliminary investigation of recent vegetation changes based on a series of aerial photographs suggested rather stable conditions have prevailed for the last 50 years. Changes in parts of the mire without obvious human interference consist of slight increases in tree cover around patches of alder stands, but it is unclear whether this is from establishment of new tree individuals, or growth of pre-existing trees that now have larger crowns. The most dramatic change has taken place along the middle reaches of Ichibangawa River (Fig. 4) that is slightly lower (ca. 20 - 30 cm) than the adjacent parts of the mire to the north and was probably formed by the changing course of river meanders. Reeds and sedges were probably dominant in 1947, mixed with some alder stands. In 1975, most of the vegetation had disappeared and was replaced by bare mud or peat in which there were shallow water bodies. The bare area has expanded towards the west since then and in 1990 occupied the whole site that supported uniform reed vegetation in 1947. Field observations in 1996 and 1999 showed that the surface water in the area was brackish and that dead shoot bases and roots of *Phragmites* and Cyperaceae formed the top layer of the substrate. *Zostera nana* grew in some shallow pools. The mechanism of this shift is not known. Increased influx of brackish water probably played an important role, although reed should tolerate considerably high salt contents. The reasons for the rising water levels also need to be explained. Land subsidence, sea-level rise or elevated river bottoms following sedimentation possibly contribute to this process.

From the information presented above some conclusions can be drawn concerning the factors that influence the distribution of vegetation types in Kiritappu Mire. Natural factors comprise the geomorphological development and the hydrology for the large-scale zonation, disturbances by tephra and tsunamis probably on a smaller scale. In addition to these, human activities have altered marginal areas especially, but it is difficult to judge upon possibly widespread diffuse changes that might have occurred as a result of former landuse practices, *e.g.* increases or decreases of certain plant species owing to horse grazing. These changes are not easily detected because reference areas without human interference cannot be found.

When generalizing its characteristics, Kiritappu Mire can be attributed to the broad category of "poor fen". Although some sites support vegetation that is indicative of ombrotrophic conditions, the size of these areas hardly exceeds several square metres. "Fen species" are mixed with "bog species" in almost all cases, especially *Phragmites australis* and *Moliniopsis japonica* are often growing around or even through *Sphagnum fuscum* hummocks. The special stratigraphical structure with numerous marine mineral layers is reflected by the vegetation in some parts of the mire, whereas in others the same plant communities occur on peat/tephra substrates and peat/tephra/marine sand substrates, respectively. The same types of substrates most likely occur also in other regions of the Pacific Rim, although reports on the vegetation of coastal mires in Pacific Alaska, Canada or the United States (*e.g.* Sjörs, 1985; Zoltai & Pollett, 1983; Hofstetter, 1983) or the Far East of Russia (Botch & Masing 1983) do not indicate that these have sufficient traits in common to place them in a special category of their own. Factors other than the disturbance by tsunamis or tephra seem to be more important for the vegetation of these mires, at least when considering a spatial scale of hundreds of metres to kilometres.

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Information about Kiritappu Mire is available on the internet: http://www.marimo.or.jp/Kiritappu_Shitsugen/

VEGETATION DIVERSITY OF VALUABLE PEATLANDS IN LATVIA

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SUMMARY

Results of an inventory of the most valuable peatlands of Latvia, carried out in 1995/1996 and funded by Small Grants Fund of the Ramsar Bureau, as well as data of vegetation studies between 1997 and 2003, are presented. In total over 160 mires were investigated throughout Latvia in all the eight geobotanical districts. Twenty-four of the most valuable mires were distinguished in the survey. Mires of international importance are located in the North Vidzeme, East Latvia, Coastal Lowland, West Latvia and Central Latvia geobotanical districts. Twenty-five wetland communities are distinguished in the most valuable mires and assigned to *Isoeto - Littorelletea, Montio-Cardaminetea, Phragmito-Magnocaricetea, Scheuchzerio-Caricetea fuscae, Oxycocco-Sphagnetea* and *Alnetea glutinosae.* New localities for protected plant species were discovered during the mire inventory, for example, the third locality of *Rhynchospora fusca* in Latvia. As a result of the project, new protected nature areas including mires are being established. The results of the project show that Latvian mires are of considerable biodiversity value and support a variety of plant communities rich in plant species. This rich diversity of mire types and communities in Latvia is of international conservation significance.

Keywords: raised bog, transition mire, fen, vegetation, Latvia, biodiversity

INTRODUCTION

Protection of mire vegetation is still ongoing because, not just in Latvia but also throughout world, their utilisation and degradation are increasing (Nord-Varhaug, 1996). Ellenberg (1988) states that in Central Europe it is almost impossible to find "living" raised bogs, even in coastal landscapes. Compared to many other European countries, mires in Latvia are in a more natural state (Pakalne, Kalniòa, 2000).

Nature in Latvia is determined by its geographical location in the western part of the East-European plain and on the eastern coast of the Baltic Sea (Fig. 1). The total area of the country covers 64,635 km^2 and its coastline exceeds almost 500 km. Latvia belongs to the Temperate Zone, whose boreo-nemoral vegetation is characterized by deciduous-coniferous (mixed) forests.

Mire development in Latvia in general is related to the deglaciation of the area and in particular to processes determined by landscape, hydrological systems and soil development. In the time frame, these events correspond to Alleröd, Younger Dryas and the beginning of the Preboreal. There are no records of mire deposits from the pre-Holocene time, although a number of sites are known, where water sorted plant detritus forms inter-layers of up to 0.3 m in late glacial deposit sections dated as Alleröd and Late Dryas. Here, the mire development was interrupted by local hydrological conditions, usually related to re-distribution of regional scale catchment areas during the early stages of river basin formation.

1 **Nomenclature**: For vascular plants – Gavrilova, Šulcs, 1999, for bryophytes – Âboliòa, 2001.

Quite stable hydrological conditions are known from the early Holocene (Preboreal time), when local lake basins were aggregated and the Baltic Glacial Lake (occupied larger area than modern Baltic Sea) found a path to be merged with the North Sea. This resulted in a fast drop down of the regional erosion base and drastic re-arrangement in river catchment areas including changes of river flows. As a consequence, mire development commenced in the stable conditions of locally isolated hollows in undulating landscapes, on river bank terraces, along ancient coastal bars, and the large plains of former lake basins, over one third of Latvia's area.

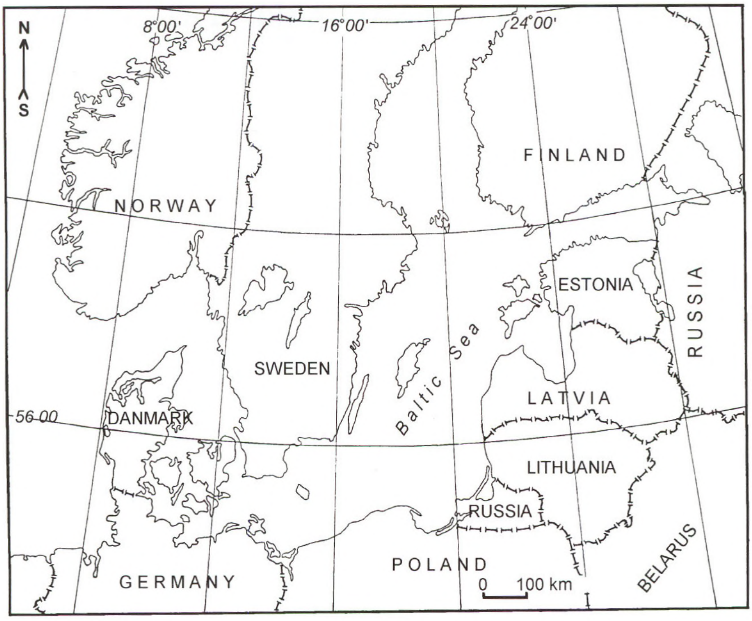

Fig. 1. Location of Latvia.

During subsequent centuries the regional water table became lower, areas occupied by raised mires dried out and became overgrown by forests. At this time, the total wetland cover did not exceed 10% of the total area of Latvia and during the next thousand years mires developed gradually until the very end of the Boreal time when, as a result, of global sea level changes the Litorina transgression took place.

During late Boreal and Atlantic times the Litorina transgression caused a rise of up to 2.5 m in the regional erosion base causing considerable re-arrangements to take place to river flows in many catchments. This resulted in over-flooding of terrace-based mires, destruction of local semi-isolated terrestrialized lakes and landscape depressions, as well as merging of isolated mires and the development of new coastal lagoon lake mires around the Baltic Sea and the Gulf of Rîga.

Mires cover 4.9% of the whole area of Latvia and include fens, transitional mires and raised bogs. Distribution of mires and diversity of their vegetation is determined by the geology of the area, origin of mires and climatic differences between coastal and continental parts of Latvia.

Mires in a broad sense represent natural archives and from the natural history perspective should be studied in detail. The aim of this paper is to reveal the results of the protected peatland inventory and mire vegetation studies in Latvia and to characterise the diversity of its mire vegetation and regional variation.

MATERIALS AND METHODS

During the summers of 1995/1996, and between 1997 – 2003, over 160 mires were investigated in eight geobotanical districts of Latvia, but only the most important mires are described in this paper. An inventory of protected mires was carried out together with those not yet under state protection. The most valuable peatlands were studied including those of international importance that meet Ramsar criteria. The study was carried out as a combination of field survey, cartographic data, aerial photographs and the existing information on mires in Latvia.

To describe mire vegetation over 3000 relevés of $1 m^2$ size were made in floristically homogenous plots. The Central European mire classification approach was used to distinguish and classify mire communities (Dierssen, 1982; Pott, 1993; Ellenberg, 1996).

Mire vegetation types were analysed according to their distribution in the geobotanical districts (Kabucis, 1995) that are distinguished according to the differences in geological development, vegetation and soil features of Latvia.

Conservation value of mires was assessed according to several criteria (Moen, 1995). Most important was the overall assessment of the investigated sites. Maps of the distribution of the studied sites and mire communities were prepared in co-operation with Lancaster University (Pakalne*et al.*, 1998).

Table 1. Valuable peatlands in Latvia

Criteria: Value as a nature feature: 1.Source of historical information, 2. Present-day developments, 3. Productivity, 4. Rarity, 5. Typical area, 6. Clarity, size, 7. Diversity, 8. Importance in a wider perspective. **Scientific value:** 1. Classic site, 2. Key site, 3. Research importance, 4. Educational importance, 5. Value as a reference area. **Present state and vulnerability:** 1. Naturalness, 2.Vulnerability, 3. Suitability for conservation.

Nr.	Mire value criteria	Value as a nature feature	Scientific value	Present state and vulnerability
	Site name			
1.	Kodu Mire (North Vidzeme)	1,2, 3,4,5, 6,7,8	1,2,3,4,5	1,3
2.	Saklaura Mire (North Vidzeme)	1,2, 3,4,5, 6,7,8	1,2,3,4,5	1,3
3.	Madiešēni Mire (North Vidzeme)	1,2, 3,4,5, 6,7,8	1,2,3,4,5	1,3
4.	Lielais and Pemme Mires (North Vidzeme)	1,2, 3,4,5, 6,7,8	1,2,3,4,5	1,3
5.	Teiči Mire (Eastern Latvia)	1,2, 3,4,5, 6,7,8	1,2,3,4,5	1,3
6.	Pelečāre Mire (Eastern Latvia)	1,2, 3,4,5, 6,7,8	1,2,3,4,5	1,3
7.	Bērzpils Mire (Eastern Latvia)	1,2, 3,4,5, 6,7,8	3	1,3
8.	Lagažu-Šņitku Mire (Eastern Latvia)	1,2, 3,4,5, 6,7,8	3	1,3
9.	Sala Mire (Eastern Latvia)	1,2, 3,4,5, 6,7,8	3	1,3
10.	Lubāna Mire (Eastern Latvia)	1,2, 3,4,5, 6,7,8	3	1,3
11.	Kaņieris Lake (Coastal Lowland)	1,2,4,5,7,8	1,2,3,4,5	1,3
12.	Randu wetlands (Coastal Lowland)	2,4,5, 7,8	1,2,3,4,5	1,3
13.	Engure Lake (Coastal Lowland)	1,2,4,5,7,8	1,2,3,4,5	1,3
14.	Inter-dune mire complex and Baži Mire (Coastal Lowland)	1,2, 3,4,5, 6,7,8	1,2,3,4,5	1,3
15.	Pape Lake (Coastal Lowland)	1,2,4,5,7,8	1,2,3,4,5	1,3
16.	Dunika Mire (Coastal Lowland)	1,2, 3,4,5, 6,7,8	2,3,4,5	1,3
17.	Sārnate Mire (Coastal Lowland)	1,2, 3,4,5, 6,7,8		
18.	Nida Mire (Coastal Lowland)	1,2, 3,4,5, 6,7,8	1,2,3,4,5	1,3
19.	Ance Mires (Coastal Lowland)	1,2, 3,4,5, 6,7,8	1,2,3, 4,5	1,3
20.	Klaņi Lake and Klani Mire (Coastal Lowland)	1,2, 3,4,5, 6,7,8	1,2,3, 4,5	1,3
21.	Ķemeru-Smārde Mire (Coastal Lowland)	1,2, 3,4,5, 6,7,8	1,2,3,4,5	1,3
22.	Abava River valley spring fens (West Latvia)	2,4,5,7	2,3,4,5	1,2,3
23.	Stikli Mires (West Latvia)	1,2, 3,4,5, 6,7,8	1,2,3,4,5	1,3
24.	Suda Mire (Central Latvia)	1,2, 3,4,5, 6,7,8	1,2,3,4,5	1,3

RESULTS OF THE MIRE SURVEY

Survey as the first, introductory stage shows that mires are nature archives and contain a rich diversity of mire types, many of which are of international importance. Latvian mires are of considerable biodiversity significance.

Mires of high conservation value are recognised in the following districts (Table 1):

- Northern Latvia (mires in the North Vidzeme Biosphere Reserve),
- Eastern Latvia (Lubâna Mires),
- Coastal Latvia (Inter-dune mire complex, Pape Lake and Nida Mire Complex, mires in the Íemeri National Park),

Table 2. Mire communities in the studied sites

Mire community	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Eleocharietum multicaulis																				•				
Schoenoplecto-Phragmitetum australis											•	•			•									
Phragmitetum communis	•					•						•	•		•				•					
Typhetum latifoliae											•				•									
Typhetum angustifoliae											•				•									
Scirpetum tabernaemontanae												•												
Cladietum marisci											•				•				•					
Caricetum acutiformis													•				•							
Caricetum diandrae										•		•		•										
Caricetum distichae															•									
Caricetum elatae											•				•									
Caricetum rostratae	•		•	•		•			•						•	•	•				•			•
Caricetum vesicariae				•																				
Caricetum nigrae														•										
Caricetum limosae		•	•		•	•	•		•										•	•	•			•
Caricetum lasiocarpae	•				•		•	•	•		•		•		•	•	•	•	•	•	•			•
Caricetum davallianae																						•		
Schoenetum ferruginei											•		•	•								•		
Cratoneurion commutati																						•		
Sphagnetum magellanici	•	•	•	•	•			•						•		•	•	•		•	•		•	•
Empetro nigri-Sphagnetum fusci	•	•				•			•												•		•	•
Sphagnetum cuspidati	•	•		•	•		•	•	•	•				•				•			•		•	•
Scheuchzerio-Sphagnetum cuspidati					•		•							•						•	•			•
Rhynchosporetum albae	•	•		•	•	•								•		•	•	•	•	•	•			•
Chamaedaphno-Sphagnetum magellanici					•	•	•		•	•														
Eriophoro - Trichophoretum cespitosi				•														•		•				•
Vaccinio uliginosi-Pinetum sylvestris									•							•		•			•		•	•
Myricetum galis											•		•	•				•	•	•				

1. Kodu Mire. 2. Saklaura Mire. 3. Madiešēni Mire. 4. Lielais and Pemme Mires. 5. Teiči Mire. 6. Pelečāre Mire.
7. Bērzpils Mire. 8. Lagažu-Sņitku Mire. 9. Sala Mire. 10. Lubāna Mire. 11. Kaņieris Lake. 12. Randu wetlands.
13. Engure Lake. 14. Inter-dune mires and Bazi Mire. 15. Pape Lake. 16. Dunika Mire. 17. Sarnate Mire.
18. Nida Mire. 19. Ance Mires. 20. Klaņi Lake and Klaņi Mire. 21Ķemeri-Smārde Mire. 22. Abava River valley spring fens.
23. Stikli Mires. 24. Suda Mire.
* Rare plant communities of Latvia are marked in bold.

- Western Latvia (Stikli Mires),
- Central Latvia (Suda Mire).

Plant communities of the 24 most valuable mire sites are shown in Table 2.

In Latvia ombrotrophic mires (raised bogs) are protected more than minerotrophic mires (fens). Nevertheless, minerotrophic mires include the Grîòi, Teièi and Krustkalni Nature Reserves, the Slîtere, Íemeri and

Gauja National Parks and the North Vidzeme Biosphere Reserve. All the mires mentioned in this paper are state protected.

Northern Latvia

Mires in the North Vidzeme Biosphere Reserve

Mires in the North Vidzeme Biosphere Reserve include peatlands of international importance, such as, , Kodu, Lielais and Saklaura Mires. The area is characterised by ombrotrophic mires that cover about 60% of the North Vidzeme geobotanical district. Small minerotrophic mires occur on bog margins and in relief depressions.

Kodu Mire is the largest mire in the North Vidzeme Biosphere Reserve with a total area of 1,925 ha. The northernmost part of the mire is about 1 km from the Estonian mire reserve Nigula. It is an open raised bog, with a large bog lake in the middle of the mire, surrounded by a bog pool labyrinth and hummock-hollow complex. Small mineral islands within the bog are covered with pine forest. Transitional mire vegetation is characterised by *Caricetum lasiocarpae* and *Caricetum rostratae* occuring on the mire margin. Occasionally, rather dense stands of *Phragmites australis* are observed showing the influence of minerotrophic water supply. Raised bog species include *Calluna vulgaris, Rubus chamaemorus, Eriophorum vaginatum, Drosera rotundifolia, Oxycoccus palustris* and *Andromeda polifolia.* accompanied by typical bryophytes, such as, *Sphagnum magellanicum, S. rubellum, S. fuscum, S. angustifolium, Mylia anomala, Kurzia pauciflora, Polytrichum juniperinum, Aulacomnium palustre, Pleurozium schreberi* The most common mire communities *are Sphagnetum magellanici* on hummocks and lawns and *Empetro nigri – Sphagnetum fusci* on hummocks. *Rhynchosporion* communities (*Rhynchosporetum albae, Sphagnetum cuspidati*) occur in bog hollows. Kodu Mire supports the rare plant species *Trichophorum cespitosum,* forming a good example of *Eriophoro vaginati – Trichophoretum cespitosi* community characteristic for this western raised bog type.

Saklaura Mire with a total area of 2,949 ha is a typical raised bog, comprising two bog lakes - Lielezers Lake (170 ha) and Mazezers Lake (25 ha) and a labyrinth of bog pools. Raised bog vegetation includes mainly *Sphagnetum magellanici, Empetro nigri – Sphagnetum fusci* and *Rhynchosporetum albae.* Species diversity is supported by a number of lichen species, for example, *Cladina rangiferina, Cladonia sylvestris* and *Cladonia stellaris,* sometimes occurring in great abundance. It differs from the other mires of the North Vidzeme Biosphere Reserve owing to the presence of species both of northern and north-eastern distribution, *Betula nana,* and species of western distribution in Latvia, *Trichophorum cespitosum.*
Presently a Ramsar site under the name Northern Mires, including Kodu and Saklaura Mire is being established.

Madieðçni Mire is also located in the North Vidzeme Biosphere Reserve. A peculiarity of this mire is that it is formed in an extensive paludified depression between the glaciotectonic landform known as "dauguls". It is a raised bog with well-developed hummock-hollow complex and is peculiar in having together species of western and eastern distribution in Latvia, for example, *Trichophorum cespitosum* and *Chamaedaphne calyculata.* Bog pools and lakes occur in the mire.
Lielais and Pemme Mires are located in Northern Latvia and together cover an area of 1,527 ha. Within a diverse landscape of bog lakes, pools, hummock-hollow complex, presence of streams and mineral islands with pine forest. Transitional mire vegetation occurs on the mire margins characterized by *Caricetum rostratae, Caricetum vesicariae* and *Caricetum lasiocarpae.* Bog hummocks support mainly *Sphagnetum magellanici.* There are areas in the mire with a high abundance of different lichen species including *Cladina rangiferina, C. tenuis* and *Cladonia fimbriata. Rhynchosporetum albae, Caricetum limosae* and *Scheuchzerio – Sphagnetum cuspidati* characterise bog hollows. It supports a good example of the raised bog community *Eriophoro vaginati-Trichophoretum cespitosi.*

RANDU WETLANDS

Randu wetlands are located along the eastern coast of the Gulf of Rîga in the North Vidzeme Biosphere Reserve. It is a unique and rare wetland type in Latvia. The area is characterised by a mosaic of small depressions and elevations. It includes meadows, coastal marshes, reedbeds and alder forest. There is a shallow lagoon – a favourite place for sea birds. In the southern part of the protected nature area, a fore-dune separates the meadows from the Gulf of Rîga. Coastal wetlands include small-sedge communities and submerged vegetation in a shallow lagoon and depressions. *Phragmitetum australis* and *Scirpetum tabernaemontani* dominate near the seacoast. On their margins, in the depressions, communities include both freshwater plants and species of salt habitats. Flooded and non-flooded meadows border on this halophytic area of the coastal meadows. Wet meadows cover the largest areas in the lowest places, being most diverse according to species number and structure of plant communities. In the herbaceous layer *Carex disticha* and *Poa subcoreulea* dominate. Meadows with halophytic species (*Trifolium fragiferum, Glaux maritima, Blysmus rufus)* appear in those places that are most intensively grazed or trampled. A high plant species diversity of more than 600 vascular plant species, found in a small area of 198 hectares, makes a striking feature of the site. It comprises 37% of all plant species found in Latvia. A high number of rare plants, included in the List of Protected Plants of Latvia) are recorded here, for example, *Herminium monorchis, Orchis mascula, Carex ligerica, Carex scandinavica, Dactylorhyza baltica, D. incarnata* and *Gladiolus imbricatus.* It is the only habitat of *Carex mackenzii* and *Eleocharis parvula* in Latvia.

East Latvia

Teièi and Peleèâre Mires

Teièi Mire is located within the Teièi Nature Reserve.Pelçèâre Mire is a protected nature area. Teièi and Peleèâre Mires has been a Ramsar site since 1995. The area of Teici Nature Reserve comprises 19,047 ha while the area of Peleèâre Mire is 4546 ha.

Within Teièi Mire there are 18 lakes larger than 2 ha covering a total area of 380 ha (Bergmanis, 1996).

Teici Mire started to develop about 10,000 years ago in the Preboreal (Lâcis, Kalniòa, 1998). The largest part of these mires consists of an open raised bog with bog lakes, pools and hummock-hollow complex. Transitional mire vegetation and fen vegetation is not so common. Raised bog vegetation of the eastern type is characteristic of these mires. The greatest value of Teièi Mire is the presence of mire communities characteristic of Eastern Latvia.

Presently, large areas have reached the last successional stage of mire development in the temperate climatic zone and form hummock-hollow and ridge-pool complexes (Bambe, 1993). Diversity of plant and animal species including rare ones is remarkable.

The bryophyte layer is homogenous and on hummocks mainly *Sphagnetum magellanici* and *Empetro nigri – Sphagnetum fusci* occur. Lichens, for example, *Cladina rangiferina, C. arbuscula and C. stellaris* grow there. Hepatics, including *Mylia anomala, Calypogeia sphagnicola* and *C. neesiana* add to the species diversity of hummocks.

Characteristic species of hollows are *Rhynchospora alba, Scheuchzeria palustris, Carex limosa, Drosera anglica* and, in the moss layer, *Sphagnum flexuosum.* In small hollows, and on the margins of larger ones, *Sphagnum tenellum* is the most frequent species. Quite often on pool margins there is a carpet of *Sphagnum magellanicum,* but small hummocks are formed by *Sphagnum rubellum. S. papillosum* occurs rarely. *Warnstorfia fluitans* grows in bog pools and lakes. In bog hollows, together with *Rhynchospora alba* moss species including *Cladopodiella fluitans, Cephalozia connivens, C. lunulifolia, Gymnocolea inflata* and *Mylia anomala* occur. Teièi Mire supports protected plant species of Latvia, including *Utricularia ochroleuca, Betula nana, Carex heleonastes, Eriophorum gracile, Liparis loeselii, Hammarbya paludosa, Carex aquatilis, Corallorhiza trifida* and the bryophytes *Helodium blandowii, Cinclidium stygium, Scapania irrigua* and *Drepanocladus vernicosus.* (Pakalne *et al.*, 1998).

Lubâna Plain Mires

Ten mires, six of which exceed 1,000 ha, are concentrated in the Lubâna Plain. The most valuable mires of this complex are Lagaþu-Sòitku Mire, Bçrzpils Mire, Sala Mire and Lubâna Mire. Large open raised bogs, bogs covered with pine and diverse minerotrophic mires support a high diversity of plant species, including rare ones. Hummock-hollow complex, bog pools and lakes occur in the raised bogs of the Lubâna Mire Complex. Strongly paludified mire margins and mineral islands covered with forest are characteristic of some of the mires.

The eastern bog community *Chamaedaphno – Sphagnetum magellanici* occurs there, characterised by the presence of *Chamaedaphne calyculata.* community. Plant species with northern and north-eastern distribution, for example, *Salix myrtilloides* and *Nuphar pumila* also grow in these mires.

Lubâna Lake, the largest lake in Latvia (80.7 km^2) is a part of this complex. Lubâna Mires include good examples of almost all types of wetlands found in Latvia – raised bogs, transition mires, fens, wet forests, river floodplain meadows and lakes, where a wide range of plant communities occurs. It supports protected plant species of Latvia, for instance, *Platanthera bifolia, Salix myrtilloides, Nuphar pumila, Hammarbya paludosa* and bryophytes, including *Sphagnum lindbergii* (one of the few known species localities in Latvia). Presently a Ramsar site is being established there comprising Lubana Mires and Lubâna Lake.

Coastal Lowland

Pape Lake and Nida Mire Complex

Pape Lake and Nida Mire Complex is situated in the very south-western part of Latvia. The area has a high natural history value, representing the Baltic Sea development history records in detail from the very beginning of the Litorina transgression up to the present day. A series of more ancient Baltic Ice Lake coastal terraces and accumulative land forms are located in the neighbourhood of the mire and the lake, subdivided by ancient mires, which are partly buried by the Litorina Sea and present dunes.

Pape Lake and Nida Mire represent the southern part of a large terrestrialised Litorina coastal lagoon chain that extends along the entire Latvian coast of the Baltic Sea. Thus, north from Pape Lake was Meíe Mire (transformed to arable land in the late 1950s), Liepâja Lake (65% overgrown), Tosmâre Lake (90% overgrown), Sârnate Mire (totally overgrown from the late 1960s). These ancient lagoons, following the coastal curve, are well represented in the Gulf of Rîga by, for example, Engure Lake, Babîte Lake, Kaòieris Lake, Kîðezers Lake and, partly, Jugla Lake. The last mentioned lakes and associated mires have similar geological history but a number of local specific differences occurring at Engure Lake will be discussed later.

The area comprises raised bog, transitional mire and fen vegetation. Part of Nida Mire includes a considerable area of rich fen vegetation dominated by *Caricetum lasiocarpae, C. diandrae* and includes a large population of *Dactylorhiza ochroleuca*. Amongst the bryophytes *Scorpidium scorpioides, Drepanocladus revolvens* and *Campylium stellatum* are in great abundance.

Raised bog vegetation of Nida Mire is represented mainly by *Sphagnetum magellanici* on hummocks and *Rhynchosporetum albae* in hollows. The species diversity is supported by diverse lichen species. A lawn community with *Trichophorum cespitosum* occurs there. Transitional mire communities are characterised by the dominance of *Carex rostrata* and *Sphagnum flexuosum*.

Fens near Pape Lake contain *Caricetum elatae, Caricetum distichae, Caricetum rostratae* and *Caricetum lasiocarpae*. Other communities with *Cladium mariscus* and *Myrica gale* cover large areas around the margins of Pape Lake.

Mires near Engure Lake

Engure Lake is located on the western coast of the Gulf of Rîga. It is the largest relict lake in the coastal area formed after the first and second regressions of the Litorina Sea when a flat, several kilometres wide inlet was separated from the open sea by an approximately 20 km long accumulative, sand dune spit (Eberhards, Saltupe, 2000).

The lake is 19 km long and 4.5 km wide with a total area of 3,500 ha. It is a shallow lake of mean depth 1m and it contains many islands. During the last three centuries a number of water level manipulation activities have been carried out on this lake, including substantial catchment re-arrangement in 1950s and early 1960s. Reed beds formed by *Phragmites australis, Typha angustifolia, Scirpus lacustris* and rich submerged vegetation now dominate in the lake together with *Cladium mariscus* around the margins.

Rich fen vegetation, characterized by *Schoenetum ferruginei*, has developed on peat in the terrestrialised western part of Engure lake and in depressions on previous lake sediments in the eastern part. .*Schoenus ferrugineus* is associated with a second dominant *Phragmites australis* and other species, including *Equisetum variegatum, Primula farinosa, Epipactis palustris, Carex panicea, C. flacca, Parnassia palustris* (Pakalne, 1994). In the bryophyte layer *Scorpidium scorpioides, Campylium stellatum, Calliergonella cuspidata, Fissidens adianthoides, Bryum pseudotriquetrum, Preissia quadrata* and *Aneura pinguis* are most abundant. In the central part of the area, small stands of *Cladium mariscus* occur.

High plant and animal diversity is recorded in this rich fen including some protected plant species, such as, *Schoenus ferrugineus, Dactylorhiza incarnata, D. cruenta, Liparis loeselii, Ophrys insectifera, Cladium mariscus* and the bryophytes *Moerckia hibernica* (one of the few known habitats of this species in Latvia) and *Riccardia multifida*.

Inter - dune mires

The very best examples of inter-dune mires are located in the coastal area of the Slîtere National Park, near Roja town and in the Ance Nature Reserve (Pakalne, 1998). They include numerous smaller and larger sites.

Mire vegetation is located between the coastal formations of the Litorina Sea parallel to the coastline of the Baltic Sea and the Gulf of Rîga (Fig. 3). The inter-dune mire complex comprises mainly poor and rich fen vegetation. Minerotrophic mire plant communities include *Caricetum lasiocarpae, Caricetum rostratae, Caricetum diandrae* and *Caricetum elatae*.

Smaller and larger lakes occur in the inter-dune mire complex, for example, Skabre Lake in the Ance Nature

Reserve. This lake is surrounded by ombrotrophic and minerotrophic mire vegetation.

Near Roja the inter-dune mire is one of the four localities of *Rhynchospora fusca* in Latvia. accompanied by *Myrica gale, Rhynchospora alba, Andromeda polifolia, Drosera anglica, D. rotundifolia, Trichophorum cespitosum, Sphagnum subsecundum, S. rubellum* and *Riccardia multifida.*

Baþi Mire belongs to the coastal raised bog type with a total area of 1,880 ha and is located in the Slîtere National Park. It borders with the inter-dune mire complex. *Sphagnetum magellanici* occurs on bog hummocks, but *Scheuchzerio – Sphagnetum cuspidati* and *Caricetum limosae* predominate in hollows and near bog pools.

The nature conservation value of the inter-dune mire complex is associated with the geological development of the area. It is connected with mire development and a high plant species diversity including a considerable assemblage of protected plant species, including *Juncus stygius*, , *Rhynchospora fusca* (one of four known localities in Latvia), *Malaxis monophyllos, Eriophorum gracile, Carex heleonastes, Trichophorum cespitosum, Dactylorhiza incarnata, D. maculata, Hammarbya paludosa, Drosera intermedia, Hydrocotyle vulgaris, Nymphaea alba, N. candida* and the bryophytes *Moerckia hibernica* and *Cynclidium stygium.* In addition, the rare plant community *Cladietum marisci* is present in a number of lakes of the inter-dune mire complex.

Mires of the Íemeri National Park

Favourable geological and hydrological conditions in the Íemeri National Park have resulted in an intensive mire formation. The area of the Íemeri National Park can be divided into two parts following the inland dune ridges. The north-east part, where Raganu, Slokas, Labais, Seklais, Kaðíu Mires and coastal lagoon lakes are located, is formed by the transgression of the Litorina Sea, but the south-western part with Íemeri –Smârde, Zaïais and Mazais tîrelis Mires was the result of abrasive-accumulation processes of the Baltic Ice Lake. Raised bogs, transitional mires, rich fens and sulphur springs all occur within the Íemeri National Park.

Of the eight bogs that were located originally in the Íemeri National Park only three have remained in their natural state. Íemeri-Smârde Mire is the largest and most valuable raised bog with an area of 9,562 ha. Mire development started during the Boreal Period in the relatively flat plain area that was covered earlier by the Baltic Ice Lake (Nikodemus *et al.*, 1997, Kalniòa *et al.*, 2003). The largest part of Íemeri -Smârde Mire, more than 8500 ha, is occupied by raised bog vegetation and only the northern and western bog margins include transitional mire vegetation. The bog area is characterised by a hummock-hollow complex and lakes.

Sphagnetum magellanici characterise the raised bog hummocks and carpets but *Empetro nigri – Sphagnetum fusci* – also occurs on some hummocks. In hollows *Rhynchospora alba, Carex limosa, Andromeda polifolia, Oxycoccus palustris* and *Drosera anglica* occur together with *Sphagnum cuspidatum, S. flexuosum* and *Cladopodiella fluitans.* Íemeri-Smârde Mire is one of the few known sites in Latvia of the rare moss *Odontoschisma sphagni. Sphagnetum magellanici* and *Rhynchosporetum albae* dominate in the raised bog vegetation. *Empetro nigri- Sphagnetum fusci* occurs more seldom on the higher hummocks.

Rich fen fragments are scattered throughout the Íemeri National Park, the largest of which are located near the ancient lagoon Kaòieris Lake. *Schoenetum ferruginei* is found there. In the herb layer *Schoenus ferrugineus* and *Carex lasiocarpa* dominate, accompanied by *Carex panicea, C. hostiana, C. dioica, Sesleria caerulea, Epipactis palustris, Primula farinosa* but in the bryophyte layer, *Campylium stellatum, Calliergonella cuspidata, Fissidens adianthoides, Scorpidium scorpioides* and *Bryum pseudotriquetrum* grow (Pakalne, 1998). Rich fen supports a number of protected plant species, including *Saxifraga hirculus, Schoenus ferrugineus, Cladium mariscus, Dactylorhiza ochroleuca, D. cruenta, Liparis loeselii, Primula farinosa, Pinguicula vulgaris* and *Carex buxbaumii.*

Íemeri National Park is one of the few places in Latvia where sulphur springs occur. The most typical are in Raganu Mire and near Kaòieris Lake where plant communities include *Cladietum marisci* and *Schoenetum ferruginei* (Salmiòa, 2003).

The other valuable mires in the Coastal Lowland include Dunika and Sârnate Mires.

<u>Dunika Mire </u>(1,391 ha), an open raised bog with pools and mineral i islands covered with pine forests, is located in the south-western part of Latvia, close to the Lithuanian border.. Transitional mire fragments with *Carex rostrata* occur on the bog margins. The bog plain is very wet. *Rhynchospora alba* and *Sphagnum tenellum* and *S. magellanicum* dominate the hollows. Medium size hummocks and bog carpets support mainly *Sphagnetum magellanici.*

Dunika Mire is a good example of vast a raised bog in a natural state. It also supports a mire community with *Trichophorum cespitosum*, typical of western raised bogs. Dunika Mire is the only recorded locality of *Sphagnum imbricatum* in Latvia.

Sârnate Mire is located in the western part of Latvia, close to the Baltic Sea, where it developed in a former ancient lagoon of the Litorina Sea. Sârnate Mire started to develop in the Preboreal (Mûrniece, et al., 1999). It is a raised bog in a natural condition with a total area of 3,271 ha. It is an open raised bog but there are no distinct hummocks in the bog plain. The mire surface consists of hollows and lawns where *Calluna vulgaris, Eriophorum vaginatum, Andromeda polifolia, Rubus chamaemorus* and different lichen species, such as, *Cladina nitis, C. portentosa* and *C. stygius* grow in the driest places (Kalniòa, Pakalne, 2003). *Rhynchospora alba* is the dominant species in bog hollows while *Trichophorum cespitosum* occurs occasionally in lawns. Sparse pine trees grow on the mire.

Sârnate Mire is geologically interesting with a macrofossil record of *Trapa natans*.

Western Latvia

Stikli Mires

Stikli Mires, located in the western part of Latvia, are influenced by the maritime climate and include 6 raised bogs, located close to each other. The area of mires varies from 281 ha to 2,019 ha. It is the greatest raised bog complex in Western Latvia and is characterised by bog pools, streams and hummock-hollow complex. The bogs are mostly open with sparse pine belts on the bog margins. The mosaic of mires with small lakes in their centre, surrounded by wet forests, has produced a large diversity of mire communities and species. The characteristic species of western bog types, *Trichophorum cespitosum,* occur here although the typical plant community, *Eriophoro - Trichophoretum cespitosi,* cannot be distinguished. Bog hummocks are characterised by *Empetro nigri – Sphagnetum fusci* and *Sphagnetum magellanici.* In bog hollows communities with *Rhynchospora alba* and *Carex limosa* occur. Transitional mire vegetation covering rather significant areas in the marginal parts of Stikli Mires includes *Caricetum rostratae.* Small fen fragments with *Carex lasiocarpa* occur also on mire margins. The rare bryophytes *Bryum cyclophyllum* and *Sphagnum lindbergii* grow on this raised bog.

Abava Rivey valley spring fens

This area includes rare and valuable spring fens of small size that are located on the Devonian dolomite stepwise slopes of the ancient Abava River Valley. They are situated in the Abava Nature Park. Mire communities, including *Caricetum davallianae, Schoenetum ferruginei* and *Cratoneurion commutati* are distinguished there. The bryophytes *Palustrella commutata, Cratoneuron filicinum, Bryum pseudotriquetrum, Fissidens adianthoides* and *Campylium stellatum* occur in the moss layer.

This type of fen and site geological history is quite rare in Latvia. Most of these sites were destroyed by human activities during the 1950s when peat and alkaline springs were used widely for soil improvement. Nevertheless, these sites require more substantial scientific study throughout the country as a whole.

Central Latvia

Suda Mire, located in the Gauja National Park of centre Latvia, has long been recognised to be of major scientific value. Suda Mire is a mire with total area of about 2,575 ha from which 2,339 includes raised bog vegetation, 188 ha – transition mire vegetation and 48 ha fen vegetation. Suda Mire has developed as a result of land paludification. There are 33 lakes in the mire. In the southern part sulphur springs occur. There are also several mineral islands .

Suda Mire is a typical raised bog with a number of bog lakes and pools. There are open bog areas as well as wooded ones. Transitional mire vegetation with *Carex rostrata* and *C. lasiocarpa* occurrs on the bog margins and near some of the bog lakes. Rare species include *Sphagnum balticum and Salix myrtilloides.*

Typical species of hummocks are *Empetrum nigrum, Calluna vulgaris, Eriophorum vaginatum, Rubus chamaemorus, Polytrichum juniperinum* but in hollows and near bog pools *Rhynchospora alba and Scheuchzeria palustris* are accompanied by the bryophytes *Sphagnum cuspidatum, S. tenellum, Cladopodiella fluitans* and *Calypogeia sphagnicola.*

Sphagnetum magellanici and *Empetro nigri – Sphagnetum fusci* characterise the bog hummocks, but *Rhynchosporetum albae, Caricetum limosae* and *Scheuchzerio – Sphagnetum cuspidati* are found the hollows. *Sphagnum magellanicum* lawns with *Trichophorum cespitosum* occur also. Suda Mire includes the rare mire community in Latvia – *Eriophoro - Trichophoretum cespitosi.*

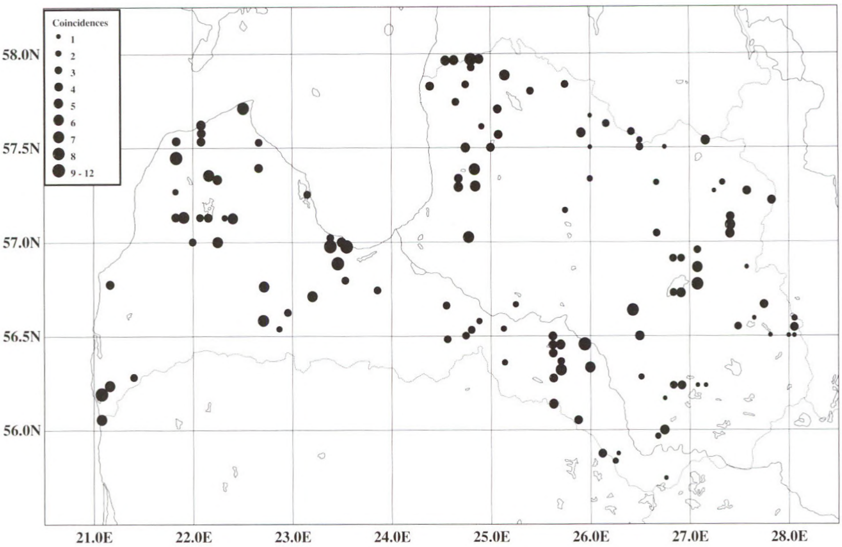

Figure 2. Distribution of the investigated mires during the course of the Latvian mire inventory

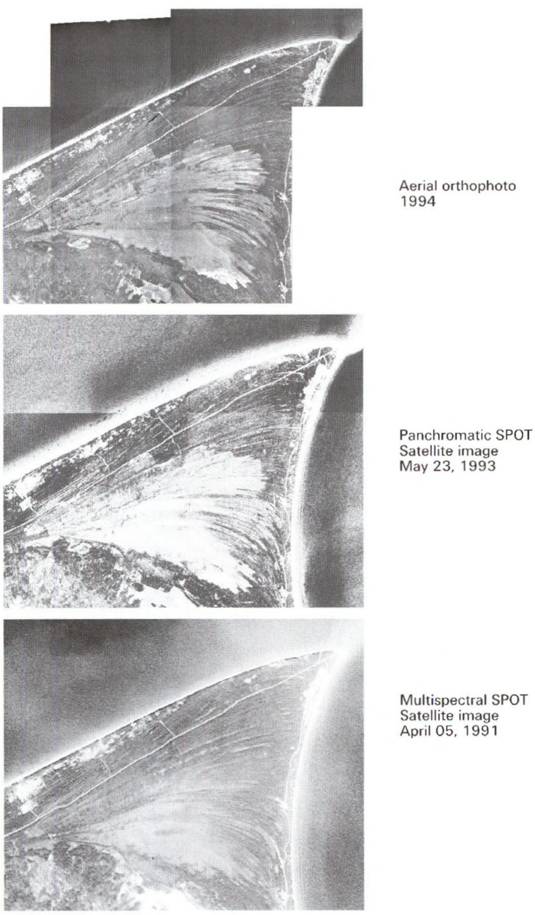

Fig. 3. Location of the inter-dune mire complex in the Coastal Lowland

The presence of mineral islands with different types of forest adds to the species richness of the mire. The mire supports a peculiar species composition, having together species of western and eastern distribution in Latvia, such as, *Trichophorum cespitosum* and *Chamaedaphne calyculata*.

Suda Mire is located close to Suda River that borders with spring and spring mire vegetation (Pakalne, Èakare, 2001). Spring area species include *Cirsium oleraceum, Poa palustris, Menyanthes trifoliata, Chrysosplenium alternifolium, Caltha palustris, Poa palustris, Crepis paludosa, Galium palustre, Cirsium palustre, Myosotis palustris.* It borders with vegetation that passes into transition mire vegetation characterised by *Betula humilis, B. pubescens, Salix rosmarinifolia and Frangula alnus* in the shrub layer, but *Eriophorum vaginatum, Comarum palustre, Equisetum palustre* occur in the herb layer. *Sphagnum teres* and *S. squarrosum* grow in the bryophyte layer and appear together with *Aulacomnium palustre* and *Calliergon stramineum.*

DISTRIBUTION OF MIRE COMMUNITIES IN LATVIA

Survey results of the most valuable mires of Latvia reveal that a wide range of plant communities occurs. Altogether 25 wetland communities were distinguished belonging to *Isoeto-Littorelletea, Montio-Cardaminetea, Phragmito-Magnocaricetea, Scheuchzerio-Caricetea fuscae, Oxycocco- Sphagnetea* and *Alnetea glutinosae.*

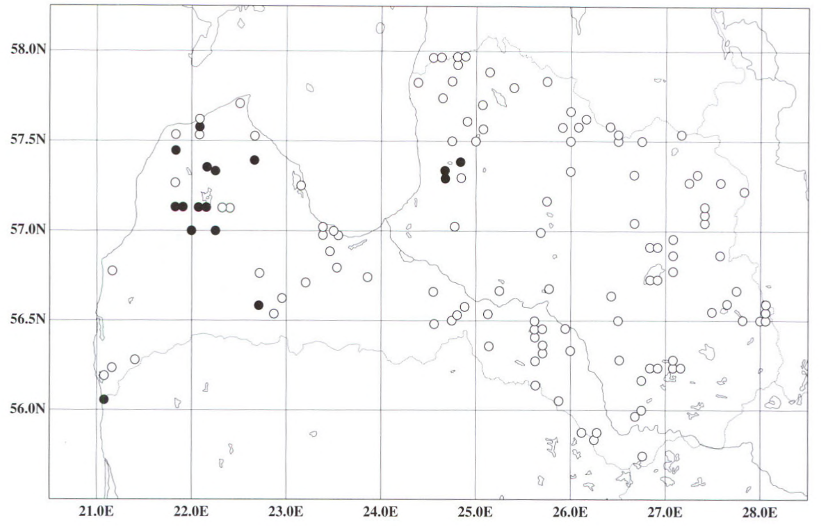

Figure 4. Distribution of Eriophoro -Trichophoretum cespitosi *in the studied mires.*

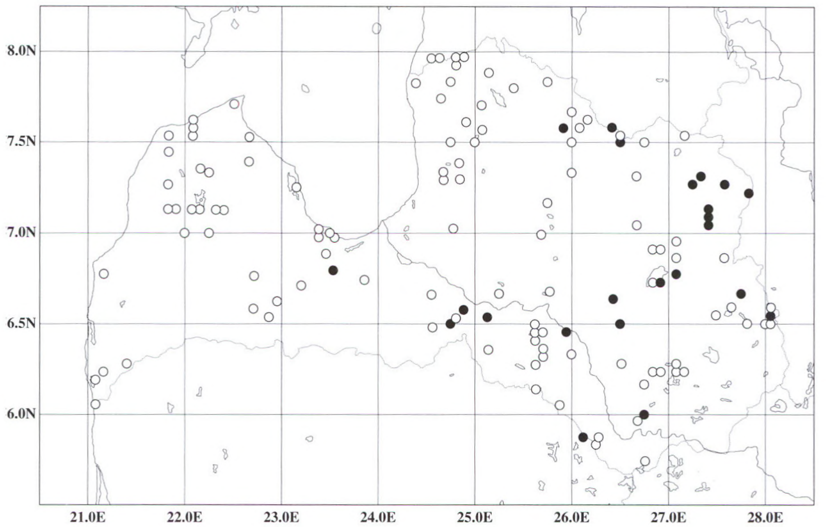

Figure 5. Distribution of Chamaedaphno-Sphagnetum magellanici *in the studied mires*

Some of these communities occur in all geobotanical districts, for example, *Caricetum rostratae, Caricetum lasiocarpae* in minerotrophic mires and *Sphagnetum magellanici, Empetro nigri – Sphagnetum fusci, Rhynchosporetum albae* in ombrotrophic mires.

Some mire communities are restricted, however, to certain districts only. For example, the main distribution area of the rare ombrotrophic mire community *Eriophoro vaginati - Trichophorum cespitosi* lies in the raised bogs of the Coastal Lowland although there are a few localities in West Latvia, North Vidzeme and Central Latvia geobotanical district (Fig. 4).

In contrast, *Chamaedaphno-Sphagnetum magellanici* is clearly characteristic of raised bogs in East Latvia (Fig. 5). In the bog hollows the most widespread association is *Rhynchosporetum albae* (Fig. 6), although *Caricetum limosae* is common in transitional mires and near bog pools (Fig. 7).

In the rich fen systems, four rare plant communities are recorded – *Cladietum marisci, Schoenetum ferruginei, Caricetum davallianae* and *Myricetum galis. Schoenetum ferruginei* is found mainly in rich fens of the Coastal Lowland, near lakes and sulphur springs. *Caricetum davallianae* is recorded from West Latvia

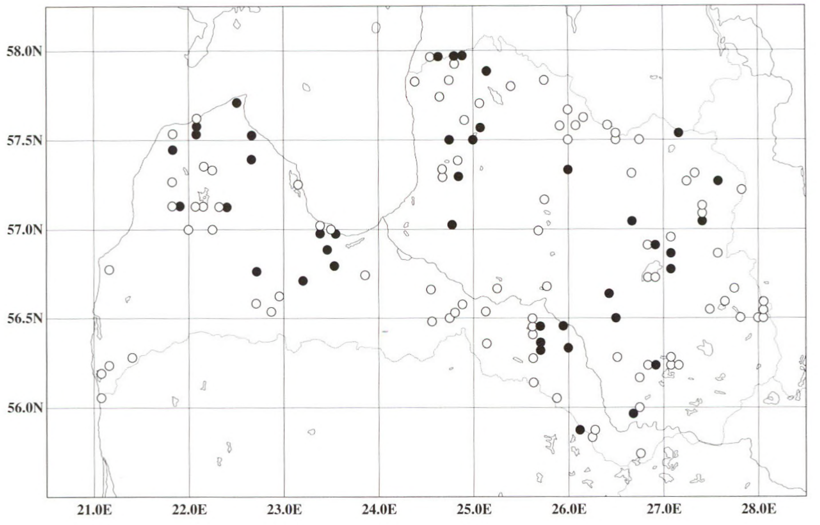

Figure 6. Distribution of Caricetum limosae *in the studied mires*

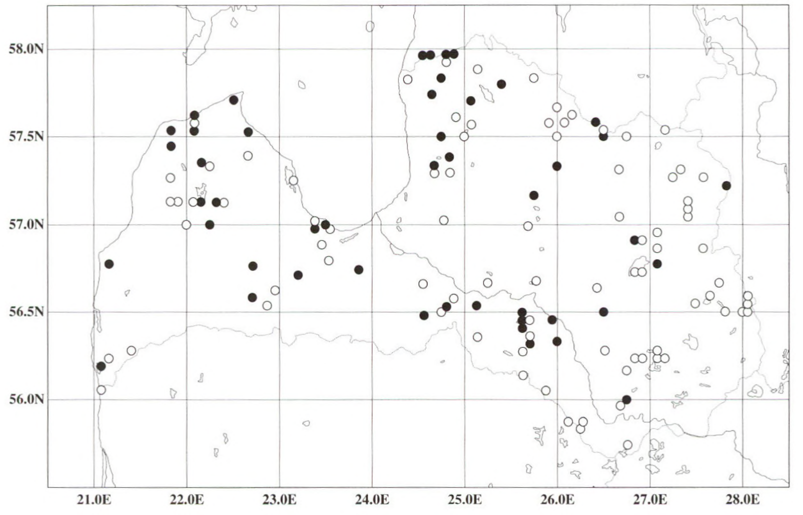

Figure 7. Distribution of Rhynchosporetum albae *in the studied mires*

geobotanical district where it occurs in a spring fen. *Myricetum galis* is located near lakes and in minerotrophic mires of Coastal Lowland and Western Latvia.

CONCLUSIONS

1. Latvian mires support a high biodiversity of species contained within a wide range and richness of plant communities. Many of the mire types are of international significance.
2. Altogether 25 wetland communities are distinguished in the most valuable mires of Latvia belonging to *Isoeto-Littorelletea, Montio-Cardaminetea, Phragmito-Magnocaricetea, Scheuchzerio-Caricetea fuscae, Oxycocco- Sphagnetea* and *Alnetea glutinosae.*
3. There are communities that occur in all geobotanical districts, for example, *Caricetum rostratae, Caricetum lasiocarpae, Sphagnetum magellanici, Empetro nigri – Sphagnetum fusci* and *Rhynchosporetum albae.* Some mire communities are restricted to certain districts of Latvia, for example, *Eriophoro - Trichophorum cespitosi* that occurs mostly in the raised bogs of the Coastal Lowland. In contrast, *Chamaedaphno - Sphagnetum magellanici* is clearly characteristic of raised bogs of East Latvia.

4. In rich fens, four rare plant communities are recorded - *Schoenetum ferruginei, Caricetum davallianae, Cladietum marisci* and *Myricetum galis.*
5. In many cases, small mire sites (up to 10 ha), especially spring mires, can support a great diversity of plants, including rare species. These mires are considered to be of great conservation value in spite of their small area.
6. Minerotrophic mires are of great importance. They support a large number of Latvian protected plant species, including *Cladium mariscus, Schoenus ferrugineus, Saussurea esthonica, Ophrys insectifera, Liparis loeselii, Dactylorhiza incarnata, D. cruenta, D. maculata, D. fuschsii, D. ochroleuca, D. baltica, Gymnadenia conopsea, Platanthera bifolia, Hammarbya paludosa, Corallorhiza trifida, Malaxis monophyllos, Primula farinosa, Pinguicula vulgaris, Saxifraga hirculus, Salix myrtilloides, Utricularia ochroleuca, Carex buxbaumii, C. scandinavica, C. heleonastes, C. davalliana, C. paupercula, Eriophorum gracile, Juncus subnodulosus, Rhynchospora fusca and Carex aquatilis* Protected bryophyte species, including *Cinclidium stygium, Moerckia hibernica, Riccardia multifida, R. chamaedryfolia, R. incurvata, Drepanocladus lycopodioides, Hamatocaulis vernicosus, Calliergon trifarium, Lophozia rutheana, Splachnum rubrum, Cinclidium stygium, Bryum neodamense, Meesia triquetra, M. longiseta, M. hexasticha, Riccardia multifida, Calliergon trifarium, Trichocolea tomentella, Paludella squarrosa* also occur.
7. Protected plant species, for example, *Betula nana, Trichophorum cespitosum, Salix myrtilloides, Drosera intermedia* occur in ombrotrophic mires. From the protected bryophyte species *Sphagnum molle, S. lindbergii, S. imbricatum, Odontoschisma sphagni, O. denudatum , Calypogeia sphagnicola, Splachnum pennsylvanicum* and *Bryum cyclophyllum* grow in raised bogs.
8. Protected plant species are also found in the coastal wetlands, including, *Trifolium fragiferum, Herminium monorchis, Orchis mascula, Carex ligerica, Carex scandinavica, Dactylorhiza baltica, D. incarnata, Gladiolus imbricatus, Glaux maritima, Blysmus rufus, Carex mackenzii* and *Eleocharis parvula.*
9. As a result of the survey results new protected areas, including mires, have been established , for example, Veseta River Floodplain Mire, and Linezers Lake.
10. Diversity of mire types and communities typical for Latvia is not adequately reflected within the range of currently protected sites. There is still a lack of information on minerotrophic mire distribution in Latvia. Detailed studies are to be continued with the aim of establishing new protected nature areas to protect the whole mire diversity in order to realise the principles of the "Convention on Biological Diversity".

ACKNOWLEDGEMENTS

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INSECT BIODIVERSITY OF CENTRAL EUROPEAN PEAT BOGS: THE HABITAT ISLAND CONCEPT OF CONSERVATION

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SUMMARY

Biodiversity of ombrotrophic mires is a phenomenon of three levels of biological organisation (Lindsay, 1995): (1) ecosystem diversity - habitat islands, (2) species diversity - biota of tyrphobiontic, tyrphophilous and tyrphoneutral species, and (3) genetic diversity of species populations - geographical races of isolated taxa. Synthesis of these three levels conforms to the conservation biology of isolated habitats of peat bogs in Central Europe.

Keywords: insects, relicts, peatbogs, tyrphobionts, Central Europe

THE BOG ECOSYSTEM - THE HABITAT ISLAND CONCEPT

Oligotrophic peat bogs form characteristic ancient habitat islands or paleorefugia (Nekola, 1999) within the temperate and southern boreal forest zones of Central Europe. The isolated pattern of these bogs has been determined by specific wetland succession during the Holocene reaching an edaphic climax of some habitat islands (see e.g. Jankovská, 1980; Rybníèek *et al.*, 1984; Spitzer *et al.*, 1999). Local micro- and meso-climate and relatively constant wetland environment of the mires have been the most important factors favouring survival of relict, cold adapted and stress tolerant species, often K-selected taxa. Because of the different histories of mires during the Holocene, each isolated large locality is unique in its species composition and genetic variability (Table 1).

THE SPECIES DIVERSITY - TAXONOMICAL APPROACH

The best method for evaluation of insect biodiversity associated with peat bogs seems to be the ecological groupings based on three classical categories.

Tyrphobionts

Tyrphobionts (see Peus, 1932; Spitzer, 1975; Rohácek, 1982; Mikkola & Spitzer, 1983; Spitzer *et al.*, 1999) are obligatorily associated with peat bogs in southern boreal and temperate zones. All the tyrphobiontic taxa have taxonomical and biogeographical affinities to boreal and subarctic zones of Northern Europe and Asia. Their most important ecological requirements are specific peat bog climate and edaphic conditions. There is a general trend to a weaker tyrphobiontic association towards the northern and alpine timber lines (Mikkola & Spitzer, 1983).

Most tyrphobiontic insect herbivores are closely associated with ericaceous shrubs, e.g. many larvae of Lepidoptera feed on *Vaccinium* species and/or *Ledum palustre* (Figure 1). Examples of characteristic tyrphobiontic moths and butterflies (Lepidoptera) are given in Table 1.

There are many other examples of other model tyrphobiontic species of other terrestrial and aquatic insects, for example, specific taxa of predatory Carabidae and Staphylinidae (beetles (Coleoptera)), some water bugs (Heteroptera) of the genus *Notonecta*, many stenotopic specialized taxa of flies (Diptera) in

Table 1. Tyrphobiontic Lepidoptera of Central European peat bogs.

Species	CB	ML	CS	JS	LS	HR	PM	IM	SH
Stigmella lediella (Schleich)	0	0	0	0	0	+	0	0	0
Lyonetia ledi (Wocke)	+	0	0	0	0	+	0	0	0
Glyphipterix haworthana (Stephens)	+	+	+	+	0?	+	+	+?	+
Coleophora ledi Stainton	+	0	0	0	0	+	0	0	+
Athrips pruinosella (Lienig & Zeller)	+	+	+	+	+	0	0	0	0
Chionodes viduellus (F.)	+	+	+	+	+	0	0	0	0
Chionodes lugubrellus (F.)	+	0	0	0	0	0	+	0	0
Chionodes nebulosellus (Heinemann)	0	+	+	+	+	0	+	0?	0
Olethreutes ledianus (L.)	+	0	0	0	0	+	0	0	+
Olethreutes turfosanus (Herrich-Sch▶ ffer)	0	+	+	0	0	0	0	0	+
Epinotia gimmerthaliana (Lienig & Zeller)	0	+	0?	+	+	0	0	0	0
Crambus alienellus (Germar & Kaulfuss)	0	+	+	+	0	+	+	0?	+
Pediasia truncatella (Zetterstedt)	0	+	+	+	+	0	0	0	0
Colias palaeno (L.)	+	+	+	+	+	(+)	+	+	+
Boloria aquilonaris (Stichel)	0	+	+	+	+	0	+	+	+
Proclossiana eunomia (Esper)*	0	+	0	0	0	0	+	0	0
Vacciniina optilete (Knoch)	+	+	+	+	+	(+)	+	+	+
Chloroclysta infuscata (Tengstr▶ m)	+	0	0	0	0	0	0	0	0
Eupithecia gelidata M▶ schler	+	0	0	0	0	0	0	0	0
Carsia sororiata (H▶ bner)	0	+	+	+	+	0	0	+	0
Arichanna melanaria (L.)	+	+	+	0	0	+	0	+	+
Syngrapha microgamma (H▶ bner)	0	0	0	0	0	0	0	0	+
Acronicta menyanthidis (Esper)	+	+	+	+	+	0	+	+	+
Amphipoea lucens (Freyer)	+	+	+	+	0?	0	+	+	+
Celaena haworthii (Curtis)	+	+	0	0	0	0	0	0	+
Lithophane lamda (F.)	+	+	+	+	0	0	0	0	+
Anarta cordigera (Thunberg)	+	+	+	+	+	(+)	+	+	+
Coenophila subrosea (Stephens)	0	+	0	0	0	+	+	+	0
Xestia rhaetica (Staudinger)	0	0	0	+	+	0	0	0	0
Xestia alpicola (Zetterstedt)	0	+	0	0	0	0	0	0	(+)
Total number of tyrphobiontic species	17	21	16	16	12	11	12	10	16

\+ = recorded, (+) old record, 0 = not recorded, ? doubtful record

CB = Červené Blato, basin raised bog, 472 m alt., Třeboň Basin, S Bohemia (Spitzer & Jaroš 1993).
ML = Mrtvý Luh near Volary, valley raised bog, 740 m alt., Šumava Mts., S Bohemia (Novák & Spitzer 1972, Spitzer 1975, Elsner et al. 1981, Jaroš & Spitzer unpubl. records).
CS = Chalupská slať near Borová Lada, upland raised bog, 950 m alt., Šumava Mts., SW Bohemia (Spitzer & Jaroš, unpubl. data).
JS = Jezerní slať near Kvilda, upland raised bog, 1050 m alt., Šumava Mts., SW Bohemia (Spitzer 1974, 1975, Elsner et al. 1981).
LS = Luzenská slať near Luzný (Lusen) Mt., upland raised bog, 1200 m alt., Šumava Mts., SW Bohemia (Jaroš & Spitzer, 1995 and unpublished notes).
HR = Hradčanské rybníky near Mimoň, basin raised bog, 275 m alt., N Bohemia (Vávra et al. 1996).
PM = P▶ rgschachen Moor near Ardning, valley raised bog, 635 m alt., Ennstal, Styrian Alps, Styria (Franz & Klimesch 1947, Spitzer et al. 1996).
IM = Ibmer Moor near Franking, raised bog, 425 m alt., Upper Austrian foothills of the Alps (Foltin 1954, 1973, Klimesch 1990).
SH = Suchá Hora, Orava bogs, valley raised bog, 765 m alt., W Carpathians Mts., N Slovakia (Janovský & Reiprich 1989, Gregor & Povolný 1951).
* *P. eunomia* is recently distributed outside peatbogs (acid wet meadows) – it seems to be not a tyrphobiontic species sensu stricto.

(After Spitzer & Jaroš 1993, modified)

the families Tipulidae and Tabanidae, and characteristic dragonflies (Odonata) associated with acid bog pools including *Aeschna subarctica* Wlk. All of these tyrphobionts are very important for characterization and evaluation of isolated peat bog localities for conservation (Peus 1932, Novák & Spitzer 1982, Spitzer *et al.* 1999).

Tyrphophilous species

Tyrphophilous insect fauna are not associated with peat bogs exclusively. This category is usually also characteristic for some other types of wetlands, for example, heathlands, acid wet meadows and some boreal forest types (Peus, 1932; Spitzer, 1981; Spitzer & Jaroš, 1993). The abundance of tyrphophilous insects, however, is always higher on peatlands compared to other wetland and forest habitats. Many tyrphophilous taxa are also very important subjects for conservation biology (Mikkola & Spitzer, 1983).

Tyrphoneutral species

Tyrphoneutral insects are widely distributed opportunistic species and their abundance is usually not very high on peatlands. As a result of modern human impact and destruction of natural landscapes in Central Europe, however, there has been a simultaneous decline in the number of tyrphoneutral insects (e.g. some moths and butterflies), and some species survive only on some peatlands. This phenomenon was described by Peus (1932) under the German term "Kulturfluchter" which means that such species are refugees on protected peatlands having 'escaped' from environmental destruction of other habitats (Peus, 1932; Spitzer, 1981). The idea of Peus's terminology is derived from the well known German word for the very opportunistic species that follow human culture and man-made habitats, namely, "Kulturfolger". *Phylodesma ilicifolia* L., which is extinct in some Western European countries, is a good example of a tyrphoneutral rare moth in Central Europe where its geographic range in Bohemia has recently been confined to several peat bogs. Early in the last century this moth was widely distributed outside of peatlands, occupying various types of open mixed forest and other habitats (Spitzer, 1981; Spitzer & Jaroš, 1993). A similar survival strategy to "Kulturflucher" seems to be characteristic also for some other vulnerable tyrphoneutral animals that have been associated recently with peat bogs. Peatlands are now very important refugia for vulnerable and endangered species within the "man made landscape".

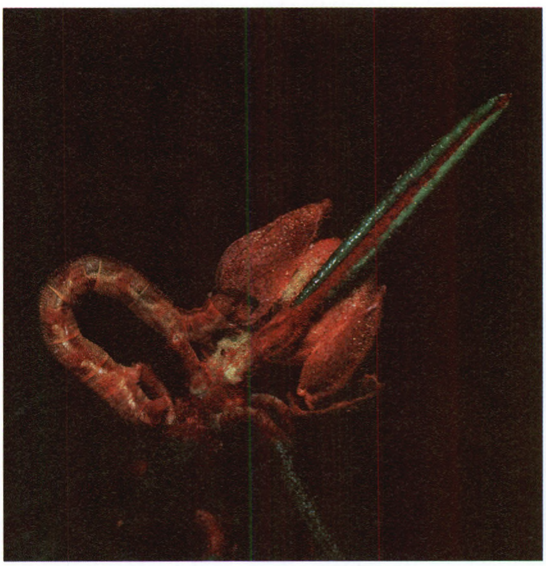

*Fig. 1: Larva of a subarctic geometrid moth (*Eupithecia gelidata *Moschl.) feeding on* Ledum palustre. *Relict tyrphobiontic population from the ervené Blato bog (South Bohemia).*

*Fig. 2: Larva of the Rosy marsh moth (*Coenophila subrosea *Steph.), associated with* Andromeda polifolia *(Mrtvý Luh bog, Šumava Mts.).*

Genetic diversity of tyrphobiontic species

Most of the isolated populations of tyrphobionts are locally characteristic geographical races or "subspecies". The best described examples are among moths and butterflies and some groups of beetles (e.g. species of the genus *Carabus*). In Central Europe a good example of genetic variability of a species is isolated populations of the tyrphobiontic noctuid Rosy Marsh Moth (*Coenophila subrosea* Steph.) (Fig. 2), several local geographical races of which are recorded from European peat bogs. In Bohemia two different local races have been recorded from two isolated bogs to each of which one species is endemic (Tillotson & Spitzer, 1998; Šula & Spitzer, 2000). Rosy Marsh Moth is also an important priority species for conservation in British bogs. A similar evolution of tyrphobiontic local populations is characteristic also for the butterfly *Colias palaeno* L. and the ground beetle *Carabus menetriesii* Humm. (Novák & Spitzer, 1982).

IMPLICATIONS FOR CONSERVATION

(1) Habitat island characteristics of oligotrophic peat bogs and their unique azonal biodiversity in Central Europe suggest a high conservation value of each specific locality. Research into bio-indicator groups of insects is basic for the complex evaluation of peat bog biodiversity (Spitzer *et al.*, 1999).

(2) The strategy of conservation is derived from the habitat island concept with preservation of the size of the bog habitat and its optimal hydrological conditions for survival of local biota. (see e.g. Bragg, 1989; Lindsay, 1995). In central Europe the optimal conditions are usually bio-indicated by the edaphic "forest/tundra" biome, which is often dominated by the endemic plant association *Pino rotundatae-Sphagnetum* and its associated tyrphobionts (see localities in Table 1.

(3) Referring to the "habitat island archipelago" of bogs, e.g. the unique Ramsar peatlands of the Šumava National Park, the conservation of the complete island complex is necessary.

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Note: Most of the references in Czech and German were published with English summaries.

TERRESTRIALIZATION OF A PEAT LAKE IN THE SIKKIM HIMALAYA, INDIA

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SUMMARY

The present study was conducted in a 7.01 ha peatland, which is an inter-linking zone between the open water and upland forest of the sacred Khecheopalri Lake in the Sikkim Himalaya. Peat formation started around 3400 years ago with the oldest age near to the forest edge and recent formation towards the lake periphery. The study revealed that successional and terrestrialization processes were dominated by mosses and herbs at the lake edge and woody arboreal species near the forest edges. The spatial expansion and depth of the peat was greater in the disturbed site compared to the undisturbed site with a dominance of *Sphagnum* moss. Acidity and organic matter content were higher near the lake edge while total phosphorus and calcium followed the reverse trend having the highest values near the forest edge. The bulk density of the peat varied widely, with higher values near forest edges. Micro-relief topography and the concavity of the lake basin revealed slow transportation of peat to the lake bottom thus reducing the depth of the lake.

Keywords: Nutrients, peat stratigraphy, radio carbon dating, succession, watershed, India

INTRODUCTION

Peatlands are wetland ecosystems that develop when plant production is greater than decomposition. Specific geographical and geological characteristics (climate and atmospheric chemistry, watershed geology and hydrologic turnover) and openness of a site largely determine peatland development and its overall chemical composition (Heinselman, 1970). Peatlands exist throughout the world, particularly in northern temperate and boreal latitudes and are common features of glaciated landscapes (Curtis, 1959; Larsen, 1982). They cover about 3% of the earth's surface, or about 400 million hectares, mostly in the former Soviet Union, Canada, Indonesia and the United States (Joosten & Clarke, 2002). Peatland in India occupies 32,000 ha (Bord na Mona, 1985) but detailed information is not available except for some preliminary work carried out by Scott (1989). The present study was designed to investigate the peatland formation and its age, succession and terrestrialization, and nutrient dynamics of the sacred Khecheoplari Lake in the Sikkim Himalaya.

THE STUDY AREA

The present study was conducted in the sacred Khecheopalri Lake known as the "wish fulfilling lake" situated at $27^0 22' 24''$ N and $88^0 12' 30''$ E at an altitude of 1700 m above sea level in the western part of the Sikkim Himalaya. The lake represents the original 'neve' region of the ancient hanging glacier, the depression being formed by glacial scooping action (Raina, 1966) (Fig. 1). The lake has an open water area of 3.8 ha with 7.01 ha of peatland within an upland watershed of 12 km^2, of which 91 ha drains directly to the lake (Jain *et al.*, 2000). Geologically the rocks belong to the Darjeeling group comprised chiefly of high-grade gneisses containing quartz and feldspar with streaks of biotite (Geological Survey of India, 1984).

Table 1. Site characteristics of Khecheopalri peatland

Site	Aspect	Distance (m)	Depth (cm) Water	Depth (cm) Peat	Dominant species	Types of disturbance
I	NW	2	3	175	*Sphagnum nepalense, Brachiaria eruciformis , Arundo donax*	Tourism, Pilgrimage and settlement
		30	2	159	*Sphagnum nepalense, Polygonum* sp., *Arundo donax,*	
		60	20	102	*Acorus calamus, Juncus reflexa, Oenanthe thomsoni*	
II	SW	2	2	500	*Sphagnum nepalense, Acorus calamus, Brachiaria eruciformis Juncus reflexa*	Trampling, grazing, fuel-wood, timber collection, agricultural practices settlements and cowsheds
		30	4	385	*Sphagnum nepalense, Equisetum debele, Acorus calamus, Potentilla pedencularis*	
		60	12	320	*Acorus calamus, Sphagnum nepalense, Potentilla pedencularis*	
		90	132	170	*Cyperus rotundus, Hemiphragma heterophylla*	
III	NW	2	4	153	*Sphagnum palustre, Saccharum* sp., *Juncus reflexa*	Fuel-wood and timber collection
		30	8	146	*Saccharum* sp., *Diplazium umbrosum, Sphagnum palustre*	
		60	10	110	*Juncus reflexa, Equisetum sp., Oenanthe* sp. *Vaccinium* sp.	
		90	53	60	*Eupatorium* sp., *Symingtonia populnea, Alnus nepalensis*	
IV	SW	2	2	207	*Sphagnum nepalense., .Arundo donax, Brachiaria eruciformis*	Fuel-wood and timber collection
		30	6	103	*Sphagnum palustre., Rhododendron lindleyi, Berberis wallichiana*	
		60	7	90	*Rhododendron lindleyi, Cyperus rotundus,,Anaphalis contorta*	

Site I & IV do not have peatland at 90 m distance

The soil is sandy loam in nature. Climate of the area is monsoonic and divisible into three seasons, rainy (June to October), winter (November to February), and spring (March to May). Mean annual precipitation was 3837 mm and temperature ranged from 4^0C to 24^0C during 1997-1998 (Jain *et al.*, 2000).

The watershed has mixed broad-leaved forests and agricultural land with 35 households residing in the top fringe and another 80 households in the vicinity. These people depend on the resources of the watershed forest. The lake water is not used for any other purposes except for rites and rituals. Fishing and boating are strictly prohibited. The lake is a resting-place for Trans-Himalayan migratory birds. There are some visible impacts of disturbance on the pristine nature of the lake and commercial and recreational tourism are high (18,713 in 1998) (Maharana *et al.*, 2000).

MATERIALS AND METHODS

Four sites were selected for the peatland study of which sites I and II have been disturbed and sites III and IV are relatively undisturbed (Fig. 1). A transect was laid out across each site perpendicular to the lake margin from the lake edge towards the forest edge and along which peat characteristics were determined at distances of 2, 30, 60 and 90 metres. Site characteristics are given in Table 1.

Stratigraphy (vertical strata) of the peatland was documented on the basis of visual colour differences, degree of decomposition, botanical composition and structure. The thickness of the peat strata was measured with a metal scale (Kratz & DeWitt, 1986). Peat bulk density was determined at one depth (50 cm). Per cent organic matter of oven-dried peat samples was determined by ignition at 450°C for 6 hours (Kratz & DeWitt, 1986). Radiocarbon dating was carried out at depths of 50, 100 and 150 cm on transect II. Samples of peat were removed through systematic excavation with a peat borer and were air dried and packed in aluminum foil before sending them to Birbal Sahni Institute of Paleobotany, Lucknow, India for ^{14}C radio carbon dating.

Cores for total nutrient analysis were taken in 1997 and 1998 from all of the sites at 0-50 and 50-100 cm depth intervals below the surface. Wet samples were transferred immediately to polyethylene bags to avoid excessive air contact. The samples were dried and sieved through a 2 mm mesh. Peat pH was determined using a digital pH meter and total nitrogen by a modified Kjeldahl method following Anderson &

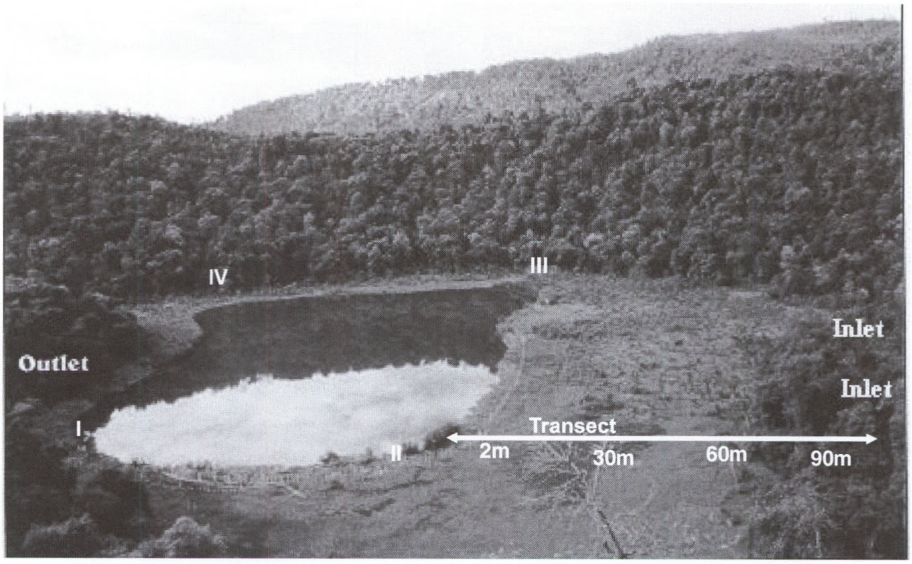

Fig. 1. Khecheopalri lake showing the peatland development around the Khecheopalri lake and the upland watershed. Different sites and locations taken for peatland studies are marked.

Ingram (1993). Total phosphorus was estimated by the chloro-stannous reduced molybdophosphoric blue colour method (Jackson, 1967) and total calcium was determined by titration following the method of Allen (1989).

The vegetation in the Khecheopalri peatland was extensively surveyed during 1997-99 and the plants were identified following standard literature (Hooker, 1857; Smith & Cane, 1911; Ganguly, 1972; Polunin & Stainton, 1984). Plant cover gradient of the peatland was estimated at four transects; considering four zones (2 , 30 , 60 and 90 m) at transects II and III and three zones (2 , 30 and 60 m) at transects I and IV from the lake edge towards the forest edge by random quadrats of 1×1m (n=48; 12 quadrats at each transect) for herbs, 5×5m (*n*=32; 8 quadrats at each transect) for shrubs and 10×10m (*n*=16; 3 quadrats each in transect I and IV and 5 quadrats each in transect II and III) for trees. Two quadrats were placed at 90m distance on both sides of the transect line adjacent to each other on transects II and III owing to the heterogeneity of tree species towards the forest.

Plant density (number of individuals of a species for unit area), frequency and basal area (average cross sectional area of the individual plants taken at or near the ground surface per unit area) of the ground vegetation of the peatland were studied seasonally (spring, rainy season and winter) during 1998 by placing random quadrats 1×1 m (n=75).

The exogenous supply of organic debris was estimated through the overland flow (Jain *et. al.*, 2000) and calculated with reference to the total runoff from the different land uses that drained the area using the delivery ratio (Sharada *et al.*, 1992; Jain *et al.*, 2000).

Analysis of variance (ANOVA) was carried out using a Microsoft Windows based statistical package (Systat, 1996).

RESULTS

Peat stratigraphy

Three relatively discrete strata are found in the Khecheopalri peatland.

1. Mat peat, which consists of poorly decomposed peat of *Sphagnum*, herbs, wood pieces and twigs. The organic matter varied from 45-93% with higher values at lake edges. The peat is light brown in color with identifiable interconnected plant remains. The mat varies in thickness from 89 to 218 cm from the lake edge to the forest edge in transect II as shown in Figure 2.
2. Debris peat that consists of moderately decomposed organic matter formed from the mat peat. Its organic content is 13-83% with a thickness ranging from 93 to 262 cm (Fig. 2).
3. Below the mat and debris peat is the gyttja layer of the lake bottom with an organic matter content of 30-70 %. The lake sediment material is dark brown to black and slimy, jelly-like without fibre content. The thickness increases from the forest edge towards the lake (5 to 97 cm) following the shape of

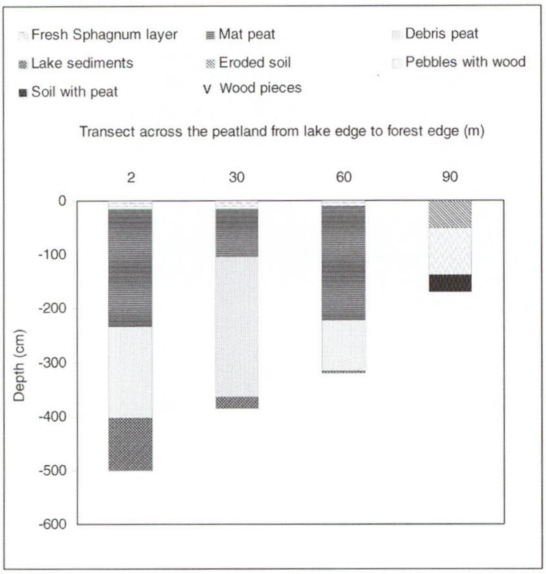

Fig. 2. Stratigraphic boundaries of the peat strata along transect from the lake edge to forest edge across the Khecheopalri peatland.

the concave basin (Fig. 2). At 90 m distance, near the forest edge, there is soil up to 50 cm depth that has been eroded from the watershed. Below this layer pebbles and wood pieces are encountered under which a mixture of peat and soil is found. Bulk density varies widely (0.074-0.917 g cm^{-3}) with distance along transects II and III with lowest values towards the lake edge (Fig. 3), although it varies significantly with sites and distance. The organic matter contents of the peat samples show a reverse trend with gradual decrease from the lake periphery towards the forest margin (Fig. 3). Analysis of variance showed significant differences of organic matter content between sites, depth and distances along transect from lake edge to forest edge.

^{14}C Radio Carbon Dating

Peat formation started about 3400 years ago as indicated by the buried sample at 90 m distance along transect II. Depth wise age of peat increased from modern (550 ^{14}C age) for 50 cm depth, 100-760 ^{14}C age for 100 cm depth and 1410-2770 ^{14}C age for 150 cm (Table 2). The peat from 60 m distance at 50 and 100 cm depth was found to be greater in age than the peat between 2m and 30 m distance. However, at 60 m distance at 150 cm sample the mean calibrated age was found to be only 1312 but at a similar depth at 30 m distance it was 2860 (Table 2). The analysis of variance showed that ^{14}C age of peat varied significantly with the various peat depths (r^2 = 0.992, P<0.001) and showed strong positive correlation (0.988). The distance also varied significantly (r^2=0.992, P<0.001) but showed a negative correlation

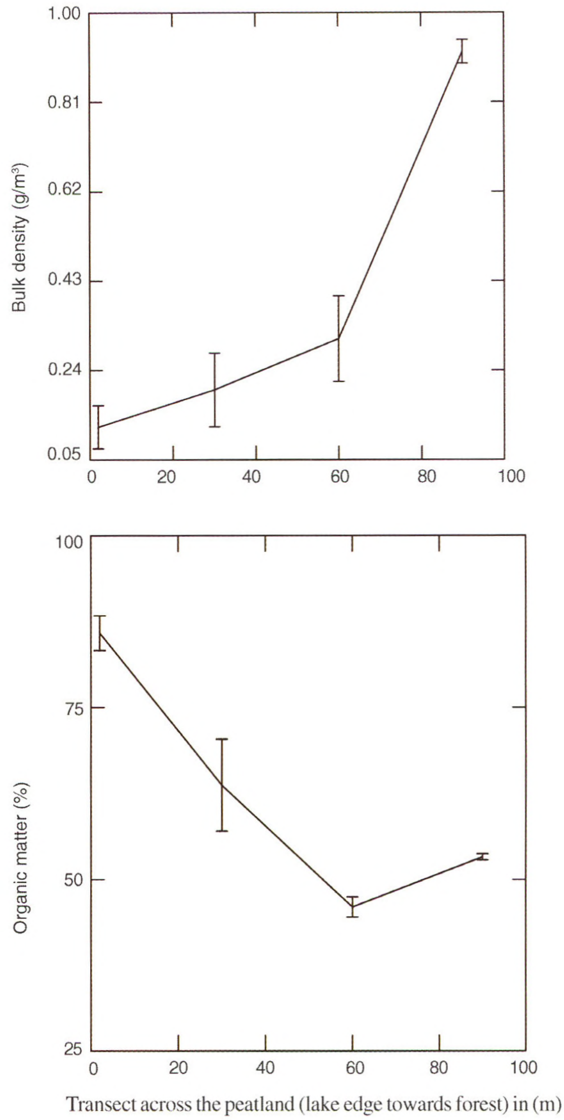

Fig. 3. Bulk density (a) and organic matter (b) along transect from the lake edge to forest edge across the Khecheopalri peatland.

ANOVA- *Bulk density Site $F_{3,24}$=368, P<0.001; Distance $F_{3,24}$=372, P<0.001; Site x Distance $F_{9,24}$=182, P<0.001; LSD (0.05)=0.02. Organic matter Site $F_{3,48}$=347, P<0.001; Distance $F_{3,48}$=1488, P<=0.001; Depth $F_{1,48}$=740, P< 0.001; Site x Distance $F_{9,48}$=182.5, P<0.001; Site X Depth interaction not significant, Site x distance x Depth $F_{9,48}$=14, P <0.001, LSD (0.05)=1*

(-0.326). The radio carbon dating of wood encountered at 120 m distance showed a calibrated age of 886-670 B.P.

Peatland formation

The history of peat formation at the sacred Khecheopalri, glaciated lake, dates back to 3400 years before present. The geological setting and land use transformation accelerated soil erosion processes that, with the movement of sediment and nutrients, resulted in the elevation of the periphery of the lake basin (Fig. 4). The high rainfall and favourable climate resulted in the development of a thick spongy mat dominated by *Sphagnum* moss with slightly elevated surface. This was invaded, at the peatland margins, by a number of plant species from the upland forest. Vegetation covers the open water surface where it developed a floating mat in a centripetal manner around the lake. From this floating mat the peat slipped down to the lake bottom (Fig. 4).

Vegetation composition

A list of plants found in the bog is presented in Appendix 1. Seasonal analysis of herbaceous vegetation showed only 20 plant species in the peatland during the spring season, which increased to 26 species in the rainy season and again reduced to 23 species in the winter season. The density (585 plants m^{-2}) and basal cover (28.96 cm^2 m^{-2}) were recorded highest in the rainy season (Table 3). The *Sphagnum* moss alone contributed around 48% and 37% of basal cover of all the species during rainy and winter seasons, respectively.

Succession and terrestrialization

The succession study showed that there was a sequential pattern of plant distribution in the peatland along transects from lake edge to forest edge. Highest basal coverage to 2 m distance from the lake was by mosses (87.9%) with some herbs (7%) and shrubs (6%). The per cent basal coverage of the mosses decreased to 65% at 30 m from the lake whereas the

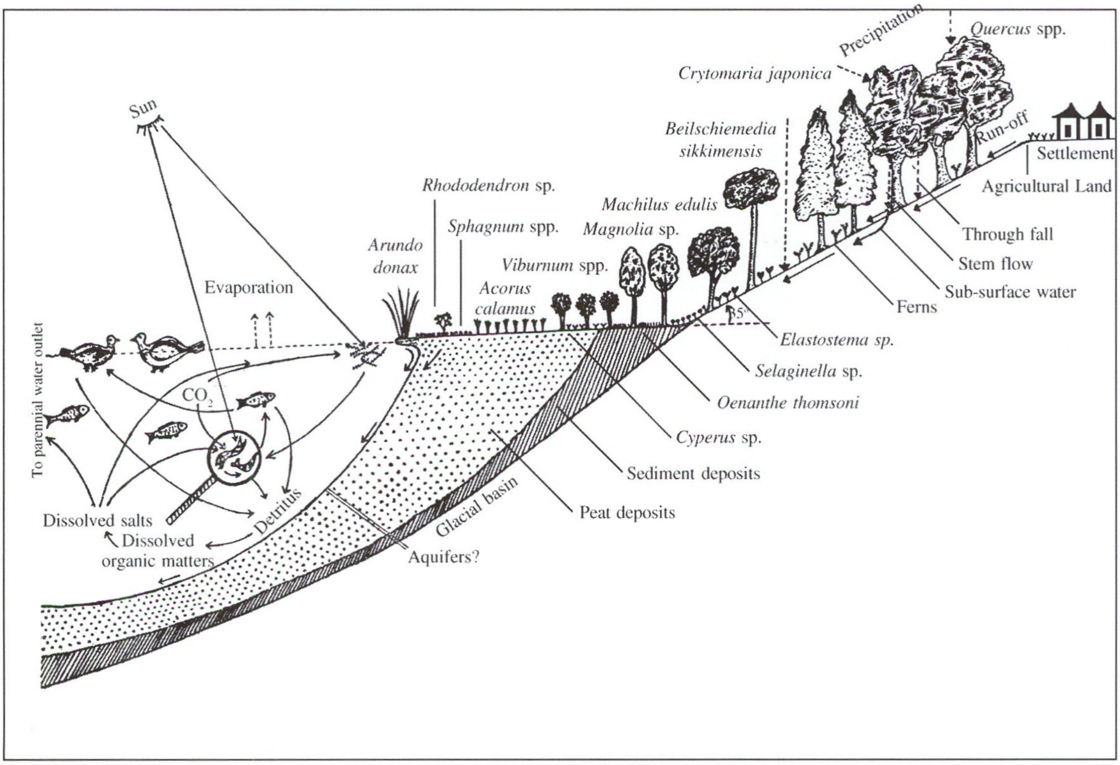

Fig. 4. Diagrammatic sketch of peatland formation in the Khecheopalri lake and its vertical transaction showing profilatic pattern of sedimentation processes, vegetation succession pattern and biotic interactions.

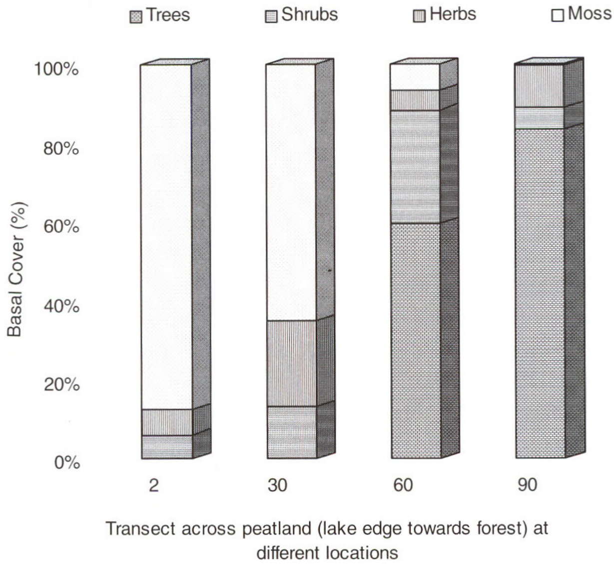

Fig. 5. Succession and terrestrialization of vegetation along transect from the lake edge to forest edge across the Khecheopalri peatland.

Table 2. Radiocarbon ages of Khecheopalri peatland.

Dated Material	Distance from lake (m)	Sample depth (cm)	Measured ^{14}C age	Calibrated age range (B.P.)
Peat	2	50	Modern	NA
Peat	2	100	220±70	284
Peat	30	50	Modern	NA
Peat	30	100	100±80	61-43
Peat	30	150	2770±90	2950-2770
Peat	60	50	550±80	640-511
Peat	60	100	760±70	725-655
Peat	60	150	1410±70	1346-1278
Peat	90	50	Modern	NA
Peat	90	80	2080±80	2140-1940
Peat	90	120	2970±100	3326-2959
Lake sediments	Lake periphery	700	37730±1300	NA
Charcoal[a]	120		260±80	430-0
Wood[b]	120	100	840±80	886-670

a = old burnt tree; b = wood piece collected from peat depth

Table 3. Seasonal variation of frequency, density and basal cover of the herbaceous vegetation of the Khecheopalri peatland.

Species	Frequency (%)	Density (plant/m^2)	Basal cover (cm^2/m^2)
Spring			
Sphagnum palustre.	11	65.65	2.06
Sphagnum nepalense	33	196.95	6.18
Acorus calamus	28	12.60	9.90
Oenanthe thomsoni	52	21.64	2.72
Amaranthus sp.	60	27.48	0.86
Brachiaria eruciformis	44	18.88	0.15
Plantago erosa	28	1.80	0.90
Cyperus rotundus	20	5.36	1.05
Lycopodium cernum	24	2.40	0.31
Anaphalis contorta	16	4.00	0.50
Centella asiatica	16	7.00	0.06
Other species		6.60	0.91
Total species		370.36	25.6
Rainy			
Sphagnum palustre	24	111.25	3.49
Sphagnum nepalense	72	333.75	10.48
Brachiaria eruciformis	64	48.16	0.38
Amaranthus sp.	56	23.68	0.74
Plantago erosa	4	0.08	4.02
Acorus calamus	28	2.40	1.88
Fimbristylis sp.	40	12.00	0.85
Heidychium ellipticum	28	2.00	1.57
Commelina paludosa	44	11.08	0.30
Oenanthe thomsoni	24	6.36	0.79
Potentilla peduncularis	20	3.40	0.96
Other species		31.28	3.49
Total species		585.44	28.96
Winter			
Sphagnum palustre	18	83.17	2.53
Sphagnum nepalense	54	249.51	7.59
Brachiaria eruciformis	84	61.88	0.49
Acorus calamus	12	8.80	6.91
Cyperus rotundus	36	12.04	2.36
Oenanthe thomsoni	32	10.56	1.32
Fimbristylis sp.	40	8.56	0.56
Vaccinium nummularia	32	3.48	0.44
Juncus reflexa	40	2.64	0.09
Plantago erosa	12	0.80	1.50
Lycopodium cernuum	32	3.08	0.38
Other species		14.44	3.26
Total species		448.96	27.42

Table 4. Exogenous deposition of organic debris from the drainage area of the lake watershed to the peatland.

Site	Land use/cover	Area (ha)	*Organic debris carried to peatland through run-off (Mg/year)
I	Forest land	5	3.93
	Cardamom agroforestry	0.1	0.03
	Agricultural land	4	5.09
	Total		9.05
11	Forest land	7.5	5.90
	Cardamom agroforestry	-	-
	Agricultural land	3	3.82
	Total		9.72
111	Forest land	40	31.44
	Cardamom agroforestry	-	-
	Agricultural land	0.5	0.64
	Total		32.08
IV	Forest land	30	23.58
	Cardamom agroforestry	0.9	0.31
	Agricultural land	-	-
	Total		23.89
	Total lake watershed	91	74.74

*Calculation based on delivery ratio (cardamom agroforestry (30%); forests (60%) and agricultural land (80%)

herbs and shrubs increased by 21% and 13%, respectively (Fig. 5). A few trees (0.07%) were also found to be growing at this distance. Gradually, the wet and swampy condition changed to drier and mesic conditions at 60 m from the lake towards the forest where the percentage of herbs and mosses declined drastically to 5% and 6.5%, respectively. However, the contribution of shrubs increased to 29% and that of trees to 60%. At 90 m distance moss became negligible (0.28%) while herbs increased slightly to 11% and shrubs decreased to 5.4%. The maximum (84%) coverage here was of tree species (Fig. 5).

Nutrient dynamics

The total area of the lake watershed draining into the lake and peatland is 91 ha. The organic matter transported from the watershed is accounted for by 127 g m^{-2} yr^{-1} from agricultural land, 78.6 g m^{-2} yr^{-1} from forest, and 33.9 g m^{-2} yr^{-1} from cardamom based agroforestry systems. The highest deposition was from the forest with 64.8 Mg yr^{-1} followed by agricultural land 9.5 Mg yr^{-1}. The net organic deposition in the lake was 0.8 Mg ha^{-1} yr^{-1} (Table 4).

The nutrient contents of the peat samples are presented in Table 5. The pH of the peat materials was acidic, ranging from 4.01 to 5.85 and was higher at the forest edge. Analysis of variance of pH showed significant differences with sites, distance, depths and year. Total nitrogen varied significantly with sites, distance, depth, and year with concentration being generally higher in the upper layer (0-50 cm) compared to the lower depth (50-100 cm). It ranged from 0.73% to 1.42% in different depths. Total phosphorus was low and ranged from 0.003% to 0.071% and increased with depth. Total phosphorus did not vary between sites and year but varied significantly between distance and depth. Calcium was low and ranged from 0.021%

Table 5. Nutrient concentration of peatland at two depths of four sites along the distance from lake periphery to forest edge. Values are means of 1997 and 1998 (n = 6).

Site	Depth (cm)	Distance (m) 2				30				60				90			
		pH	TN	TP	Ca	pH	TN	TP	Ca	pH	TN	TP	Ca	pH	TN	TP	Ca
I	0-50	4.41	0.83	0.017	0.056	4.07	1.42	0.008	0.064	5.35	1.15	0.008	0.064	-	-	-	-
	50-100	4.79	0.87	0.019	0.072	4.51	1.50	0.046	0.077	5.13	1.26	0.070	0.081	-	-	-	-
II	0-50	4.01	1.19	0.018	0.071	4.91	1.42	0.016	0.077	4.83	1.31	0.029	0.076	4.96	1.15	0.050	0.132
	50-100	4.28	0.95	0.019	0.073	5.11	1.37	0.028	0.078	5.29	0.91	0.047	0.080	5.24	1.13	0.045	0.139
III	0-50	4.58	1.05	0.013	0.062	4.56	1.21	0.017	0.081	5.79	0.85	0.026	0.081	5.42	1.17	0.071	0.152
	50-100	4.71	0.87	0.023	0.065	4.96	0.82	0.036	0.086	5.71	1.11	0.043	0.087	5.85	1.08	0.064	0.154
IV	0-50	4.05	1.29	0.003	0.021	4.57	0.77	0.004	0.022	5.34	0.73	0.025	0.023	-	-	-	-
	50-100	4.45	0.89	0.005	0.022	4.79	0.65	0.005	0.025	5.62	0.68	0.025	0.024	-	-	-	-

TN = total nitrogen (%); TP = total phosphorus (%); and Ca = Calcium (%); dash = no peatland at this distance.

ANOVA: pH - Site $F_{3,96}$=19.28, P<0.001; Distance $F_{2,96}$=14.34, P<0.001; Depth $F_{1,96}$=83.37, P<0.001; Year $F_{1,96}$=171.9, P<0.001; LSD $_{(0.05)}$=0.08. Total nitrogen - Site $F_{3,96}$=59.95, P<0.001; Distance $F_{2,96}$=19.73, P<0.001; Depth $F_{1,96}$=66.55, P<0.001; Year $F_{1,96}$=88.63, P<0.001;LSD$_{(0.05)}$=0.04. Total phosphorus - Site not significant; Distance $F_{2,96}$=11.72, P<0.001; Depth $F_{1,96}$=6.37, P<0.05; Year not significant; LSD$_{(0.05)}$=0.007. Calcium - Site $F_{3,96}$=422, P<0.001; Distance $F_{2,96}$=88.49, P<0.001; Depth $F_{1,96}$=18.78, P<0.001; Year $F_{1,96}$=36.02, P<0.001;LSD$_{(0.05)}$=0.003. Interactions were mostly significant in all the cases (ANOVA calculated upto 60 m distance).

to 0.154% and showed increasing trend from the lake edge towards forest edge. Calcium varied significantly among sites, distance, depth and year (Table 5).

DISCUSSION

Peatland formation is intimately tied to geographical setting, hydrology, vegetation biomass and the succession and chemistry of an area thus involving both physical and biotic processes. Khecheopalri Lake had an open water area of 7.4 ha and peatland of 3.4 ha recorded in 1963 but this changed over 35 years with the open water area being reduced to 3.8 ha and peatland increased to 7 ha (Jain *et al.*, 2000). The peatland is covered with 85% of herbaceous vegetation and moss and 15% by shrubs and woody vegetation. Sediments are filling up the lake gradually through peatland increase and sliding of peat. Around 141 Mg of sediments along with 1.42 Mg of total nitrogen, 0.31 Mg of total phosphorus and 6.88 Mg of organic carbon annually have found their way to the lake (Jain *et al.*, 2000). Peat bulk density was low at the lake edge and gradually increased along the transects and showed a positive correlation (0.701) with distance indicating that the peatland is entrapping the silt coming from the disturbed land use. However, during the rainy season when most of the precipitation (85%) fell the inflow to the lake was highest along with the higher nutrient load in lake water (Jain *et al.*, 1999).

Radiocarbon dating showed that the samples from the forest edge were older than the samples near the lake edges where the vegetation covers the open water surface. At 150 cm depth the calibrated age of peat was more at 30 m distance compared to 60 m. This distortion of data was the result of peat sliding down slope owing to concavity of the lake basin. Mat peat showed the greater accumulation time with increased distance from the lake edge and with depth. Kratz & DeWitt (1986) have reported similar results. In peatland the depth of the boundary between peat strata with the original basin showed a feeble positive correlation with depth (0.193) but a negative correlation (-0.178) with distance. The absence of a relationship between the depth of the peat strata and the distance from the lake edge is a result of the siltation process. Peat was not encountered at 90 m distance owing to soil erosion from the watershed. The radiocarbon age of wood and charcoal in the peatland provided evidence that terrestrialization commenced around 800 years ago while the oldest tree present at the peatland was around 400 years old.

The seasonal vegetation analysis revealed that rainfall favoured the growth of a number of species. In addition, grazing pressure affects the growth of vegetation on the peatland. Unpalatable species such as *Acorus calamus, Amaranthus* sp., *Lycopodium* sp, *Anaphalis contorta, Potentilla peduncularis* and less preferred species, including *Oenanthe thomsoni*, showed an increasing trend during the spring season with high pressure of grazing during this period. Some terrestrial plants such as *Rhododendron lindleyi, Sambucus adnata* were found growing in the peatland but were not recorded in the watershed forest, hence their source might be through birds, grazing animals or human activities (pilgrimage offerings).

Peat soils have many characteristics which distinguish them from mineral soils, including low bulk density (Boelter, 1974), high water holding capacity (Thorpe, 1968), and high organic matter content (Pollett, 1972). The results of this study showed that the peat contained high organic matter and had low bulk density. The nutrient content of the peat is often an indicator (especially if the peat is drained) of its nutritive value for plant growth (Stanek, 1975). Highly acidic peat has low contents of total phosphorus and calcium (Richardson *et al.*, 1978; Lucas & Davis, 1961) and this was confirmed by the results of this study. Peat acidity and organic matter decreased with depth and distance from the lake periphery towards the forest margin and phosphorus and calcium showed increasing trends along with pH near the forest edge suggesting that peat deposition was arrested as a result of the accretion of sediments at this site from the disturbed watershed. The nutritive data in terms of plant growth from Table 5, when coupled with Malmstrom's guidelines (1956), suggest that peatland is deficient in phosphorus and calcium while nitrogen is slightly higher.

CONCLUSIONS

The geographic setting, watershed geology, climate and hydrological processes have led to the formation of peatland in the sacred Khecheopalri Lake. Succession and terrestrialization processes have already been encountered in the peatland with the invasion of woody arboreal species from the upland watershed. Peat was thicker at the sites where *Sphagnum* moss is dominant. Radiocarbon age of the peat revealed that the peat is increasing horizontally, covering the open water surface while peat slurry is being deposited at the lake bottom. The discovery of this unique peatland in the Himalayan belt opens a door for new ecological studies.

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Appendix 1

List of plants encountered, by life form, in the Khecheopalri peatland

Habit/Species	Vernacular name	Family	*Life-forms
Climbers			
Smilax aspera Linn.	'Kukurdaney'	Smilacaceae	Ph
S. rigida Wallich ex Kunth	-	Smilacaceae	Ph
Epiphytes			
Aeschynanthus sikkimensis Stapf.	-	Gesneriaceae	Ph
Bulbophyllum sp.	-	Orchidaceae	Ph
Rhaphidophora glauca Schott	'Kanchirna'	Araceae	Ph
Herbs			
Ageratum conyzoides Linn.	'Ilamay'	Asteraceae	Th
Amaranthus sp.	'Saag'	Amaranthaceae	Th
Anaphalis contorta Hook.f.	'Bukiphool'	Asteraceae	Th
Arisaema intermedium Blume	'Laruwa'	Araceae	Cr
A. costatum Martius ex. Schott.	'Bariko'	Araceae	Cr
Bidens pilosa Linn.	'Kuro'	Asteraceae	Th
Commelina paludosa Blume	'Kanay'	Commelinaceae	Ch
Corydalis juncea Wallich	-	Papaveraceae	Th
Cyanotis vaga Schuttes & Schuttes	-	Commelinaceae	Ch
Cynoglossum glochidiatum Wall.	-	Boraginaceae	Th
Cyperus rotundus Miq.	-	Cyperaceae	He
Drymaria cordata Willd.	'Abijalo'	Caryophyllaceae	Ch
Elatostema platyphyllum Wedd.	'Chiplay'	Urticaceae	Ch
Eupatorium cannabinum Linn.	'Banmara'	Asteraceae	Th
Eurya acuminata Royle	'Jhinguni'	Theaceae	Ph
Fimbristylis sp.	-	Cyperaceae	Th
Fragaria nubicola Lacaita	-	Rosaceae	He
Gnaphalium hypoleucum DC.	-	Asteraceae	Th
Gynura nepalensis DC.		Asteraceae	Th
Hedychium ellipticum Smith	'Jhankriphool'	Zingiberaceae	Cr
Hemiphragma heterophyllum Wall.	-	Scrophulariaceae	Ch

Hydrocotyle javanica Thunb.	'Golpata'	Apiaceae	He
Hypericum japonicum Thunb.	-	Hypericaceae	Th
Impatiens stenantha Hook. f.	-	Balsaminaceae	Th
Juncus sp.	-	Juncaceae	Th
Lindenbergia sp.	-	Scrophulariaceae	Ph
Lonicera glabrata Wall.	-	Caprifoliaceae	Ph
Lycopodium cernuum	'Nagbeli'	Lycopodiaceae	He
Mazus surculotus D. Don	'Kukur phool'	Scrophulariaceae	Th
Nasturtium officinale R. Br.	'Simrayo'	Brassicaceae	Th
Oenanthe thomsoni Clarke	-	Apiaceae	Ch
Pilea scripta Wedd.	'Chipley'	Urticaceae	Th
Plantago erosa Wall.	-	Plantaginaceae	Th
Persicaria capitata Gross	'Ratnaulo'	Polygonaceae	Th
Polygonum sp.	-	Polygonaceae	Th
Potentilla peduncularis D. Don	-	Rosaceae	Th
Rumex nepalensis Spreng	'Halhalay'	Polygonaceae	Th
Saccharum sp.	-	Poaceae	Th
Stellaria sp.	-	Caryophyllaceae	Ch
Tupistra nutans Wall.	'Nakima'	Liliaceae	Ch
Viola canescens Wall.	-	Violaceae	Th
Hydrophytes			
Aponogeton monostachyon Linn.	-	Naiadaceae	Cr
Ceratophyllum sp.	-	Ceratophyllaceae	-
Monochoria vaginalis C. Presl.	-	Pontederiaceae	Th
Scirpus sp.	-	Cyperaceae	Th
Semi-hydrophytes			
Acorus calamus Linn.	'Bojho'	Araceae	Cr
Alocasia sp.	'Ban Pindalu'	Araceae	Cr
Brachiaria eruciformis Griseb.	'Bonso ghans'	Poaceae	He
Sphagnum nepalense H. Suzuki.	-	Sphagnaceae	Ch
S. palustre Linn.	-	Sphagnaceae	Ch
Oxalis corniculata Linn.	'Amilo'	Oxalidaceae	Ch
Shrubs			
Arundo donax Benth.	'Narkat'	Poaceae	Ph
Berberis wallichiana DC.	'Chutro'	Berberidaceae	Ph

Hydrangea aspera D. Don	-	Hydrangeaceae	Ph
Mussaenda frondosa Wall.	'Dhobi'	Rubiaceae	Ph
Rhododendron lindleyi T. Moore	'Gurans'	Ericaceae	Ph
Sambucus adnata Walich ex DC.	-	Sambucaceae	Ph
Viburnum cordifolium Wall.	'Asare'	Sambucaceae	Ph
Trees			
Alnus nepalensis D. Don	'Uttis'	Betulaceae	Ph
Andromeda elliptica Sieb & Zucc.	'Angeri'	Ericaceae	Ph
Artocarpus lakoocha Roxb.	'Badar	Moraceae	Ph
Beilschmiedia sikkimensis King.	'Thulotarshing'	Lauraceae	Ph
Castanopsis tribuloides A. DC.	'Musray katus'	Fagaceae	Ph
Ficus benjamina Linn.	'Kabra'	Moraceae	Ph
Lyonia ovalifolia (Wallich) Drude	-	Ericaceae	Ph
Machilus edulis King.	'Phunsey'	Lauraceae	Ph
Magnolia campbellii Hook. f & Th.	'Gogey champ'	Magnoliaceae	Ph
Symingtonia populnea R. Br.	'Pipli'	Hamamelidaceae	Ph
Under shrubs			
Aconogonum molle *(D. Don) Hara*	'Thotney'	Polygonaceae	Ph
Agapetes serpens Sleumer	'Bandre-Khorsaney'	Vacciniaceae	Ph
Diplazium umbrosum Willd.	'Ningro'	Athyriaceae	He
Dryopteris sp.	'Unyo'	Dryopteridaceae	He
Equisetum sp.	'Kurkuray'	Equisetaceae	Th
Gaultheria sp.	-	Ericaceae	Ph
Melastoma normale D. Don	'Sindoore'	Melastomataceae	Ph
Osbeckia stellata *D. Don.*	'Chulesee'	Melastomataceae	Ph
Rubus ellipticus Wall.	'Aiselo'	Rubiaceae	Ph
R. paniculatus Roxb.	'Aiselo'	Rubiaceae	Ph
Solanum ferox Linn.	-	Solanaceae	Ph
Vaccinium nummularia C.B. Clarke	-	Ericaceae	Ph
V. vacciniaceum Sleumer	-	Ericaceae	Ph

*(Ph= phanerophyte, Th= therophyte, Ch= chamaephyte, He= hemicryptophyte, Cr= cryptophyte)

THERMAL TREATMENT OF TROPICAL PEAT SOILS FOR IMPROVED ADSORPTION PROPERTIES

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SUMMARY

The effect of thermal treatment on the adsorption properties of tropical peat soil was studied by using Cibacron Brilliant Red B (RR12) and Remazol Brilliant Blue R (RB19) dyes. It was found that the adsorption of both dyes on raw and treated peats from both Gunung Jerai (GJ) and Batu Pahat (BP) followed the Langmuir and Freundlich isotherms very well, except for the adsorption of RR12 on GJ raw peat. Besides improved adsorption properties, thermal treatment of peat increased its wettability and reduced leaching problem of peat soil.

Keywords: Peat, thermal treatment, wettability, adsorption, cibacron brilliant, remazol brilliant.

INTRODUCTION

Much interest has been focused on the utilisation of peat soil in wastewater treatment owing to its abundant presence in many countries, environmental friendliness, ability to remove both organic and metal ions, ability to be modified for more specific and better adsorption as well as its relative cheapness (Couillard, 1994). Research on its applications have ranged from removal of metals, hydrocarbons, pesticides and herbicides, textile dyes to dissolved organics from sewage. Several extensive reviews in this direction have been published (Couillard, 1994; Malterer *et al.*, 1996; Martin, 1991; Spedding, 1988).

Most of the published work, however, has involved mainly temperate peat especially that of sphagnum moss origin (Boulanger, 1989; Winkler & Veneman, 1991; Bradeen, 1983). Very little work on the application of tropical peat soil in wastewater treatment has been reported. This is probably because of its very amorphous nature linked to poor hydraulic conductivity, moderate cation exchange capacity, poor adsorption properties and severe leaching problems.

In particular, no work has been published on the effect of thermal treatment of tropical peat in relation to its adsorption characteristics although thermal treatment of sphagnum moss peat of low degree of decomposition showed that the mechanical strength of peat was improved (Thun *et al.*, 1983).

The purpose of this study was to develop a convenient pre-treatment method for a typical tropical peat soil of woody nature and high degree of decomposition from the northern and southern region of Malaysia for improved adsorption properties and also to reduce leaching of peat.

MATERIALS AND METHODS

Peat samples and reagents

Peat samples were obtained from two locations, Gunung Jerai (GJ) in the northern region of West Malaysia at a depth of 0.5 m and Batu Pahat (BP) located in the southern region of West Malaysia at a similar depth. Both peats were air dried and ground into powder using a mechanical grinder. No attempt was made to separate peat particles of different sizes.

Cibacron Brilliant Red B (RR12), C.I. 18156 and Remazol Brilliant Blue R (RB19), C.I. 61200 textiles dyes were obtained from Ciba-Geigy and BASF (M)

Sdn. Bhd., respectively. Other chemicals were of analytical grade and obtained from either R&M Chemical, BDH Chemicals, Merck, Riedel-de Haen, Fluka or Unilab Chemical.

Analysis of peat soil

Percentage of total organic and ash content were determined using a dry ashing method at 600°C in a carbolite muffle furnace (Papp & Harms, 1985). The percentage of ash and organic content were calculated from the weight of residue and the weight loss, respectively.

Organic constituents were fractionated using various schemes which have been used for the fractionation of peat (Walmsley, 1973). For this purpose, 5 g peat sample was fractionated consecutively according to the given procedures.

The analysis of organic carbon was done by weighing accurately 1 g of air-dried and ground peat samples into 500 ml conical flasks and following the procedure of Piper (1950). The inorganic composition of peat samples was determined by dry ashing and fusion methods as detailed by Papp and Harms (1985). Fusion method was used in the analysis of Si while other elements were determined by the dry ashing method. For this study, 10 g of peat were weighed into a crucible and ashed by heating in a furnace at 550°C overnight. Determination of Ca, Fe, and Al were made by atomic absorption spectrophotometry. C, S and O were estimated from EDX data. For the analysis of silica, 100 mg of dry peat were fused with 2 g sodium hydroxide pellets in a platinum crucible in a furnace at 1000°C in order to bring the silicon into solution (Robinson, 1945).

The measurement of pH for peat samples was carried out by shaking 3 g ground, air-dried peat in 50 ml distilled water according to the ASTM method (ASTM, 1971). The surface area of peat samples were analysed based on the adsorption and desorption of nitrogen on peat by using ASAP 2000 porosimeter.

Thermal treatment

About 50 g air dried peat was placed in a 250 ml beaker. It was then covered with aluminium foil and heated in a muffle furnace at a series of different working temperatures ranging from 300°C to 700°C for the required period of time. Afterwards, the treated peat was removed from the furnace and left to cool to room temperature.

Peat leaching analysis

The leaching of peat samples was conducted by shaking 2 g each of raw air dried peat or thermally treated peat samples in 25 ml distilled water in a 150 ml conical flask for 30 min at 350 osc min^{-1}. The water from each sample was then filtered using the fritted glass filter funnel and its COD value measured by spectrophotometry according to the HACH procedures (HACH, 1992). The process was repeated with the same peat samples up to ten times with each leachate monitored for its respective COD value. Higher COD value indicates a higher leaching problem.

Measurement of the uptake of the dyes by peat samples

The wavelength for maximum absorbance of RR12 and RB19 was obtained by scanning a 25 ppm solution of each dye by using a Hitachi U2000 spectrophotometer and was found to be 534 and 603 nm, respectively. A calibration curve for each dye was then produced by using standard solutions with concentrations ranging from 0 to 10 ppm. The determination of the uptake of each dye by the peat samples was based on these calibration curves, which were prepared prior to each measurement.

The effect of pH on the uptake of the dyes by peat samples

The effect of pH on the uptake of RR12 and RB19 dye solutions by peat samples was studied by using 200 ppm and 500 ppm dye solutions, respectively. For each peat sample, two series (one for each dye) of 2 g sample each were weighed out into respective 125 ml conical flasks. To each flask from both series were added 25 ml solutions of the respective dye solutions with pH pre-adjusted to a desired value by using either concentrated HCl or 10% NaOH solutions. Each series would cover the pH range of 3-10. Prior to shaking of each flask, the pH of each solution was again verified and readjusted to the desired pH as above. Each flask was then shaken by using the wrist action shaker SF1 (Stuart Scientific) at 300 osc min^{-1} for 1 hour. The uptake of each dye by peat samples was measured on the filtered solutions via spectrophotometric method as stated earlier.

Adsorption studies

The adsorption studies were conducted by shaking the peat with dye solutions by using the wrist action shaker SF1 (Stuart Scientific). Since pH did not affect the uptake of the dyes by peat samples, no pH adjustment of the solutions was made in this study. For the determination of equilibrium times for the adsorption of Cibacron Brilliant Red B (RR12) and Remazol Brilliant Blue R (RB19) on GJ and BP peat, a series of 2 g peats each with 25 ml of dye solutions (200 ppm RB19 and 200 ppm RR12 for raw GJ peat, 400 ppm RB19 and 200 ppm RR12 for thermally treated GJ peat, and 200 ppm RR12 and 200 ppm RB19 for raw BP peat) was shaken in 125 ml conical flasks at 300 osc min^{-1} at a series of different contact times. A plot of the uptake of each dye against contact times should reveal the equilibrium time required for each dye solution. By using these equilibrium times, the adsorption of RR12 and RBl9 dyes were studied to produce either Freundlich or Langmuir adsorption isotherms. For this purpose, a series of different weights of peat were shaken in 25 ml dye solution using 200 ppm RB19 and 150 ppm RR12 for raw GJ peat, 200 ppm RB19 and 150 ppm RR12 for raw BP peat and 500 ppm RB19 and 300 ppm RR12 for thermally treated GJ peat. The measurement of the uptake of each dye by each peat sample was carried out spectrophotometrically as stated earlier. The adsorption data were plotted according to the Freundlich and Langmuir adsorption isotherms to get the characteristics of the dyes adsorption.

Determination of the percent of wettable peat samples

Wettability was determined by an approximate analysis. One gram of peat was shaken in 50 ml distilled water in a 125 ml conical flask at 300 osc min^{-1} by using the wrist action shaker SFI (Stuart Scientific) for 30 min. The mixture was then left to settle for 10 minute. For our purpose, only those peat particles that settled to the bottom of the flask were considered as wettable. The floating peat particles were then removed by filling up the flask with water under a flowing tap water to flush most of them out with the aid of a spatula or glass rod. All peat particles that settled at the bottom of the flask were then filtered and dried in the oven at 100°C overnight. The weight of the dried residue was assumed as the weight of the wettable peat.

RESULTS AND DISCUSSION

Two peat samples of different chemical composition taken from two locations separated far apart were specifically chosen for this study. In this way, different adsorption characteristics of peat samples would be more clearly highlighted. The two peat samples were of hemic to sapric types with no visible fibres.

Table 1 gives the results of the fractionation analysis of the peat samples. The well decomposed nature of the peats was supported by their low a-cellulose and hemicellulose contents and also their relatively high humic acid contents. It should be noted, however, that Gunung Jerai (GJ) peat had more than 30% ash content while Batu Pahat (BP) peat had only 11%. Thus BP was more organic than GJ even though both had almost similar organic carbon contents. Therefore, as expected, BP was more acidic and had a lower pH value than GJ. Further analysis of the ash contents revealed the presence of relatively high Si, Al and Fe contents in GJ peat compared to BP peat reflecting the presence of mud in the former sample. Table 1 highlights the contrasting chemical composition of the peat samples used in this study.

Table 1a shows the effect of thermal treatment on the chemical characteristics of pyrolyzed peat samples. In general, elemental oxygen dropped significantly owing to the removal of carboxylic functional groups as indicated by Table 1c. The decrease of carboxylic functional group was also in line with the drastic drop in humic acid content of the thermally treated peat. Table 1c affirmed the destruction of humic acid from the significant disappearance of CEC values of the treated peat samples. The increase in carbon content is probably a result of carbonization of peat samples as indicated by the lowering values of organic carbon content (Table 1c) and increased total carbon in Table 1a. However, for an unknown reason, carbonization of GJ peat was less than that of BP peat.

An approximate analysis of the wettability of thermally treated peats is shown in Figure 1. The wettability of both peat samples decreased with the experimental temperatures to a minimum value for both at 350°C. The wettability then increased with temperature to reach 100% at 500°C and beyond. The trend of the wettability can be easily explained since peat became more hydrophobic with increasing temperature up to 350°C because of the melting of wax, bitumen and lipid. Beyond 350°C, the wettability increased as wax, bitumen and other lipid materials started to degrade and burn off. The removal of these materials would be almost complete at 500°C and above. Thus thermally treated peat improved their wetting properties.

The adorption properties of thermally treated peat was investigated using textiles dyes Cibacron Brilliant Red B (RR12) and Remazol Brilliant Blue R (RB19). Their structures are given in Figure 2. The effect of pyrolysis temperature on the uptake of RR12 dye is shown in Figure 3. For thermally treated GJ peat, it

Table 1: Composition of Raw and Thermally treated peat soils (at 500 °C for 3 hours).From Gunung Jerai (GJ) And Batu Pahat (BP) Peat, Malaysia.

a) Inorganic compositions

Elements(ppm)	Raw GJ	Heat treated GJ	Raw BP	Heat treated BP
Al (wt %)	3.23	6.78	0.36	1.72
Ca (mg/L)	69.8	174.3	28.9	22.2
Fe (mg/L)	1.16	2.09	0.29	ND
Si (wt %)	4.17	8.22	0.34	3.07
C (wt %)	34.07	33.77	49.58	80.88
S (wt %)	1.25	0.12	ND	ND
O (wt %)	45.87	22.13	21.83	14.33

(b) Organik composition

Components (%)	Raw GJ	Heat treated GJ	Raw BP	Heat treated BP
Lipid	12.59	4.78	17.11	4.15
∝-cellulose	5.79	12.70	3.71	3.00
Hemicellulose	6.73	6.11	2.27	ND
Lignin	13.43	9.47	16.08	7.36
Fulvic Acid	3.93	0.29	4.18	ND
Humic Acid	26.21	2.37	40.92	ND
Free Sugars, amino acids, pigments, etc.	11.22	ND	7.51	ND
Insoluble materials	20.10	64.28	8.22	85.49

c) Functional groups

Functional groups	Raw GJ	Heat treated GJ	Raw BP	Heat treated BP
Organic Carbon (%)	20.63	15.77	21.59	4.53
Silica in insoluble component (%)	93.95	95.05	84.54	22.86
Carboxyl (meq COO^-/g)	1.41	0.23	3.84	0.55
CEC (meq/100g)	104	0.88	143	0.06

*ND: Non detectable; CEC : cation exchange capacity

was found that the trend followed peat wettability very closely. No uptake was recorded at all at 350°C while more than 98% uptake occurred at 500°C and beyond. The fact that the uptake reduced with temperature up to 350°C even though the trend of the surface area (as shown in Table 2) was otherwise, seems to enhance further the role of wettability. This is easily understood since adsorption depends on the diffusion of adsorbates to the surface of adsorbents. At the very low wettability value, there is minimal contact between the solid-liquid interface owing to the hydrophobicity of the peat surface thus resulting in a very small uptake. However, the result with BP peat was completely different. Minimal uptake was observed for BP peat samples even up to 450°C. At 500°C, the uptake was only 6.80 % even though the wettability was 100%. Even at 600°C, the uptake of RR12 by BP peat was only 37.60 % although its surface area was more than double of GJ peat as shown in Table 2. Apparently, thermal treatment of the BP peat sample did not significantly improve the uptake of this anionic dye. This fact highlights the important role of peat chemical composition in its adsorption characteristics. One significant different was the low mineral content of BP

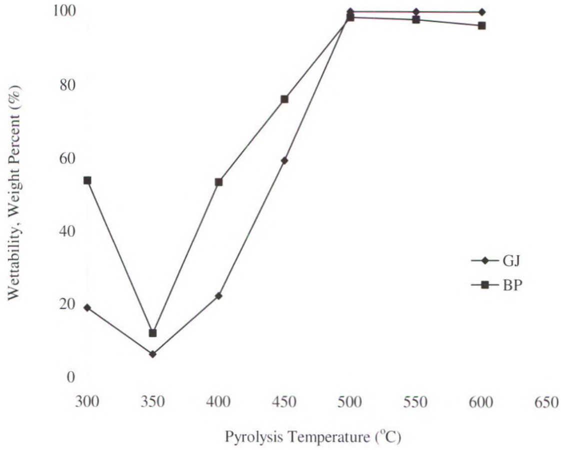

Figure 1: Percent weight of wettable soil of thermally treated tropical peat soils with respect to pyrolysis temperatures (GJ = Gunung Jerai; BP = Batu Pahat)

peat compared to GJ peat (low Al, Fe and Si). Thus the lower adsorption sites available on BP peat sample because of the smaller amounts of these components may have lowered the uptake of this anionic dye.

The optimum heating temperature and the time of heating were deduced by monitoring the COD of the leaching water from thermally treated GJ and BP peat samples that were heated at 500°C. These samples were chosen since the maximum uptake of RR12 dye began at 500°C. As shown in Figure 4, the leaching from thermally treated peat at 500°C decreased with washing indicated by the COD value of less than 5 ppm on the tenth washing. Figure 4 also shows the severe leaching problem of raw BP peat as well as the continuous leaching problem of raw GJ peat.

The ability of temperate peats to adsorb textile dyes had been well-documented (Poots *et. al.,* 1976a,b; Allen, 1987). According to Poots *et al.* (1976b) the presence of phenolic and carboxylic functional groups in peat made them effective in adsorbing cationic or basic dyes. Their adsorption capacities were, however, significantly lowered with anionic dyes. Similarly, it was rather expected that the tropical peat used here would have low adsorption capacity for anionic dyes. Both raw GJ and BP peat were tested for their adsorption capabilities with two types of anionic dyes (RR12 and RB19). Further dye adsorption analysis by thermally treated GJ peat was carried out. From the time equilibrium study for both raw and treated peat with both dyes, it was found that equilibrium times for raw GJ in the uptake of RR12 and RB19 were 20 and 10 minutes, respectively. Thermally treated peat improved the equilibrium time by 10 minutes in relation to the uptake of RR12 but did not improve the time for RB19. Figures 5 and 6 show the Freundlich and Langmuir adsorption isotherms of RB19 for both raw GJ and thermally treated GJ (THGJ) peat samples, respectively. It was observed that both peat samples adsorbed RB19 more significantly than RR12. The

Table 2: BET and Langmuir surface areas, and average pore diameters of raw and heat treated peat from 300°C ke 700°C for GJ dan BP

Pyrolysis Temperature (°C)	Types of peat soils	BET surface areas (m^2/g)	Langmuir surface areas(m^2/g)	Average pore diameter 4V/A from Langmuir (Å)
Raw	GJ	4.3882	8.4802	193.4805
	BP	0.6336	1.0577	214.3382
300	GJ	3.4418	6.6465	180.0046
	BP	1.0168	1.8284	102.8452
400	GJ	6.8838	13.0681	153.9050
	BP	1.3735	2.4827	105.0770
500	GJ	19.8721	35.3950	51.1007
	BP	2.5450	4.5116	92.1173
600	GJ	30.2290	52.1535	41.8289
	BP	74.9727	125.8999	20.2894
700	GJ	68.3354	116.1449	29.4475
	BP	172.2837	286.8197	15.4149

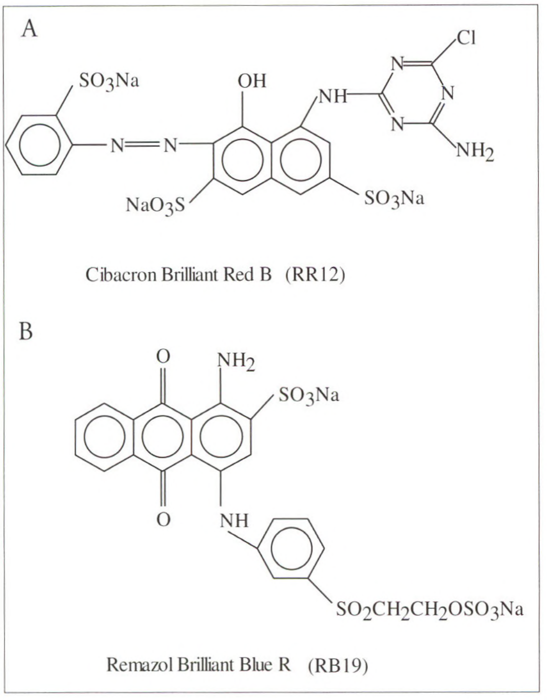

Figure 2 : Chemical structure of Cibacron Brilliant Red B (RR12) and Remazol Brilliant Blue R (RB19)

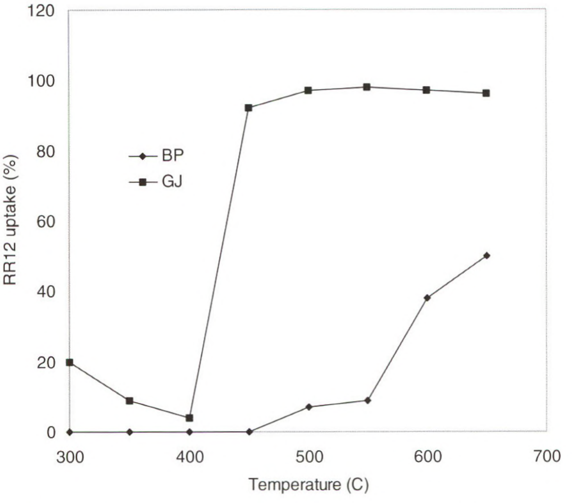

Figure 3: Percent uptake of RB19 by thermally treated Gunung Jerai and Batu Pahat tropical peat soils at different pyrolysis temperatures. For each case, 2 g treated peat was shaken at 350 osc per minute in 25 mL 200 ppm dye solution for 1 hour.

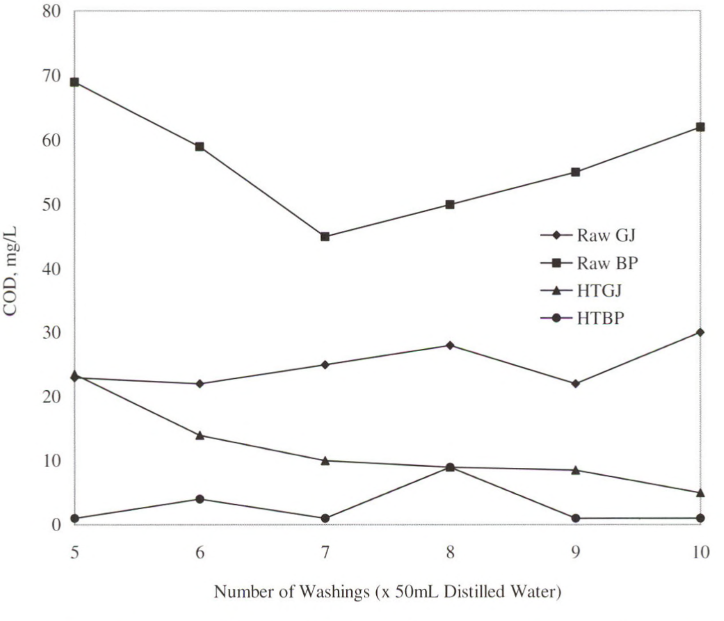

Figure 4: Chemical Oxygen Demand (COD) of leachates from raw and thermally treated tropical peat soils at 500 °C. (GJ = Gunung Jerail BP = Batu Pahat; HT = heat treated)

Table 3: Langmuir and Freundlich parameters for the adsorption of RR12 and RB19 by raw and thermally treated treated GJ dan BP peat soils at pH 3.6

(a) Langmuir isotherms

Types of peat soils	Types of dyes	Monolayer capacity, Q_o (mg/g)	Langmuir constants, b (L/g)	Correlation factor, R
Raw GJ	RR12	4.45	0.0312	0.9952
	RB19	9.03	0.0819	0.9964
Heat treated GJ	RR12	8.00	0.1157	0.9936
	RB19	12.80	0.0855	0.9557
Raw BP	RR12	0.45	-0.2898	0.9966
	RB19	3.02	0.0811	0.9991
Heat treated BP	RR12	1.62	0.2321	0.9857
	RB19	3.12	0.2234	0.9918

(b) Freundlich isotherms

Types of peat soils	Types of dyes	1/n (L/g)	log K	Correlation factor, R
Raw GJ	RR12	0.3938	-0.2657	0.9876
	RB19	0.3492	0.1999	0.9948
Heat treated GJ	RR12	0.1086	0.6264	0.9719
	RB19	0.1810	0.6418	0.9528
Raw BP	RR12	-0.1899	-0.0138	0.6478
	RB19	0.2164	-0.0076	0.9670
Heat treated BP	RR12	0.1626	-0.1259	0.9226
	RB19	0.1830	0.1235	0.9821

lower uptake of RR12 by the peat samples could be for many reasons, one of which could be the size of the RR12 molecule, which is slightly bigger than RB19. In addition, it has more negative charges owing to the presence of three sulphonate groups and one phenolic hydroxyl group. Furthermore, RR12 should provide bigger steric hindrance than RB19 in the adsorption process as a result of its non-planar side-chain moieties.

In general, the overall uptake of these two dyes by the two types of tropical raw peat was relatively low compared to temperate peat. This is apparent from the low Freundlich constant, K value as well as low Langmuir monolayer capacity, Q_o, as shown in Table 3. Poots *et al.* (1976b) obtained Qo between 9-16 mg g^{-1} depending on the peat particle sizes used with an almost similar chemical based anionic Telon Blue dye, was due to the lower surface area of our peat samples. As shown in Table 3, the BET surface areas of GJ and BP for nitrogen adsorption were 4.39 m^2 g^{-1} and 0.634 m^2 g^{-1}, respectively. Poots & McKay measured the sphagnum peat surface area for nitrogen adsorption and found the value to be 27.3 m^2 g^{-1} (Poots & McKay, 1980).

The Freundlich adsorption isotherms given in Figure 5 clearly show that thermal treatment of GJ peat improved the uptake of both dyes. It is seen that both raw and treated peats followed the Langmuir curve while raw GJ did not correlate well with the Freundlich curve for uptake of RR12. The raw GJ peat adsorbed RB19 10 times better than RR12. The thermally treated GJ peat adsorbed RR12 six times better and only 1.2 times better for RB19 than its raw counterpart. The b values for the thermally treated peat were all higher than its raw counterpart indicating stronger adsorption properties. In general the adsorption isotherms for the thermally treated GJ peat were

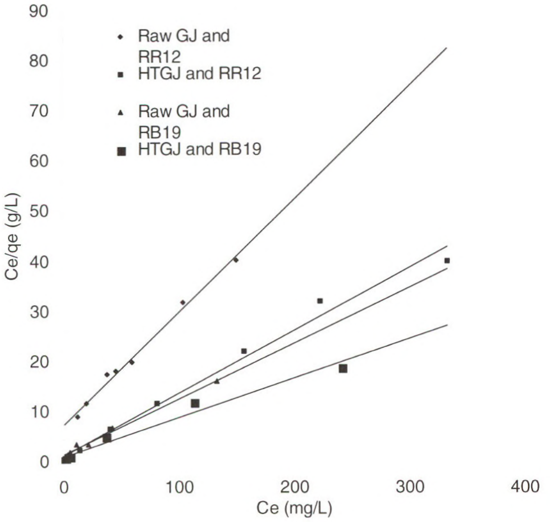

Figure 6: Langmuir adsorption isotherm for the removal of RR12 (Cibacrom Brilliant Red B) and RB19 (Remazol Brilliant Blue R) by raw and heat treated GJ peat (HTGJ) at pH 3.60.

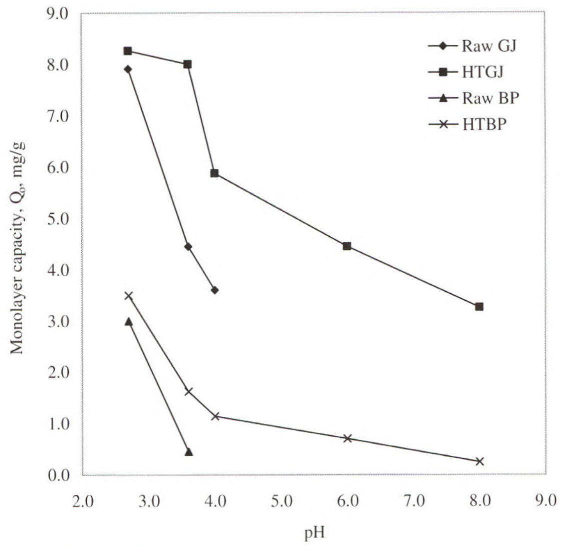

Figure 7 : The effect of pH on the values of monolayer capacity for the adsorption of RR12 (Cibacrom Brilliant Red B) by heat treated Gunung Jerai (HTGJ) and Batu Pahat (HTBP) peats.

located higher than those of raw GJ peat. The isotherms for the treated GJ peat were almost horizontal for both dyes. This indicates that good adsorption capacities can also be achieved at low concentrations of the dyes. The adsorption isotherms for raw peat samples were steeper especially in the case of RR12. Thus the raw peat capacities for the removal of these dyes were clearly lower in more dilute solutions.

Figure 7 shows the effect of pH on the adsorption of RR12. A similar trend was also observed for RB19. For raw peat samples, the pH could not be extended beyond pH 4 because of a colour leaching problem and this did not occur with treated peat samples. The uptake of dyes decreased significantly with pH. At low pH values, carboxylic functional groups as well as dyes molecules were protonated. Coulombic repulsion between the adsorbent and the dyes molecules would be less and this resulted in higher monolayer capacity. As pH increased, negative charges on both peat samples and dye molecules increased and this resulted in increased coulombic repulsion. In addition, OH^- ions would be expected to compete for any available positive sites on the adsorbent. Consequently, the uptake of both dyes decreased significantly with pH.

CONCLUSIONS

In this study, it has been shown that raw tropical peat soils from two regions of West Malaysia did not exhibit good adsorption properties for anionic dyes. The adsorption properties as well as the severe leaching problem of these peats could be improved via thermal treatment of the soils. However, the study has also proven that peat with different chemical characteristics showed totally different adsorption properties even after similar thermal modifications. Thus, heat treated GJ peat with higher ash content showed significantly better adsorption characteristics than its BP counterpart. In addition, the uptake of these anionic textiles dyes was not influenced solely by the surface areas of peat adsorbents but may involve other factors such as the wettability and chemical characteristics of the adsorbents as well as that of the adsorbates. The anionic dye, RR12, with higher negative charges was adsorbed less compared to RB19. The adsorption of these dyes was also significantly affected by pH.

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