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PROPERTIES OF CULTIVATED GYTTJA SOILS

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SUMMARY

Gyttja soils are a mixture of organic and minerogenic materials deposited in water. Their organic matter content and the occurrence of diatoms give them characteristic chemical and physical features. All gyttja soils shrink irreversibly on drainage and permanent cracks are formed. Comprehensive measurements on 9 Swedish soils showed that even a very small proportion of gyttja will decrease particle density and dry bulk density and increase porosity and the amount of physically available water. The main restriction in the water supply to plants on gyttja soils is root depth. Profiles with unrestricted root development will have an ample supply of water. However, high sulphur contents and low pH (aluminium toxicity) are common in gyttja soils and where this leads to restricted root depth, drought problems can arise.

This investigation showed that important criteria in identifying gyttja soils are (1) an organic matter content $>1\%$ in the subsoil, (2) a dry bulk density $<1.1\text{ Mg/m}^3$ and (3) a porosity $>60\%$ by volume. All these criteria must be met at the same time.

INTRODUCTION

Gyttja soils are composed of a mixture of organic and minerogenic materials deposited in lakes and shallow gulfs with clear water rich in nutrients. Included in the mixture are humus and clay colloids, various chemical precipitates and occasionally coarser mineral material. The organic component, detritus, consists of plant and animal remains at different stages of decomposition. Gyttja is a Swedish word first introduced as a scientific term by von Post (1862). He defined gyttja as a grey deposit of decomposed plants and diatoms found at the bottom of lakes and watercourses.

Gyttja soils not only consist of lacustrine and, less frequently, fluvial materials but also of marine and brackish water sediments (Fredriksson, 1953). The exact meaning of the word gyttja and other related terms describing organic deposits have been reviewed by Hansen (1959) and Grosse-Brauckmann (1961).

The organic matter content in gyttja soils can vary from a few per cent up to more than 30 per cent. This great variation poses problems in most classification systems. The difficulties in classifying gyttja soils according to international soil classification systems have been discussed by many authors (Finney et al, 1974; Larsen, 1978; Öborn, 1989). In the American soil classification system, Soil Taxonomy (Soil Survey Staff, 1975), gyttja soils generally fall in between the soil groups Histosols and Entisols or between Histosols and Inceptisols. In the FAO system (1974) most gyttja soils are classified as Gleysols, Fluvisols or Regosols. Gyttja soils are sometimes classified as acid sulphate soils (Öborn, 1989), but far from all gyttja soils are acidic or potentially acidic.

Most gyttja soils are covered with peat in the natural (undisturbed) state. The thickness of the peat varies greatly, from several metres to a few centimetres. In some cases however, unmantled gyttja soils can be found, for instance where a shallow lake has been drained. The thickness of the gyttja layers can vary from a few centimetres up to several metres. Most gyttja soils are found in flat, low-lying areas. The gyttja soils in this investigation were all situated between present sea level and 30 m above present sea level. Approximately 10 % of the arable land in Sweden consists of organic soils (250 000 ha) and about 1/3 of this area is covered with soils containing gyttja in or just below the topsoil. In many drained and cultivated peatland areas, mineralization and erosion of the peat will eventually expose further gyttja soils, since these form the subsoil in many cases.

Even a small percentage of gyttja in soil has a substantial impact on its physical properties (Ekström, 1927). Characteristic physical properties of gyttja soils are high porosity, low bulk density and a tendency towards shrinkage and the formation of permanent cracks upon drying (Ekström and Flodkvist, 1926; Kivinen, 1938; Andersson, 1955). Distinctive chemical features are high C/N-ratio, often low pH and high sulphur content and low availability of phosphorus (Torstensson and Eriksson, 1938; Ståhlberg, 1974; Öborn, 1989).

The aim of this paper is to characterize gyttja soils physically and to some extent chemically, and to define some criteria that are unique to cultivated gyttja soils and can be used to identify them.

MATERIALS AND METHODS

Ekström (1927) proposed a simple classification system for gytija soils. The system was slightly revised in 1953 (Jordartsnomenklatur) and according to this system gytija-containing soils with more than 30 % organic matter (as ignitable gytija substance) were called gytija soils, those with 6-30 % organic matter were classified as clay gytija and those with 3-6 % organic matter were determined gytija clay. The mineral fraction sometimes consists of coarser material and the soil is then named accordingly. This simple classification system has been used in this investigation with the exception of the lower limit for gytija clay. This was set at 1 % in accordance with the original classification system of Ekström (1927). The organic matter content was estimated from both the organic C content (58 % org-C in the gytija substance) and the loss on ignition (550°C for 2 hours) corrected for the loss of structural water from clay minerals (Ekström, 1927). For clay contents of 20 % or lower, the correction factor is $k = 0.1 \times (\text{clay content})$ and for clay contents higher than 20 % $k = 1.06 + 0.047 \times (\text{clay content})$.

All sampling sites were located in the southern part of Sweden in the country's major agricultural areas (Fig. 1). At each sampling site undisturbed soil cores, 10 cm high and 7.2 cm in diameter, were taken from successive 10 cm layers (2-4 replicates per layer) from the soil surface to 1 m depth. Additional disturbed soil samples were taken from the same layers. The undisturbed soil cores were used to determine the water release characteristic in the laboratory at soil moisture tensions 0.05, 0.2, 0.5

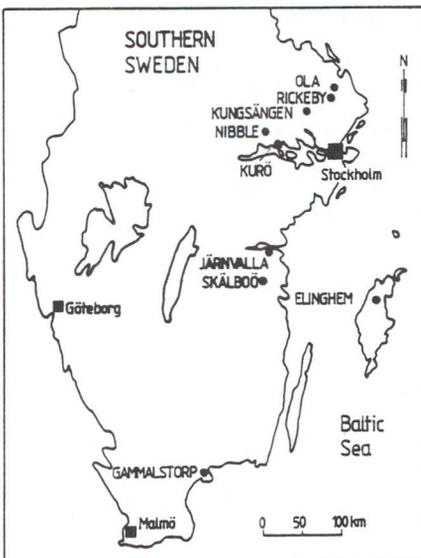


Figure 1. Location of sites investigated in southern Sweden.

metre water column (mwc) using a tension table and at 1.0, 2.0, 4.0, 6.0 and 10.0 mwc using pressure plate apparatus. The full range of tension determinations was not carried out on every profile. Disturbed soil samples were used to determine the water content at 150 mwc (pressure chamber), loss on ignition, and in some profiles, texture analysis by the pipette method. Two additional soil cores were taken from each layer to determine the biological wilting point. Total porosity was calculated from particle and dry bulk densities. All soil cores were vacuum-dried at 60-70°C before dry bulk density measurements were made. Low temperature was used to avoid any loss of organic matter during the drying process (Landva et al, 1983). Shrinkage was measured only on a few of the profiles and has not been considered when calculating water contents at different tensions. Saturated vertical hydraulic conductivity was measured on undisturbed soil cores in the laboratory with a constant head permeameter under a unit hydraulic gradient.

Chemical analyses were made on duplicates of finely ground air-dried samples from every 10 cm layer. Total C, inorganic C and total S were analyzed by dry-combustion on a LECO analyzer. Organic C was calculated as the difference between total C and inorganic C. Total N was analyzed by the conventional Kjeldahl method and the pH of fresh soil samples was measured in deionized water at a soil-solution ratio (v/v) of 1:2.5. Some measurements of biogenic silica were made according to a method developed by DeMaster (1981).

RESULTS AND DISCUSSION

Geological Development

Gyttja soils in Sweden consist of young Quaternary sediments mainly deposited during the last 10 000 years. The geological development of two typical gyttja profiles is described in Figures 2 and 3. The depositional environment varies from freshwater to saline water depending on the post-glacial phase of the Baltic Sea at the time of deposition.

Gyttja Content

The characteristic components of gyttja soils are mainly more or less well preserved remains of aquatic algae which dominate the fine detritus of the gyttja and give rise to the typical gelatinous consistency. Whereas algae, with organic cell walls, will decompose and dissolve almost completely, diatoms, with cell walls consisting of biogenic silica, are very resistant to decay. The very porous structure of diatoms

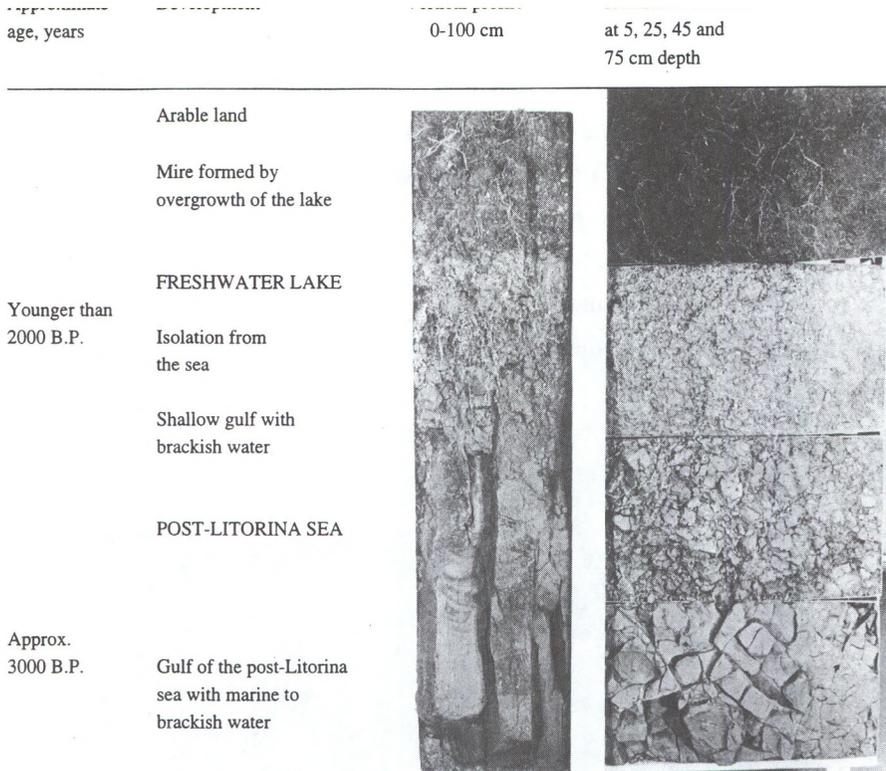


Figure 2. Ola. A typical gyttja soil profile with large permanent cracks in the subsoil. The topsoil (0-20 cm) consists of highly decomposed peat soil, 20-60 cm clay gyttja (~6 % gyttja), 60-100 cm clay gyttja (~9 % gyttja). The geological development of the profile is described on the left. The soil surface is 5-10 m above present sea level.

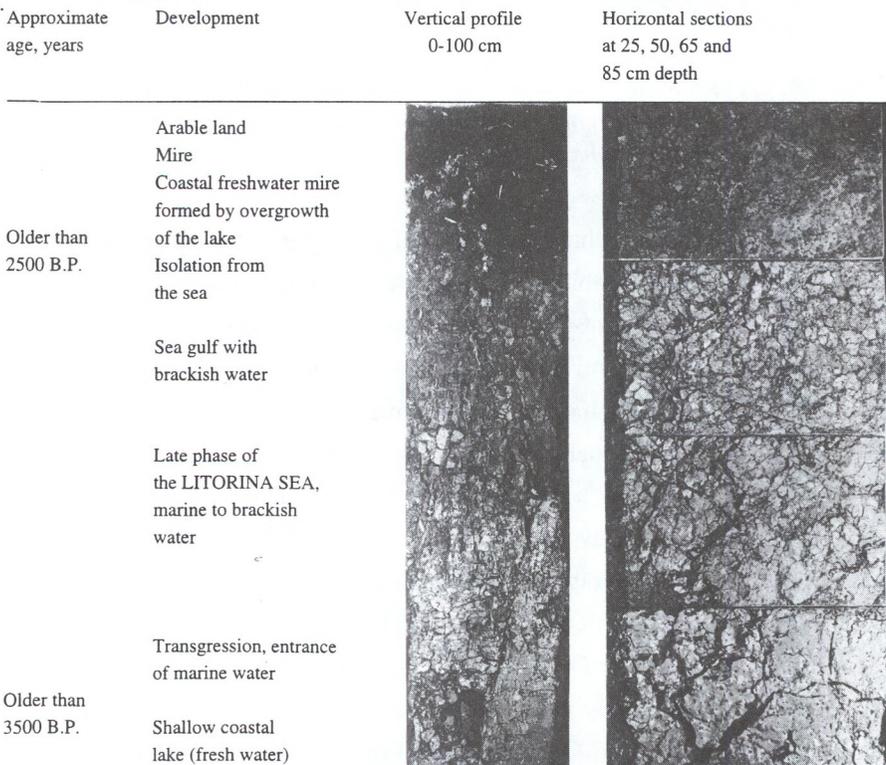


Figure 3. Järnvalla. A typical gyttja soil profile with prismatic aggregates and permanent cracks in the subsoil. The topsoil (0-22 cm) consists of peat mixed with gyttja soil, 22-30 cm clay gyttja (~9 % gyttja), 30-100 cm gyttja clay (~5 % gyttja and >60 % clay). The geological development of the profile is described on the left. The soil surface is 10-15 m above present sea level.

(Figure 4) will influence the physical properties of the soil. Diatoms are usually of the same size as the mineral silt fraction (2-60 μm) but due to their porous structure (particle density approx. 2.0 g/cm^3 ; Hurd, 1983) their behaviour in water resembles that of clay. Diatoms can also in some cases cause flocculation of the soil sample. This complicates the textural analysis of gyttja-containing soils. The clay-like behaviour might falsely indicate a high clay content and the flocculation a high content of coarse material.

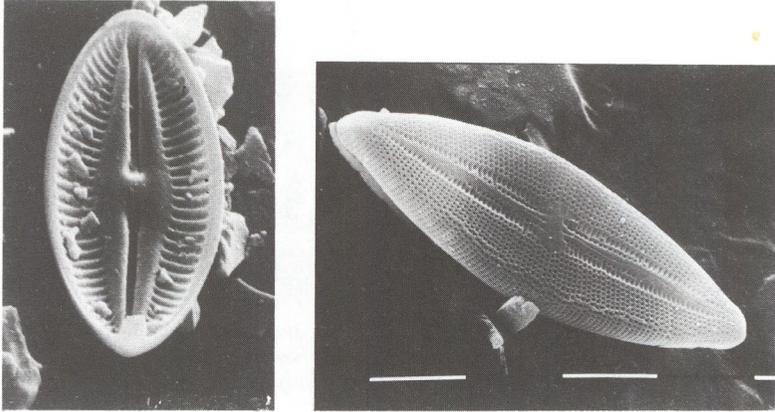


Figure 4. *Diploneis smithii* (left), a diatom species common in saline to brackish water and *Mastogloia braunii* (right), common in brackish water. Scanning electron microscope (SEM) micrographs. White bar = 10 microns.

The organic carbon content (Org-C) of the organic fraction (OM) of mineral soils and peat soils is commonly assumed to be 58 % or conversely, $\text{OM} = 1.724 \times \text{Org-C}$. In Figure 5, the Org-C content of some gyttja soils is plotted against the corrected loss on ignition. Assuming that loss on ignition (corrected for the loss of structural water from clay minerals) is a measure of organic matter in gyttja soils, the results in Figure 5 indicate that the Org-C content of the organic matter in gyttja soils is 61 % (conversion factor = 1.645). Since the correction factor for the loss on ignition is based on the clay content, there is a risk that in diatom-rich soils the correction factor will be too big due to a falsely assumed high clay content. A smaller correction factor would result in a slightly higher organic matter content and that in turn would result in a lower Org-C content in the organic matter of gyttja soils. It is suggested that the commonly used conversion figure 1.724 can be used to estimate organic matter content from Org-C values even in gyttja soils. Hansen (1959) and

Larsen (1978) report lower Org-C contents of OM in gytija soils (<50 % and 40 %, respectively) but both authors used loss on ignition as an estimate of organic matter without making a correction for the loss of structural water from clay minerals.

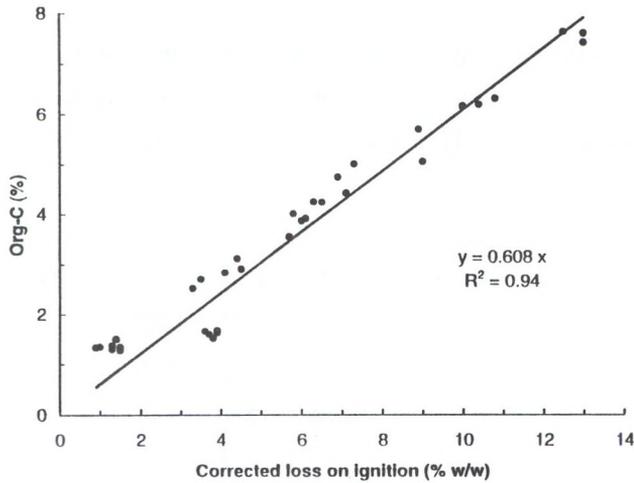


Figure 5. Relationship between loss on ignition corrected for the loss of structural water from clay minerals and the org-C content for 35 gytija soil samples.

The organic matter content (OM) of the gytija soils analyzed in this investigation (excluding layers mixed with peat) varied from a few per cent up to more than 30 % (Tables 1 and 2). One soil (Elinghem, Table 2) had a very high calcium carbonate content (80-90 % of dry matter) and was classified as a marl-containing gytija.

Even if loss on ignition or Org-C can be used to estimate the OM content in gytija soils, both methods will in most cases underestimate the gytija content of the soil. These methods will give a correct gytija content only if the dominant organic component consists of algae with organic cell walls. However the organic component is very frequently dominated by diatoms rich in biogenic silica which are not taken in account in either the loss on ignition or the Org-C determinations. Both OM content and biogenic silica should then be determined, in order to give a more correct measure of the gytija content. Table 1 shows the results of a limited number of biogenic silica determinations and corresponding organic matter contents, porosities, dry bulk densities and particle densities for six soils with varying gytija content. The phenomenon that even a very small amount of organic matter in gytija soils has a considerable effect on their physical properties (see Table 1) can be at least partly

explained if both the biogenic silica content and the organic matter content are combined in determining the gyttja content. For example Kurö (Table 1) has an organic matter content of only 1.3 % but with the biogenic silica the gyttja content rises to 6.3 % and then it is easier to understand the great effect of gyttja on for example porosity. However not all biogenic silica originates from diatoms. It also occurs in other microfossils such as phytoliths, which are common especially in the topsoil of arable land, but since these organisms are very compact they will not have the same effect on soil physical properties as diatoms (see Äckerud, Table1).

Table 1. Organic matter content ($OM = 1.724 \times Org-C$), biogenic silica content (SiO_2), porosity, dry bulk density and particle density at 30-40 cm depth in the soil profiles at 6 test sites (clay soil without gyttja, used as reference)*

Site	Soil type	OM %	Biogenic silica % (SiO_2)	O.M.+ SiO_2 %	Poro- sity %	Dry bulk density Mg/m^3	Particle density Mg/m^3
Äckerud *	clay	0.5	3.7	4.2	46.5	1.47	2.74
Kurö	gyttja clay	1.3	5.0	6.3	65.2	0.95	2.72
Kungsängen	gyttja clay	2.6	7.5	10.1	63.4	0.92	2.50
Järvalla	clay gyttja	6.5	6.6	13.1	66.6	0.80	2.39
Skälboö	clay gyttja	8.9	14.0	22.9	75.3	0.55	2.25
Gammalstorp	gyttja	26.0	25.5	51.5	84.9	0.31	2.04

Soil Structure And Hydraulic Conductivity

All gyttja soils shrink irreversibly on drainage and permanent cracks are formed mainly in the subsoil (Ekström & Flodkvist, 1926; Kivinen, 1938). Fast initial drainage will in general give rise to larger permanent cracks (Fig. 2) than slow initial drainage (Ekström and Flodkvist, 1926). Soil freezing and cultivation can destroy the crack system and instead create prismatic aggregates. This phenomenon is well illustrated in the Ola soil profile (Fig.2) where frost has influenced the soil down to approximately 50 cm depth. Peat from the topsoil can sometimes fall down into the cracks and fill them up. The permanent crack system gives rise to a very high hydraulic conductivity (Ekström & Flodkvist, 1926; Andersson, 1955). The saturated vertical hydraulic conductivity was measured on a few of the profiles. Conductivity in the topsoil varied between 1.4 and 291 mm/h, while in the subsoil it was more than

Table 2. Summary of loss on ignition, organic carbon content (Org-C), total nitrogen content (N), total sulphur content (S), C/N-ratio, pH(H₂O) and clay content for soil profiles at 9 test sites (n.d. = not determined)

Depth cm	Loss on ignition %	Org-C %	Total N %	Total S %	C/N	pH (H ₂ O)	Clay content %
Gammalstorp (gyttja, topsoil mixed with peat)							
0- 20	40.0	19.95	1.58	0.95	12.6	5.3	n.d.
20- 30	38.0	17.88	1.47	1.1	12.2	4.4	n.d.
30-100	31.5	16.89	1.54	2.7	11.0	4.0	n.d.
Skälboö (clay gyttja, topsoil mixed with peat)							
0- 20	41.5	22.90	1.22	0.20	18.8	5.4	n.d.
20- 30	37.9	21.24	1.18	0.20	18.0	4.8	n.d.
30- 40	24.6	8.34	0.52	0.15	16.0	4.0	n.d.
40-100	13.9	6.50	0.52	0.49	12.5	3.4	49.5
Rickeby (peat on clay gyttja)							
0- 20	67.2	16.39	1.23	0.36	13.3	5.2	n.d.
20- 40	31.9	4.33	0.52	0.20	8.3	4.9	46.2
40-100	14.2	4.46	0.58	0.38	7.7	5.4	45.4
Ola (peat on clay gyttja)							
0- 20	44.2	24.27	1.79	0.52	13.6	4.6	n.d.
20- 30	9.1	3.54	0.38	0.41	9.2	4.1	49.2
30-100	11.1	5.02	0.59	0.59	8.5	3.6	45.8
Järnvalla (clay gyttja, topsoil mixed with peat)							
0- 20	16.8	5.98	0.49	0.14	12.2	5.9	58.6
20- 30	15.4	5.08	0.43	0.12	11.8	5.9	60.9
30-100	8.9	3.11	0.38	0.30	8.2	3.9	64.2
Nibble (gyttja clay, topsoil mixed with peat)							
0- 20	18.8	10.85	0.86	0.13	12.6	4.4	54.8
20- 30	17.3	10.54	0.91	0.14	11.5	4.3	56.0
30- 40	15.5	5.50	0.45	0.09	12.3	4.0	56.1
40-100	5.6	1.61	0.19	0.31	8.5	3.8	56.5
Kungsängen (gyttja clay)							
0- 20	9.7	3.76	0.41	0.04	9.2	5.5	45.2
20- 40	10.6	1.56	0.18	0.03	8.7	6.0	46.6
40-100	5.3	1.35	0.18	0.05	7.5	4.6	49.7
Kurö (gyttja clay)							
0- 20	8.9	4.56	0.21	0.10	21.7	5.6	47.6
20- 30	8.0	1.52	0.15	0.06	10.3	5.2	48.4
30-100	5.3	0.73	0.09	0.03	8.1	3.6	57.1
Elinghem (marl-containing gyttja)							
0- 20	12.2	5.60	0.51	0.44	11.0	7.6	n.d.
20- 40	9.4	4.04	0.35	0.46	11.5	7.9	n.d.
40-100	6.2	3.30	0.25	0.47	13.2	8.1	n.d.

100 mm/h in all profiles. A plough pan between topsoil and subsoil sometimes lowered the conductivity in that layer to a few mm/h.

Characteristic Chemical Properties

A C/N ratio of about 10 is common for many neutral well-drained agricultural soils (Russell, 1973). Gyttja soils in this investigation had C/N ratios slightly higher than 10 in the topsoil where the gyttja soil was mixed with peat. A general tendency for the ratio to decrease with depth indicated the presence of more nitrogen-rich organic material lower in the profile (Table 2). Elinghem, with its high carbonate content, was an exception. Similar results were found by Hansen (1959), Larsen (1978) and Öborn (1989).

The sulphur content is commonly about 0.02-0.05 % in Swedish agricultural mineral soils (Wiklander, 1976) compared to gyttja soils where values well above 0.2 % sulphur are not uncommon (Larsen, 1978; Öborn, 1989). In drained and cultivated gyttja soils, some sulphur can be leached out of the upper layers but very high sulphur contents can still be found in the lower subsoil. The highest value found in this investigation was 3.7 % in the 90-100 cm layer of the gyttja profile at Gammalstorp. Consequently, many soils containing gyttja have a low pH. However, the pH value is also dependent on the carbonate content, as clearly seen in the Elinghem profile (Table 2). This profile had a high sulphur content (0.44-0.47 %) which would normally indicate a low pH, but the very high calcium carbonate content (80-90 % throughout the profile) gave an actual pH of 7.6-8.1 (Table 2).

The carbonate content in all the other profiles was less than 0.1 % at all depths. More commonly, a pH value of 5-5.5 is found in the topsoil of Swedish cultivated gyttja soils, often dropping below pH 4 at a depth of about 0.5 m in the profile (Ståhlberg, 1974; Öborn, 1989). This reasonably high pH in the topsoil of cultivated gyttja soils is often due to liming and to some extent leaching of the sulphur. A low pH in gyttja soils is more serious than in other organic soils because the high mineral content will give rise to a greater risk of aluminium toxicity.

Characteristic Physical Properties

The texture of gyttja soils is very often dominated by clay and to some extent silt. Texture analyses were made on some of the soils in this investigation. Clay contents (particles < 0.002 mm) were commonly between 45 and 65 % (Table 2). The sand fraction (particle size 0.06 - 2.0 mm) rarely exceeded 10 %. The marl at

Elinghem had only a few per cent mineral material apart from an 80-90 % calcium carbonate content

Densities of solids, dry bulk densities, porosities and percentages of macropores and micropores for all profiles are summarised in Table 3. Volume relationships with depth at different matric tensions are shown in detail for four profiles in Figure 6. Dry bulk densities of gyttja soils are in general much lower than in mineral soils and higher than in peat soils (Ekström & Flodkvist, 1926). All gyttja soils in this investigation had dry bulk densities lower than 1.1 Mg/m^3 with a tendency for values to decrease with depth. In profiles with peat on clay gyttja (Rickeby and Ola), dry bulk densities were somewhat lower in the topsoil. Similar results were found by Andersson (1955) for two clay gyttja profiles and two gyttja clay profiles. The density of solids of gyttja soils is influenced by the low density of diatoms (approximately 2.0 Mg/m^3 ; Hurd, 1983) and the organic matter content. However, a high mineral content, as in the Kurö profile (Table 3), can raise the density of solids well above 2.0 Mg/m^3 and sometimes as high as 2.8 Mg/m^3 .

The gyttja profiles in this investigation had densities of solids between 1.66 and 2.75 Mg/m^3 , which is in accordance with results by Kivinen (1938), Andersson (1955) and Larsen (1978). The lowest values were found in topsoils influenced by peat and crop residues (Table 3; Rickeby and Ola).

As a group, gyttja soils are porous and hold large amounts of water when saturated. Porosity is in general over 60 % (Table 3 and Figure 6). Normal drainage (to approx. 1 m) will remove quite a large portion of the saturated water content. Consequently, aeration problems are very rare on these soils since most of them hold 15-20 % of air at field capacity, at least in the topsoil and the upper subsoil. On the other hand, problems with seed germination can arise if the air-filled porosity of the topsoil is too high. Such problems have been noted in the field as, for example, at Järnvalla (Table 3 and Figure 6).

Table 3. Summary of density of solids, dry bulk density, porosity, macropores and micropores for soil profiles at 9 test sites

Depth cm	Density of solids Mg/m ³	Dry bulk density Mg/m ³	Porosity % by volume	Macropores >30·10 ⁻⁶ m % by volume	Micropores < 0.2·10 ⁻⁶ m % by volume
Gammalstorp (gyttja, topsoil mixed with peat)					
0- 20	1.90	0.47	75.5	14.1	21.9
20- 30	1.96	0.37	81.0	14.8	21.4
30-100	2.03	0.29	85.7	7.8	17.8
Skälboö (clay gyttja, topsoil mixed with peat)					
0- 20	1.97	0.66	66.5	12.8	26.0
20- 30	2.11	0.64	69.9	14.4	31.9
30- 40	2.25	0.55	75.3	16.5	35.6
40-100	2.37	0.40	83.2	5.8	24.6
Rickeby (peat on clay gyttja)					
0- 20	1.66	0.39	76.4	14.0	20.8
20- 40	2.08	0.34	83.8	8.1	12.6
40-100	2.43	0.48	80.3	9.9	13.2
Ola (peat on clay gyttja)					
0- 20	1.82	0.52	71.6	16.6	21.4
20- 30	1.88	0.58	69.4	12.2	23.2
30-100	2.49	0.60	76.0	13.1	17.4
Järnvalla (clay gyttja, topsoil mixed with peat)					
0- 20	2.20	0.63	71.4	33.2	21.0
20- 30	2.19	0.88	59.9	8.5	29.0
30-100	2.42	0.65	73.3	13.5	25.5
Nibble (gyttja clay, topsoil mixed with peat)					
0- 20	2.28	0.74	67.9	22.5	22.8
20- 30	2.32	0.78	66.6	19.3	24.1
30- 40	2.45	0.88	64.1	18.0	22.9
40-100	2.55	0.88	65.3	9.1	25.3
Kungsängen (gyttja clay)					
0- 20	2.53	1.05	58.4	10.8	20.6
20- 40	2.51	1.00	60.5	11.2	21.8
40-100	2.65	0.89	66.4	14.0	24.4
Kurö (gyttja clay)					
0- 20	2.64	1.06	60.0	15.0	24.4
20- 30	2.74	1.07	60.9	11.9	25.5
30-100	2.75	0.89	67.4	14.0	25.8
Elinghem (marl-containing gyttja)					
0- 20	2.36	0.70	70.6	12.6	19.0
20- 40	2.43	0.68	72.1	12.4	18.2
40-100	2.47	0.47	80.9	11.3	12.2

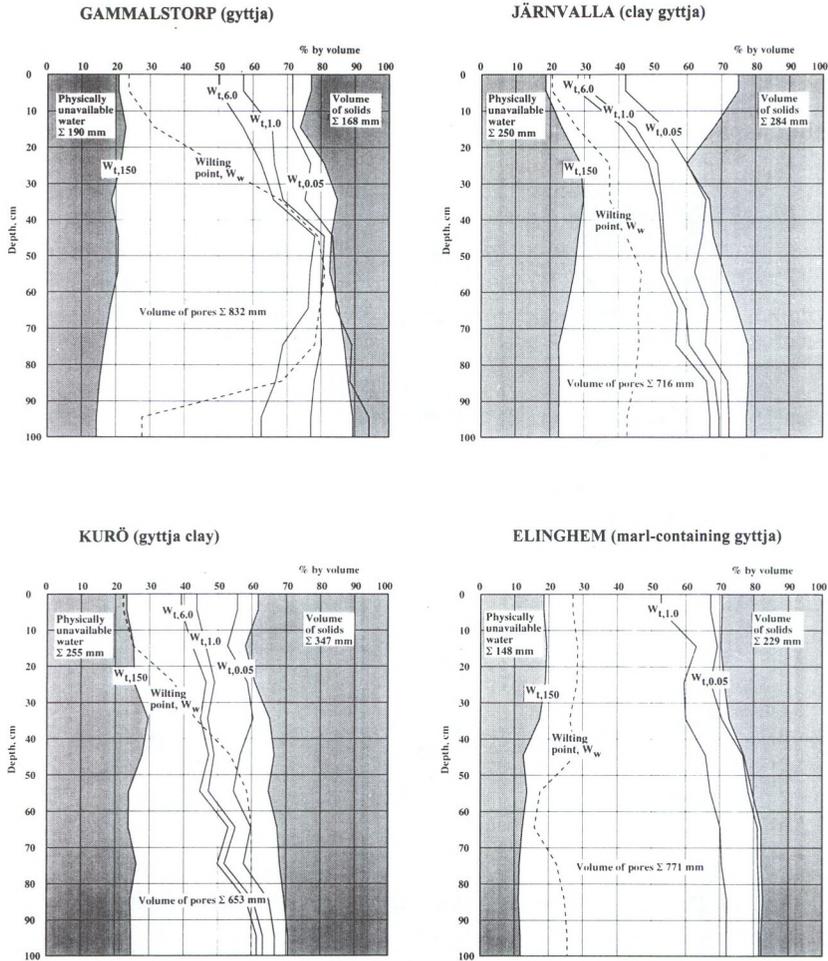


Figure 6. Volume relationships with depth at matric tensions (W_t) of 0.05, 1.0, 6.0 and 150 m water column and at wilting point (W_w) for four gyttja soils. Water content at wilting point for layers 70-100 cm at Kurö are extrapolated.

Due to their high porosity, gyttja soils in general have large amounts of physically available water (Table 4 and Figure 6) measured as water content at field capacity minus water content at a matric tension of 150 metre water column (W_{t150}) down to 1 metre depth (Andersson, 1955). Water content at field capacity was calculated as the moisture content of the profile at matric tension equivalent to 1.0 m drainage or water-table depth ($W_{dr1.0}$). Water retention data were used to calculate water contents in each 10 cm layer. For example, at a drain depth of 1.0 m, the

average matric tension in the uppermost 10 cm layer of the soil is 0.95 mwc (9.5 kPa); the water content of this layer was found by interpolation between the 1 mwc (10 kPa) and the 0.5 mwc (5 kPa) value. At high evaporative demand the upper layers will, due to evapotranspiration, be much drier than indicated by the drainage depth.

Table 4. Physically available water, water easily available to plants, estimated root depth and water accessible to plants ($W_{dr1.0}$ = water content at a matric tension equivalent to 1.0 m drainage, W_{t150} = water content at a matric tension of 150 metre water column, W_w = water content at the biological wilting point)

Site	Physically available water $W_{dr1.0} - W_{t150}$ 0-100 cm depth mm	Water easily available to plants $W_{dr1.0} - W_w$ 0-100 cm depth mm	Estimated root depth cm	Water accessible to plants $W_{dr1.0} - W_w$ to root depth mm
Gammalstorp	583	187	40	88
Skälboö	440	234	50	123
Rickeby	604	355	40	81
Ola	436	218	40	116
Järnvalla	308	166	90	137
Nibble	284	-	70	-
Kungsängen	300	209	100	210
Kurö	274	-	60	60
Elinghem	552	456	50	171

Some of the gyttja profiles have very large amounts of physically available water, most of them with more than 300 mm down to 1 metre depth, compared to about 150 mm in a well-structured clay profile. Due to low pH in gyttja soils, this physically available water might not be easily available to plants. This is reflected in the big difference between the water content at 150 metres water column (W_{t150}) and the biological wilting point (W_w)(see Figure 6). The amount of water easily available to plants down to 1 m depth in the profile (Table 4) was considerably less than the amount of physically available water, but more than 150 mm was easily available in all profiles.

The main restriction in the water supply to plants on gyttja soils is not the amount of available water but the amount accessible to plant roots. Profiles with unrestricted root development will have large amounts of water accessible to plants but on some gyttja soils with very low pH (aluminium toxicity), root development will be restricted even at 30-40 cm depth, resulting in a shortage of water. Root depths in the gyttja profiles were estimated from field studies. Roots tended to concentrate on

crack surfaces and to avoid the inside of columns. A pH below 4 (Table 2) was the main restriction to root development. The amount of water actually accessible to plants was calculated (Table 4) and it can be concluded that root depth is of vital importance to the supply of soil water to plants on a gyttja soil. Thus root depth determines how suitable the soil is for arable use. On Kurö, where root growth is restricted (Table 4), it is very likely that drought problems will arise during a dry summer. On Kungsängen, however, deep root development (Table 4) will ensure an ample water supply and create a very high-yielding arable soil. Elinghem with its high pH (Table 2) is an exception to the rule. Here, the supply of easily available water in the upper part of the profile is sufficient and deep root penetration is not necessary. Many gyttja soils are situated in low-lying areas where it is possible to regulate the groundwater level. Water can either be pumped out of or into the area. The permanent crack system makes it easy to subirrigate and therefore the adverse effect of limited root depth can in many cases be counter-acted by maintaining a high water-table.

The Effect Of Gyttja On Soil Properties

As shown earlier (Table 1) even a very small gyttja fraction has a great influence on the physical properties of soils. Figures 7 and 8 show the effect on porosity and dry bulk density of increasing gyttja content (measured as loss on ignition, corrected for the loss of structural water from clay minerals). Only soil samples from the subsoil were used, to ensure that the organic matter originated from gyttja and not from peat or crop residues in the topsoil. A good correlation was found between corrected loss on ignition and porosity (Fig. 7) and dry bulk density (Fig. 8), respectively. Even a small amount of organic matter (gyttja) raised porosity above 60 % compared to 50 % in a "normal" clay soil (Fig. 7). At zero corrected loss on ignition, porosity is 63.7 % (Fig. 7), which is still very high, and a consequence of the corrected loss on ignition not being a true measure of the gyttja content. At zero corrected loss on ignition (zero OM) there is still a considerable amount of gyttja in the soil. This can be measured as biogenic silica (Table 1), and obviously this gyttja has a great effect on the porosity. At higher "gyttja" contents (Fig. 7), porosity approaches values common for well-humified peat soils. An increase of the corrected loss on ignition from 5 to 10 % resulted in a porosity increase from around 70 % up to 80 %. The effect of gyttja on volume relationships can also be clearly seen in Figure 6 with decreasing gyttja content from gyttja (Gammalstorp) to clay gyttja (Järnvalla) and gyttja clay (Kurö). Gyttja also had a marked effect on dry bulk density (Fig. 8),

due to high porosity and low particle density. Bulk densities dropped considerably with an increase in gyttja content (Fig. 8). The same inconsistency at zero corrected loss on ignition is found here as with the porosity.

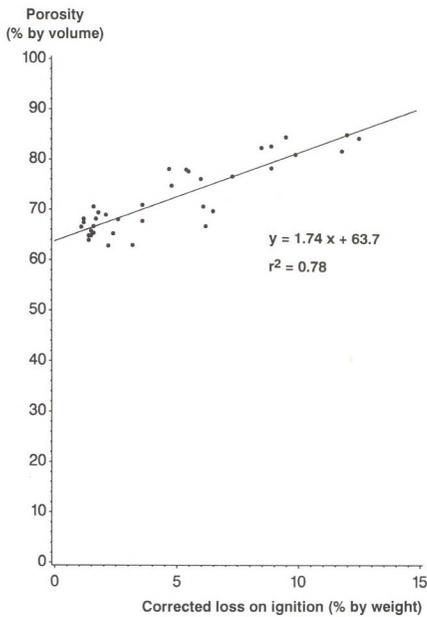


Figure 7. Relationship between loss on ignition corrected for the loss of structural water from clay minerals and porosity for 36 gyttja soil samples.

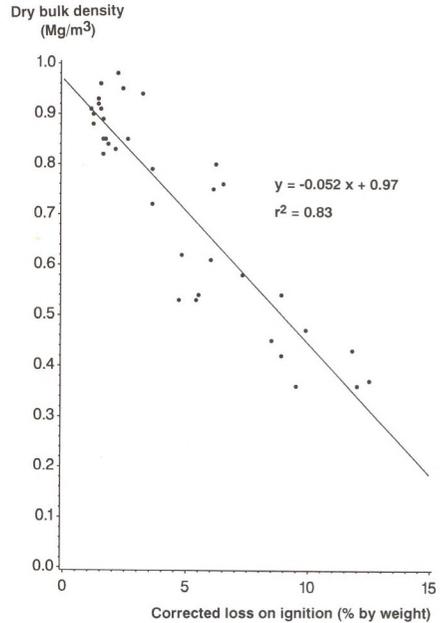


Figure 8. Relationship between loss on ignition corrected for the loss of structural water from clay minerals and dry bulk density for 36 gyttja soil samples.

Diagnostic Features

This and other investigations (Ekström, 1927; Kivinen, 1938) have shown that important criteria to identify drained gyttja soils in the field are:

1. Gyttja soils are in general found in flat low-lying areas,
2. Gyttja subsoils have a permanent crack system often stabilized by precipitation of iron oxides,
3. Gyttja soils often have a grey to greenish colour

Gyttja aggregates break very easily, even at high water contents (low tensile strength), compared to a "normal" clay .

In this investigation the following laboratory data were found to be important criteria in identifying cultivated gyttja soils:

1. An organic matter content >1 % by weight in the subsoil,
2. A dry bulk density <1.1 Mg/m³
3. A porosity >60 % by volume.

These last three criteria must all be met at the same time.

ACKNOWLEDGEMENTS

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PEAT RESOURCES IN CUBA

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SUMMARY

During the last five years the drastic cut in oil supply provoked a critical situation in Cuba. The shortage of domestic oil production and the absence of alternative energy sources, such as wide rivers and coal deposits, drove us to decide that the most promising option was to develop our huge peat deposits. However, there are problems concerning skill and finance.

This report reviews the potential for peat development to date in the Cuban territory. The figures and characteristics are partly taken from the surveys done by Russian and Cuban specialists during the 60's. There is some new data compiled from the work done more recently in some of the Cuban peat deposits. The conditions for draining and harvesting are very challenging and difficult if the peat deposits are to be developed without doing any unnecessary damage to the fragile environment of Cuban wetlands. However, if the required financing and skills are available, the work can be carried out and significant risks avoided.

INTRODUCTION

The Republic of Cuba has significant peat resources and eight major peat deposits have been identified in the western part of the country. The reserves of the three most important peatlands are estimated to be half a billion tons (40 % water content). The quality of the reserves is generally high. Presently, small-scale peat mining operations are taking place in South Havana and detailed prospecting is being implemented at the Cienaga de Zapata wetland. Samples of some thousands of tons will be mined to study the behaviour of peat as a raw material in cement production and as an alternative source of fuel for domestic use.

The Cuban Government assigns a high priority to energy in general and to indigenous fuels in particular. The drastic cut in oil products makes the situation critical, and the most promising option to solve this problem is to develop peat, firstly as a fuel to substitute imported fuel oil, primarily in electric power generation, and secondly as an alternative to charcoal, wood and fuel oil for industrial as well as household consumption.

In the early 60's, specialists from the former Soviet Union in co-operation with a small group of national specialists studied the potential of Cuban peat, undertaking comprehensive investigations on wetlands in the country and assessing peatland reserves in the Zapata wetlands in particular.

The present report reviews the potential for peat development to date.

PEAT RESOURCES

Results of surveys on peat resources by Russian and Cuban geologists are shown in Table 1. (Fig. 1).



Figure 1: Map showing the location of the main peat deposits in Cuba.

Table 1. Area, depth, reserves, ash and water contents and degree of decomposition of peat from nine deposits in Cuba.

Deposit	Area (10 ³ ha)	Depth (m)	Reserves (10 ³ m ³)	Ash %	Water %	Decompo- sition %
Cienaga Zapata	125.6	2.96	3474.7	15.9	85	49
Peninsula Zapata	89.8	2.95	2490.2	19.3	85	52
Gardenas	5.1	1.91	97.4	36.6	85	50
Lanier	1.5	1.07	15.7	22.5	85	50
Moron	0.5	1.29	6.5	34.8	85	50
Remates	0.7	0.87	5.7	-	-	-
Majana	0.9	1.17	10.6	-	-	-
Esperanza	0.03	1.13	0.3	-	-	-
Sur de Havana	5.8	2.46	142.5	19.4	85	55

Peatlands with first priority for exploration and future exploitation were selected on the basis of geographical location and characteristics, namely Cienaga de Zapata and Sur de Havana. However, field work is being carried out in all peat deposits in order to assess their potential use for domestic purposes. An exception has been made in the case of the Peninsula de Zapata deposits, which is in contact with sea water and exhibits complex primary features. It was considered that mining this deposit would be very dangerous for the environment, causing irreversible damage due to salinisation of the whole area. However, an ecological survey will be carried out by the Academy of Science in order to obtain a more detailed impact assessment.

From the above information our main target and first priority will be the Cienaga de Zapata peatland and this paper will deal with the main features of this deposit.

CIENAGA DE ZAPATA PEAT DEPOSIT

The Cienaga de Zapata deposit forms part of one of the most developed wetlands in the Caribbean. It covers 432 200 hectares and runs from east to west on the southern coast of the Matanzas province some 140 km from Havana. This wetland contains the two largest peat deposits on Cuban territory: Cienaga de Zapata and Peninsula de Zapata. (Fig. 2).

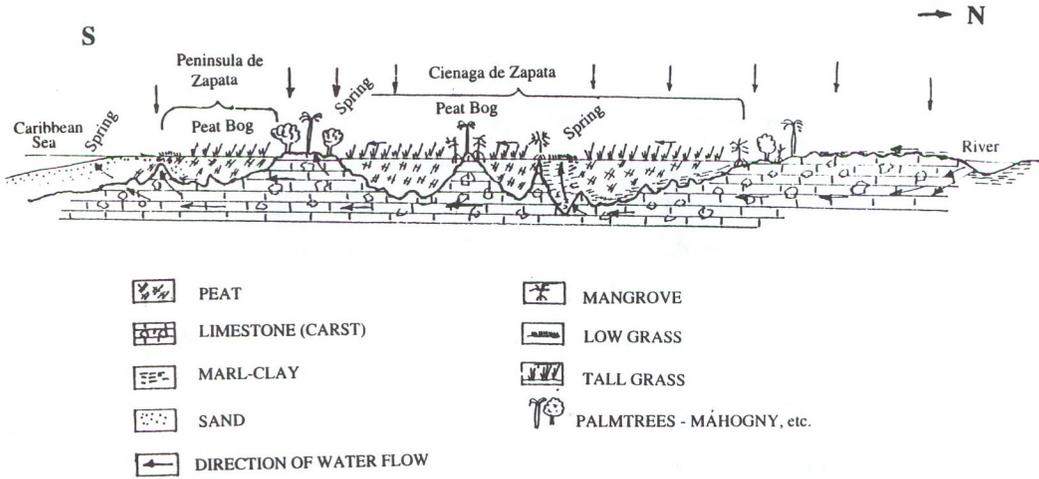


Figure 2. Schematic section across the wetlands in Matanzas province showing the Cienaga de Zapata and the Peninsula de Zapata peat deposits.

The deposits are divided by a long open belt, some 60 km in length and 7 km wide, of carstic limestone running in the same direction. The two peat deposits occupy an area of around 211 000 ha or 50 % of the wetland area, within which the depth of peat is not less than 1.0 m.

The Peninsula de Zapata deposit is not considered further due to the problems mentioned above and Cienaga de Zapata was chosen for all experimental work, including survey and pilot exploitation. This deposit appeared to be the most suitable site because it had:

- the highest peat volume
- the lowest ash content
- an acceptable degree of decomposition
- good access to roads and railtracks
- the lowest environmental impact
- no conflict with agriculture or tourism

However, the great amount of work to be done on survey, assessment and exploitation is being considered a challenge on account of the special tropical conditions of a mangrove swamp with a very complex water system fed mainly by underground water running south through a very complicated carstic limestone structure, which also incorporates two fault systems. These faults in Miocene Limestone of the Güines Formation originally were responsible for the formation of the basin in which the wetland developed. Contact with sea water on the western side and continuous irrigation from underground water have determined the hydraulic conditions in the area. The main problem is that this huge wetland cannot be drained because of its comparatively low altitude and also because the bottom of the deposit is below sea level.

Based on a close examination of the situation, a detailed environmental conservation plan is being designed in order to avoid unnecessary risks while the future exploitation is in progress. That is why a 4 km² pilot plot was selected in order to undertake experimental work on methods of survey and exploitation and environmental monitoring prior to large-scale development. Obviously a deposit like this has never before been mined industrially and new and special skills and techniques will be required to develop it.

From the preliminary approach, it seems that an area for drying raw peat has to be established outwith the swamp on the limestone at the northern edge of the peat deposit where sod or milled peat for domestic or industrial use can be dewatered and harvested by conventional methods and machinery.

The Ciénaga de Zapata deposit has been divided into three main sectors. The main characteristics of each sector are presented in Table 2.

Table 2. Area, volume, ash content and degree of decomposition of peat in the Ciénaga de Zapata peat deposit

Sector	Area (ha)	Volume (10³m³)	Ash %	Decomposition %
Eastern	27 800	798.33	17.21	49
Central	56 300	1 660.99	14.80	51
Western	39 100	1 015.41	16.79	46
Total/mean	121 200	3 474.73	15.63	50

As shown above, the most suitable area in terms of peat volume and quality is the central sector. Other favourable features are absence of direct contact with sea water, proximity to roads and railways, low potential environmental impact and a favourable water-contact balance. In addition, the projected drying platform could be located not far (12 km) from the mining site and close to the sugar mill in which the peat could be piloted as a fuel substitute for the sugar cane waste hat has been used to date.

The pilot area (4 km²) is located in this central sector and a waterway and a road have already been constructed to reach the mining site from the northern limit of the wetland. The waterway and road are about 4 km long and will be used primarily for the transportation of men and equipment but also for transporting the peat to the drying area.

USES OF PEAT IN CUBAN CONDITIONS

The strategic problem is to resolve, to some extent, the need for alternative fuel to generate electricity. This could be achieved by a country-wide analysis of requirements and capacities and the conversion of some of the units to burn solid fuel instead of oil. Another alternative could be to locate a number of 20 or 50 MW units around the wetland, not far from the drying site, in order to avoid excessive costs in transporting peat with 30 to 40 % water content.

The generation of electric power in the sugar mills using peat as a fuel could be an attractive though not expensive alternative. The main problem is transportation because, in Cuba, the sugar mills are spread throughout the country. However, some five or six mills are located within a radius of 60 km from the Cienaga de Zapata deposit and this alternative is being analysed by experts on power generation in the sugar industry.

The cement industry could also benefit from burning peat by:

- adapting solid fuel burners and
- mixing the mass of raw material driven to the kilns with a proportion of peat and lowering the amount of fuel oil currently used in cement production.

So far, tests carried out using an admixture of peat at cement factories have been positive, resulting in a saving of some 20 to 30 % fuel oil.

In domestic field, the peat could be used as a substitute for kerosene and charcoal in schools, small towns and farms and for other small facilities around the deposit. Some pilot schemes in small country towns are producing good results.

Apart from the above mentioned utilisation of peat as a fuel, consideration must also be given to its uses as a soil conditioner and fertiliser, properly mixed with zeolite and plant nutrients. This field of development is well known from experiences in Europe and North America, and the Cuban authorities are very interested in developing their own peat fertiliser industry to support the ambitious food production programme throughout the whole country and to take advantage of the mild climate and overall meteorological conditions that permit the all-year-round harvesting of peat.

PROBLEMS TO BE SOLVED

First of all a framework is being designed to accomplish all the complex work derived from a new concept in the fuel industry. The first step has been taken but due to lack of experience in the peat industry risks have to be recognised and faced.

Another problem, on which work is already in hand, concerns the assessment of the ecological impact of mining, harvesting and burning. At the outset, some advice was obtained from overseas but the development of our own expertise is of first priority in order to solve the problems associated with this complex task.

From our point of view, the main question is how to resolve the problem of mining and transporting the peat from the deposit to the drying area. Peat producers in Europe and North America have little if any experience in mining such waterlogged swamps, with no chance of drainage, and in transporting the wet raw peat to an alternative site where it can be dried and harvested by conventional techniques and equipment. That is why the work in the experimental area is so important in order to avoid the introduction of expensive production methods that could become an obstacle to future development.

CONCLUSIONS

In Cuba, peat resources exist as does the need for an alternative fuel to overcome the shortage of crude oil. The conditions are difficult but the challenge cannot be avoided. A framework for the development of a strong industry is being constructed and the will to succeed also exists.

The main challenge is to produce peat without unduly harming the environment. This can be achieved by good mining practices, which require careful environmental

impact assessments, in collaboration with scientific institutions such as the Cuban Academy of Science. Both environment and development are arms of the same organisations and to think and work together in a unified direction will result in securing the best options for our development.

COMBINED PRODUCTION OF MIXED PEAT AND WOOD FUEL: STARTING POINTS IN FINNISH CIRCUMSTANCES

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SUMMARY

The technology of peat production has developed greatly in Finland since the time of the energy crisis. In particular, the development of fluidized bed combustion has made it more attractive to use mixed biofuels, for example peat mixed with wood chips or crushed wood residue. In this account possibilities of practical production chains are discussed both on a general level and with respect to detailed studies. Some basic factors which affect mixed biofuel production systems are also considered.

INTRODUCTION

The basic production process for peat has been developed solely for peat utilization. Therefore the production and handling of mixed biomass-based fuels, such as peat, wood and straw-like biomass, is a more recent area of research. At present, this topic is of growing importance because of the development of combustion technology, mainly the fluidized bed process.

THE PEAT PRODUCTION CHAIN

The present share of peat, about 5%, in the Finnish energy budget is due largely to the efficient production chain. Weather-wise, the evaporation potential is utilized efficiently and production machinery is also tuned to give the most efficient results (Leinonen, 1993).

The previous OPTIMITURVE- research programme during 1988-92 actually showed the methods most urgently needed to improve production efficiency

(Leinonen, A., Erkkilä, E., 1993). The peat harvest obtained during the summer season actually gives the production level which in turn roughly determines the price of the peat, presently varying 47-57 FIM/MWh. In recent years, the price of peat fuel has been quite steady compared with that of oil or even coal (Fig.1).

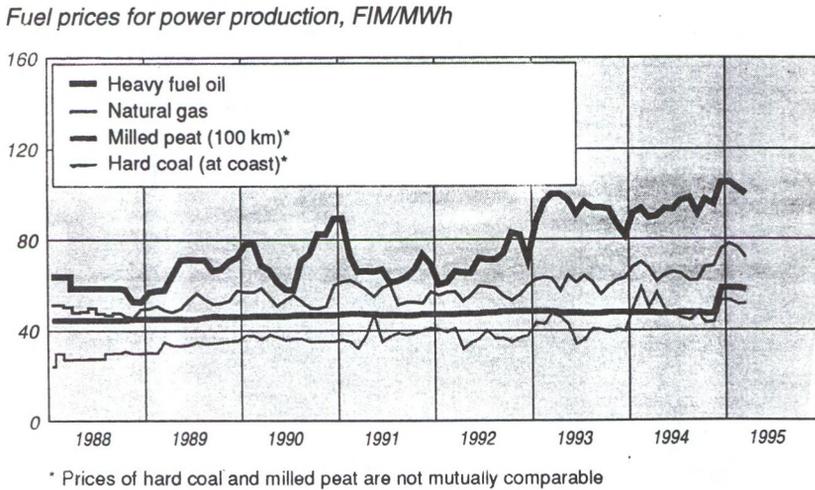


Figure.1. Price development by fuel types in Finland in 1988-95 (Finnish Energy Review 3/1995)

The numerical value of the energy unit price in peat has remained fairly constant; without the clear developments in technical efficiency and also organisation, the price would probably have increased markedly.

ENERGY WOOD PRODUCTION

One essential feature of wood fuel, compared with peat fuel, is the different production technology. Peat is produced under favourable weather conditions using cyclic, mainly industrial, mass production processes. The production of wood fuel necessarily consists of more piecemeal processing of stem wood, at least in thinnings. The logging residue from the final cutting is also an attractive source of wood fuel because, in this case, the material for processing is easily stacked. The important price-availability factors in wood fuel production are shown in Fig. 2.

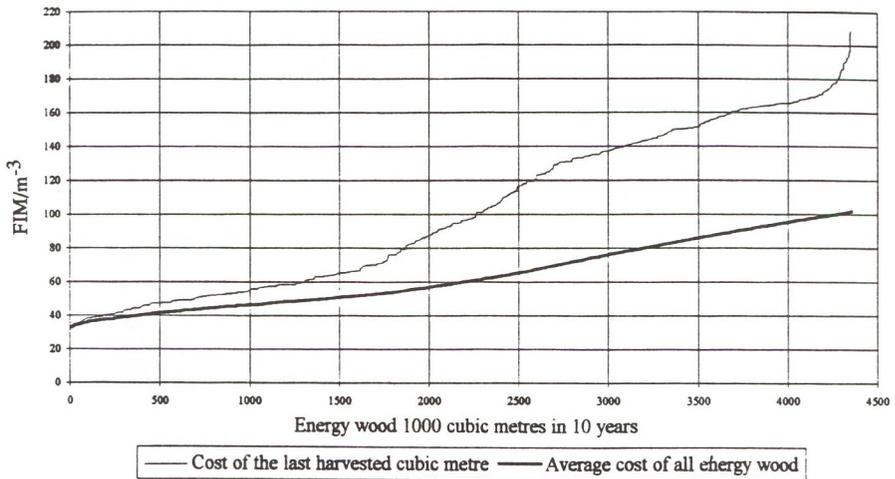


Figure.2. Variation of simulated energy wood production prices on a given forest area (Leiviskä et al.,1994).

The figure shows that if the energy wood of a given region is utilized close to one hundred percent then the last few cubic metre will be very expensive. The figure also shows that the most profitable energy wood is obtained from final cuttings and that wood from thinnings forms the most expensive part of the energy wood stock on a given area. This dependency has been stated earlier clearly by Hakkila (1992).

One way for wood to approach the energy price level of peat is by the direct technical development of an energy wood chain; another way could be to combine conventional wood harvesting with another production chain, for example energy peat production, in some synergetic way. Wood harvesting for pulp and timber operates in nearly all forest areas on a rotation basis. Therefore the conventional forestry chain is the most obvious production chain for integration. Actually there is no other feasible alternative integration partner.

Much effort has already been put into investigating the technical methods of energy wood production the Finnish BIOENERGY program 1993-98. This research concerns both the production of wood fuel from final cuttings and thinnings; simultaneously, the production of pulp and energy wood has been studied by VTT/Energy (MASSAHAKE system)

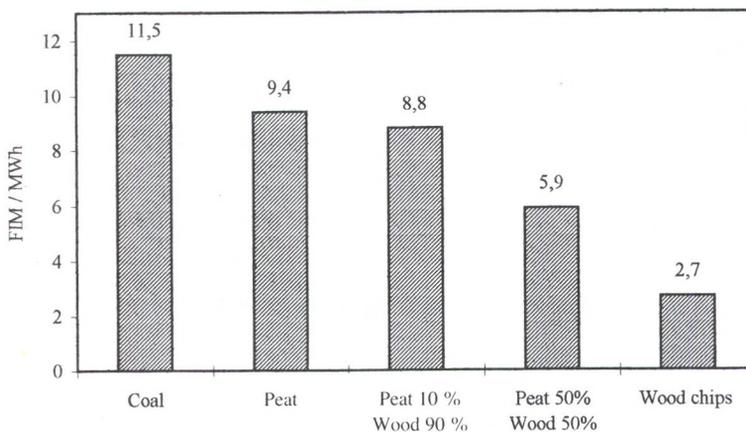
STRAW-LIKE ENERGY CROPS

Production of non-food crops on agricultural areas is presently an interesting topic as an alternative use of land. It has been estimated that about one third, or 1Mha, of the agricultural area of Finland could be utilized for energy biomass production because of the structural changes of farming. On the other hand, growing possibilities of using mixed biofuels in boiler plants may also involve the use of straw-like fuel materials such as *Phalaris arundinaceae* and some other species.

The interesting feature of *P. arundinaceae* is its fast growing biomass. In experimental areas, an annual production of more than 10 tonnes dry matter per hectare has been obtained. The corresponding price of energy is approximately at the same level as the energy price of energy wood from thinnings. The local price is of course dependent on many factors like dry matter yield per annum per hectare, investment in harvesting systems, running costs of harvesting, transportation to users etc. However, the use of straw-like material as one component of biofuel mixes is also attractive. It is well known that tests have been carried out to mix peat and wood and also straw.

LIMITATIONS OF FUEL PRICE AND QUALITY

If the boiler plant is planned for solid biofuels like peat and utilizes fluidized bed combustion, there are no obvious reasons to avoid using mixtures of biofuels. Different mixtures of peat and wood are even desirable because the sulphur content of flue gases can be reduced and a larger proportion of fast renewable biofuel can be used.



The decisive variable of the components adopted in the fuel mix will be the energy price. For example, using a proportion of wood in a peat-fired boiler plant is acceptable in practice if the energy price of wood is equal to or lower than that of peat.

The technical quality of the mixed biofuel will, in practice, similarly be constrained by the quality of fuel peat. This means that the energy content (moisture content) and particle size of the mixture must stay within certain limits. This is to ensure that the combustion process and the feeding equipment can be operated reliably .

PULP AND TIMBER WOOD PRODUCTION CHAIN

With regard to mixed fuels, the actual forestry production chains are very interesting. We may ask, for example, how much energy biomass can be obtained per hectare from final cuttings and thinnings in different areas.

As a by-product of forestry, a certain amount of wood residue is obtained annually from thinnings and final felling. This amount can be estimated as a percentage of the timber and pulp wood produced. In Finland, a typical figure would be about 20 % of the volume of final cutting (see Alakangas, 1995). Based on this relationship, regional 'upper limit' values for energy wood from final cuttings can be obtained.

The primary energy wood material comes from the final cuttings which economically is 'self supporting' in the sense that the price of the energy wood starts from zero because the residue has had no market value up to now. If we compare this kind of energy wood production with stand-alone energy wood harvesting, the former has many advantages, especially because no costs are associated with the cutting residue or the costs are presumed covered by the price paid for the pulp or timber. Also the residue material is available on relatively open land adjacent to relatively accessible transport roads. The simultaneous harvesting of energy wood and other wood material is regarded as a great advantage.

This leads straight to the idea of simultaneous energy wood and pulp wood and timber harvesting. The idea is by no means new but a serious examination of alternative ways of achieving such integration is very worthwhile.

THRESHOLD FACTORS FOR THE INTEGRATION OF PEAT PRODUCTION AND ENERGY WOOD FROM FORESTRY

An obvious starting point for both the peat production and wood production chains is that both should receive some benefit from an enlarged operation with common purpose, mixed fuel production.

The following list shows some of the advantages (a) and disadvantages (d) for both participants:

Peat producers:

- a1.** use of wood as cover of peat stockpiles
- a2.** additional annual working time for production machines
- a3.** additional annual working time for personnel
- d4.** requires additional familiarization with a 'neighbouring' operation

Wood producers

- a1** the conventional cutting areas by joining silviculturally meaningful objectives
- a2.** additional annual working time for machines
- a3.** additional annual working time for personnel
- a4/d1** environmental effects have both advantages and disadvantages compared with conventional forestry
- d2.** requires some changes in normal wood production operations

The above list can no doubt be extended. When the factors listed are evaluated economically, it will be possible, in principle, to obtain sufficient information to decide whether or not the mixed fuel procedure should be adopted for use on large scale.

It is expected that the common trend to minimize costs and environmental effects will gradually make the evaluation of the above factors necessary in order to establish whether or not and how peat and wood production can be integrated on a large scale.

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CONTROLS ON THE TEMPORAL AND SPATIAL LOCATION OF POOLS ON A MIRE WITH EXTENSIVE CUTAWAY.

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ABSTRACT

Natural drawdown of the water-table at the edge of a raised mire, and the temporal and spatial location of pools is shown to be a function of the hydraulic flow length and hydraulic gradient rather than the extent of cutting or the depth of edge drains. The increase in acrotelm depth at the mire margin is reflected in increased vegetation height and species diversity. The damaged mire margin is shown to have a maximum width of 40 m although cutaway length ranges up to 320 m. While fire damage affects the microtopography, surface gradient and vegetation, the hydrological behaviour of the burnt and unburnt areas may be modelled together.

INTRODUCTION

The hydrology of a raised mire is a balance between incoming precipitation and losses by evaporation, overland flow and, where the geology is appropriate, groundwater loss to mineral soil (Ingram, 1982; Ingram & Bragg, 1984; Kneale, 1987). The rate of flow through the mire depends on the hydraulic conductivity of the peat and the hydraulic gradient of the mire. Excess water runs off as surface or overland flow (Bakker, 1992; Kirkby *et al.*, 1995).

This paper looks at the summer and winter distribution of pools and a weekly piezometer record for a raised mire to see to what extent the pool system is vulnerable given the extent of marginal peat cutting, drainage and burning.

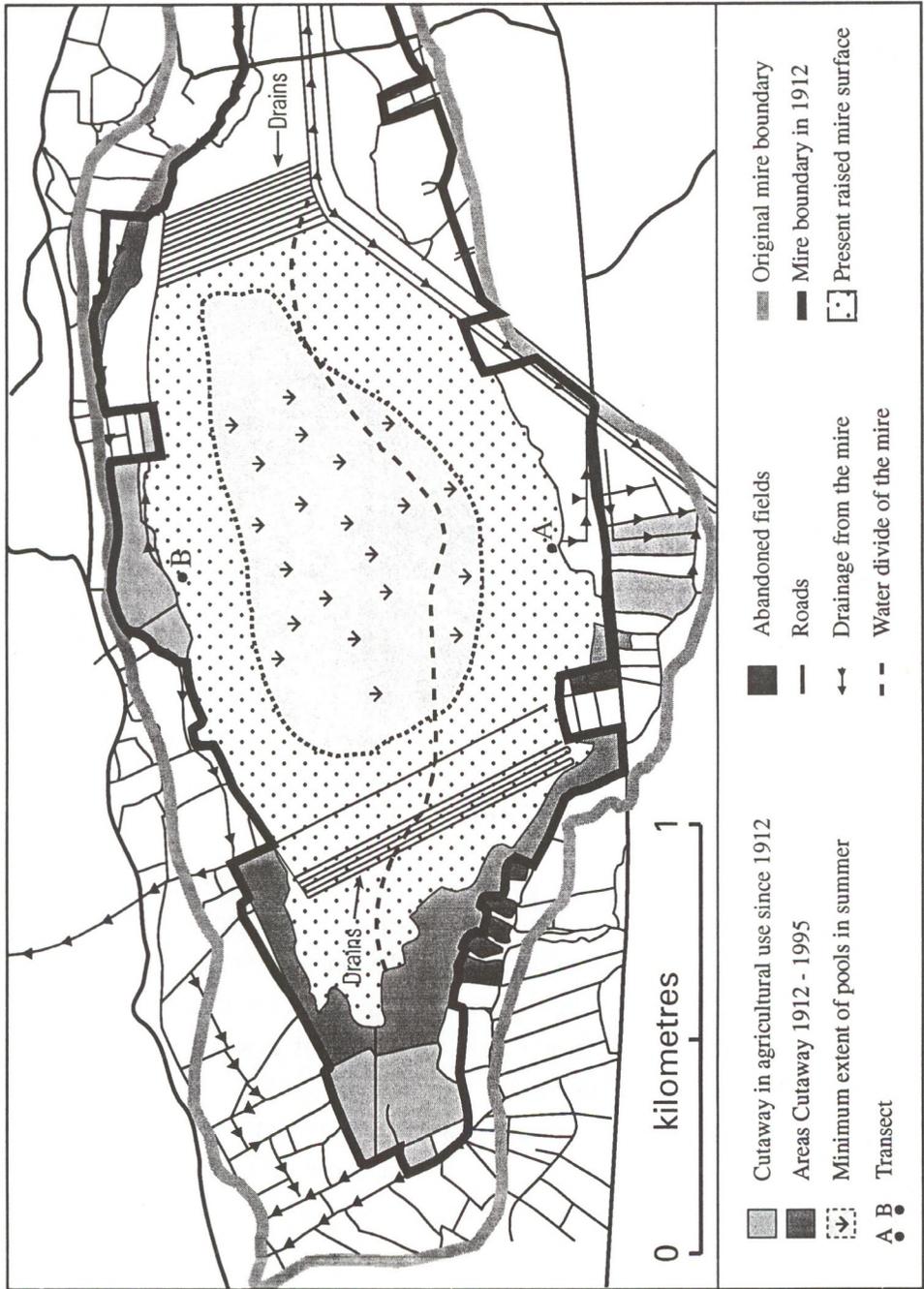


Figure 1. Map of Mongan Bog, information adapted from the 1811 and 1912 surveys, air photos and field survey.

Mongan Bog is an ombrotrophic raised mire in County Offaly (Fig. 1). It is in the ownership of An Taisce and within the Clonmacnoise Heritage zone (Tubridy, 1984; Tubridy & Jeffrey, 1987). The mire developed from a lake, through a fen stage in a small natural basin surrounded by eskers. Today the only input of water is from precipitation although during its earlier evolution the lake and fen will have received runoff from the esker slopes. Mongan is a typical raised mire. It has a convex surface, a high water-table with permanent pools in the central area and is sealed at its base by glacial clay.

The mire is diplotelmic; the catotelmic core is by definition permanently saturated. Decomposition by anaerobic micro-organisms is very slow and there is good preservation of the peat. The catotelm is overlain by the acrotelm which is effectively defined by the maximum depth of the seasonally oscillating water table. As the water-table falls, aerobic decomposition occurs at a faster rate than in the catotelm. The microtopography of the pool and hummock surface is irregular as the mire accumulates material at differential rates as a function of micro-vegetation patterns.

Precipitation in the area averages 870 mm, with evapotranspiration accounting for some 450 mm. The balance, 420 mm, serves to recharge the mire with some losses by overland flow and discharge to marginal drains. The mire's hydrological regime is modified because of exploitation and damage to the boundaries. Figure 1 shows the estimated maximum extent of the mire using information from the 1811 map and ground survey, the mire margins in 1912 and 1984, and areas cut away for fuel and agricultural reclamation. All the edges have been cut to some extent. The original lagg stream has disappeared. The north side is the least damaged but field drains have been dug around land reclaimed for pasture.

In addition to the edge cutting, a number of surface drains, 0.3-0.5 m deep, have been dug across the mire surface at both the east and west ends. Exploitation of the eastern part of the mire by Bord na Mona and the installation of an access track have required further drainage work at the east end (Fig. 1).

SITE INSTRUMENTATION

Detailed study of the water relations at Mongan was made for the period August 1983-July 1984. Groundwater levels in the peat were monitored with piezometers and drawdown at the edges with tensiometers. Daily rainfall was recorded on an autographic gauge and spot runoff measurements were made from drains and the mire surface. The

location of surface pools was recorded in March and July 1984 to compare driest and wettest conditions on the mire. The objective was to define

- factors controlling the spatial extent of pools in the wettest and driest periods, and
- factors controlling the drawdown of the water-table at the mire margin;
- what impact burning had on mire saturation.

Nineteen transects from the water divide on the mire to the edge were selected. All sections were located parallel to the direction of flow and such that they did not intersect surface drains at either the east or west end. The variables used in this analysis are defined in Table 1.

Table 1 Variables in correlation and regression analysis

LDIV	Length from water divide to present mire edge	m
HLOSS	Loss in height over distance LDIV	m
HL	Topographic gradient (HLOSS / LDIV)	
DRAIND	Depth of drain at mire edge	m
CUTAWAY	Length of cutaway from present to estimated maximum mire edge	m
CVH	Average height of <i>Calluna vulgaris</i> in edge 30	cm
SURFL	Minimum length from mire edge to winter pools	m
WDWT2M	Distance to water-table, 2 m from mire edge, winter	m
SDWT2M	Distance to water-table, 2 m from mire edge, summer	m
WPOOL	Length from water divide to limit of mire pools, winter	m
SPOOL	Length from water divide to limit of mire pools, summer	m

RESULTS

The extent of the pools in winter is explained by the length from the water divide on the mire to the present mire edge (LDIV) and the length of the cutaway.

$$WPOOL = -19.66 + 1.027LDIV - 0.114CUTAWAY$$

$$R^2 = 99.7\% \quad F_{2,16} = 2958 \quad (p > 0.01)$$

The inclusion of the CUTAWAY length, indicating the lost length, is more important than the depth of the edge drawdown. Drain depth at the cut edge is not related to the winter pool (WPOOL) distribution.

The summer extent of pool distribution can be modelled by

$$\text{SPOOL} = -153.24 + 0.90 \text{LDIV}$$

$$R^2 = 77.4\%, F_{1,17} = 58.12 (p > 0.01)$$

The lower R^2 is due to non-linearity introduced by including data from 4 transects which have no pools in summer. Three of these are located on the west end of the mire, beyond the surface drains that cut northwest to southeast across the bog (Fig. 1). Here the bog is at its narrowest and drainage to both the cut face and surface drains combine to significantly lower the water-table. The fourth transect at the eastern margin is again affected by the local drains.

Looking at the area of mire permanently affected by drawdown the best fit, linear, parsimonious model to predict the width of the permanently dry surface (SURFL), where water table does not come to the surface at any time of year, is:

$$\text{SURFL} = 1.168 + 0.113(\text{CUTAWAY}) + 952.7(\text{HL})$$

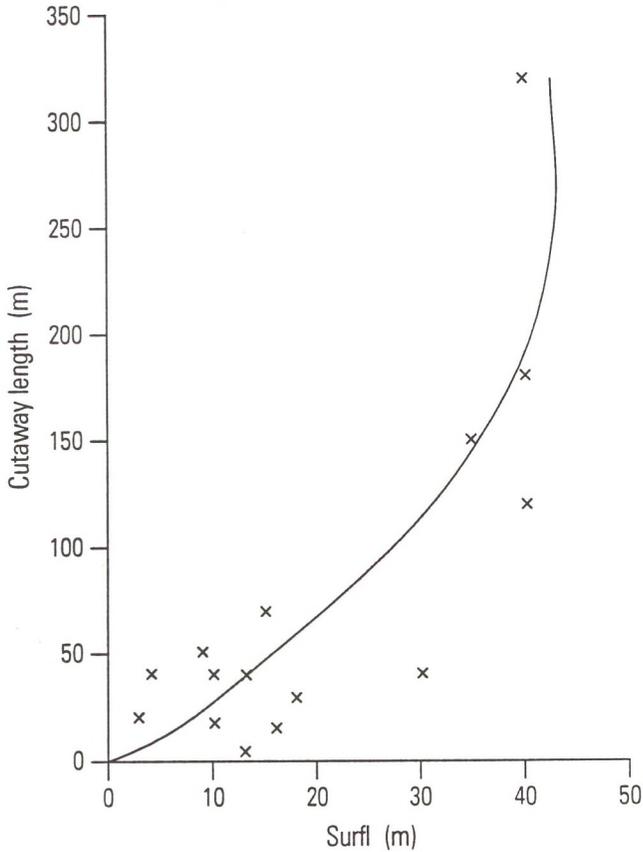
$$R^2 = 71\%, F_{2,16} = 39.2 (p > 0.01)$$

This shows that the drying of the mire margin is a function of the volume of material already removed from the mire by turf cutting, and the change to the surface gradient. This model can be improved by a polynomial function:

$$\text{SURFL} = 2.615 + 0.299 (\text{CUTAWAY}) - 0.00055 (\text{CUTAWAY})^2$$

$$R^2 = 73\%, F_{2,16} = 43.25 (p > 0.01)$$

Figure 2 plots this relationship to show that where the cutaway is less than 75 metres the pools are found to within 30 m of the mire margin. Where cutaway exceeds 75 m pools are 30-40 m from the margin. It would appear that despite cutting of up to 350 m on the southern margin pools are still found within 40 m of the edge in winter. Examination of maps and aerial photographs show that the main peat cutting took place before the 1950's. Some 40 years later pools in winter are still found over most of the mire surface.



$$\text{Surfl} = 2.615 + 0.299 (\text{Cutaway}) - 0.00055 (\text{Cutaway})^2$$

$$r^2 = 73\% \quad f_{2,16} = 43.25$$

Figure 2. Relationship between pool distribution and cutaway length.

The drawdown of the water-table was further examined through the winter and summer water-table position 2 m from the mire margin. In the winter, WDWT2M is significantly related to LDIV, HL, CUTAWAY and SURFL

The most useful predictive model for water table drawdown is

$$\text{WDWT2M} = 0.0095 + 28.93 (\text{HL}) + 0.0009 (\text{CUTAWAY})$$

$$R^2 = 65\%, F_{2,16} = 29.7 \quad (p > 0.01)$$

This shows that the distance to the water-table two metres from the cut face is independent of cutting depth and drain position. It is dependent on the hydraulic

gradient of the slope and the length of the cutaway, controlled by supply side from the mire rather than drainage effects.

This position changes in summer when drain depth is positively correlated with SDWT2M ($r = 0.906$), and the multiple regression model is:

$$\text{SDWT2M} = 24.086 + 43.137 \text{ DRAIN} - 0.1662 \text{ CUTAWAY}$$

$$R^2 = 89.8\%, F_{2,16} = 70.45 (p > 0.01)$$

Figure 3 plots the minimum extent of the pools in August 1984. There is asymmetry in pool elevation with respect to the position of the water divide. On the northern slope pool limit is found between 44 m and 45 m O.D. On the south side pools are not found below 46.5 m O.D. This asymmetry is caused by the more extensive cutting on the southern mire margins. The depth of the acrotelm is greater on the southern margins and water table oscillation is greater. Figure 4 shows the water table record from three of the twenty one piezometers installed across the mire.

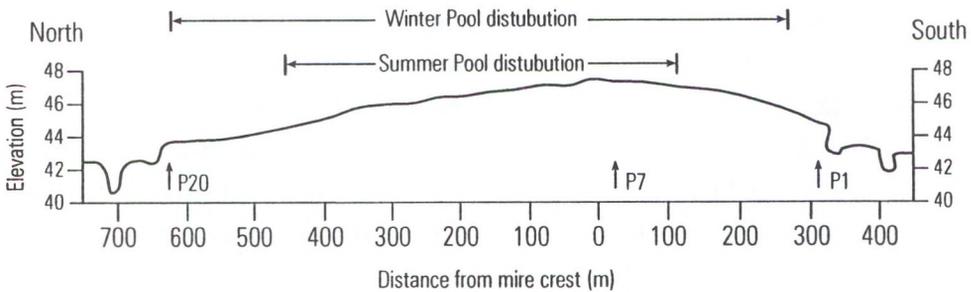


Figure 3. Maximum and minimum extent of the pools across the central transect.

In the centre of the mire, there are permanent pools with the water-table fluctuating through 0.10 - 0.15 m depending on hummock height. The average height of *Calluna vulgaris* at the edge of the mire is controlled by the distribution of winter pools.

$$\text{CVH} = 26.3 - 0.0275 \text{ WPOOL}$$

$$R^2 = 28\%, F_{1,17} = 6.66 (p > 0.05)$$

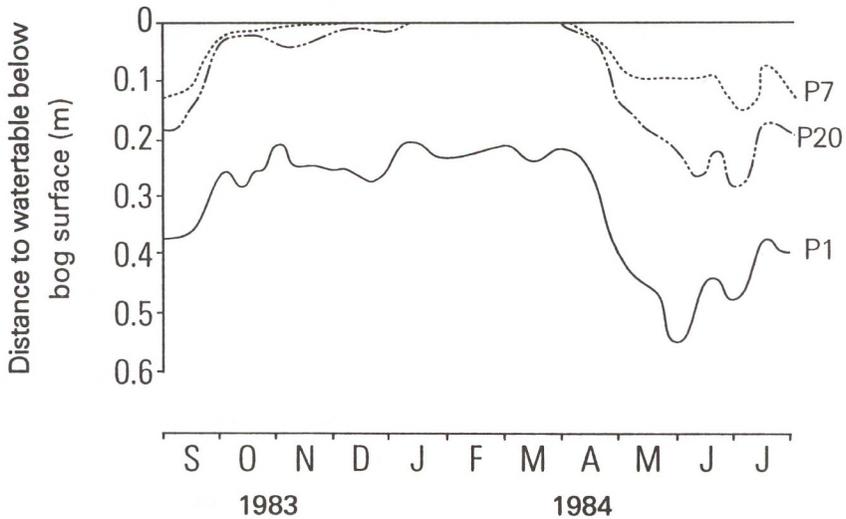


Figure 4. Relative water-table levels for three standpipes, location shown on Fig. 3.

Average vegetation height is shown to be independent of the length of the cutaway and drain depth. The critical factor is the winter surface saturation extent, which affects the rooting depth of mire vegetation. The dominant species in the damaged margin are *Calluna vulgaris* and *Erica tetralix*. *Myrica gale* is found in isolated areas, as is *Betula pendula*. The height of *Calluna vulgaris* increases as the depth of the aerobic acrotelm increases; plants at the edge of the raised mire are over one metre in height. In limited areas where the mire vegetation has been damaged, weed species have invaded. The absence of surface pools and *Sphagnum* species makes the marginal areas susceptible to fire.

Figure 5 plots the relative topographic elevation along 16 of the transects. The surfaces which have been subject to burning are less steep and less elevated. The northern part of the transect plotted on Figure 3 has been burnt, the break in slope at 400 m from the water divide on the mire marks the edge of the burnt area. Analysis showed that, in terms of hydrology, the transects from the burnt and unburnt areas can be modelled together. What is noticeable is the loss of pool and hummock topography in the burnt areas and the colonization of grass dominating species at the expense of *Erica spp.* and *Calluna vulgaris*. The flatter, lowered surface fed by flow from the mire supported a relatively high water-table through the winter, with surface saturation and surface flow at times of heavy rainfall.

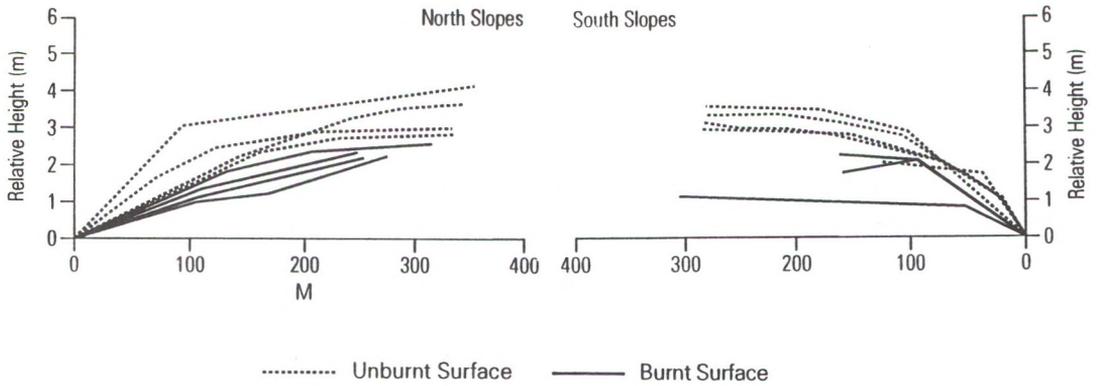


Figure 5. Surface topography along burnt and unburnt transects relative to edge elevation.

DISCUSSION AND CONCLUSIONS

Peat extraction from the cutaway and the installation of drains by farmers serve to lower the water-table at the margin of a raised mire. At the margin, the water-table fluctuates through a greater depth, part of the earlier catotelm becomes seasonally aerated and the more rapid aerobic decomposition processes restart. When the water-table is lowered, the desiccation of the peat causes shrinkage and fractures. Severe drying can cause this alteration to be permanent when peat becomes hydrophillic. Peat dewatering and compaction has two effects. Firstly, peat is more dense after compaction so the hydraulic conductivity is reduced, although there may be rapid water movement through fractures below the water-table. This effect is counterbalanced by an increase in hydraulic gradient and increased incidence of overland flow runoff from hydrophillic and crusted surfaces during precipitation. Secondly, fractures cracks and pipes develop with desiccation and remain after rewetting as preferential drainage paths (Anderson *et. al.*, 1982). These processes will locally increase the dewatering rate of the mound, but examination of this mire some 40 years after most of the edge cutting stopped suggests a stable position has been achieved. However, when looking at the whole mound and estimating total losses, these local variations must be recognised as possibly no greater than natural point to point variations in hydraulic conductivity, which are a function of peat material type and degree of decomposition.

Peat extraction has led to the marginal areas becoming drier and the area of permanent pools declining, but this loss is not linear; the zone with the permanently

lowered water table is shown to be restricted to a maximum of 40 m whether the cutaway loss is 80 m or 300 m. (Fig. 2).

The effect of fire is to reduce surface elevation and to damage or destroy the vegetation cover depending on the degree of burning. Regeneration of vegetation is very slow. Where the burn is severe the natural hummock and hollow microtopography is replaced by a planar surface, with the water-table reaching the surface and observed to be subject to overland flow on the crusted surface. In terms of hydrological impact on the drawdown of the water-table, the presence or absence of burning is not important and the transects can be modelled as a single group.

Digging the shallow surface drains right across the mire lowered the water-table locally in the vicinity of the drains, causing surface drying in the summer and decreasing the long term rate of peat accumulation. Drains in the centre of the mire greater than 0.2 m deep impinged locally on the catotelm, increasing the acrotelm depth and water-table oscillation. These drains have since been blocked with peat, and *Sphagnum* growth has restarted in the new pools.

In some ways it was useful that the water-table monitoring was undertaken in 1984, a drier than average year. Where the mire is large enough, the effect of drawdown is shown to be limited and predictable. Despite cutting of up to 320 m into the mire the transition zone of 'altered' vegetation is limited to a maximum of 40 m. In the unusually dry summer of 1984, the pool area was reduced to 35% of the mire surface but they did not disappear.

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RELIABLE ANALYTICAL TECHNIQUES FOR THE EVALUATION OF PHYSICAL AND CHEMICAL PROPERTIES OF LOWLAND TROPICAL PEAT SOILS.

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SUMMARY

The methodology for a correct physico-chemical characterisation of lowland tropical peat soil was investigated using a *Typic Tropohemist* (USDA Soil Taxonomy) from West-Kalimantan, Indonesia. It is recommended that the moisture content be determined at a drying temperature of 60°C for 24 hours. The concept of the water retention curve for horticultural substrates proved to be appropriate for the evaluation of the water availability at low tensions. A desiccator experiment using saturated salt solutions, showed that drying - rewetting is reversible in the moisture content range of 5% to 20% (on a wet weight basis), but irreversible for the range 20% to 40%. With the image processing techniques presently available, the sessile drop method was considered preferable for assessment of wettability. The *R*-value (DIN 11542) is proposed as a quantified expression of the degree of decomposition. An refined technique is presented for an indirect experimental determination of the standard redox potential. A method for the determination of the Cation Exchange Capacity (CEC) using 0.1 M BaCl₂ and 0.5 M MgCl₂ is proposed and a linear relationship of $CEC = -52 + 33 \times pH$ was obtained.

INTRODUCTION

This study concentrates on ways of analysing lowland tropical peat soils. At present, it is not always easy to find proper procedures for their characterisation because until now research on these acid peat soils has concentrated on management practices,

based on soil fertility experiments in the field. Very little attention was given to research on reliable analytical techniques or to physico-chemical studies in the laboratory. Peat soils cover more than 420 million ha worldwide (Clymo, 1987), of which about 40 million ha are found in the tropics (Andriess, 1988). Some 70% of the latter have formed in the coastal lowlands of South-East Asia, principally in Indonesia, where 4 million ha have undergone some form of development (Maltby & Immirzi, 1992). But peat soils are not uniform in their physico-chemical properties as is generally supposed. The practice of evaluating peat soils with mineral soils as a reference and the failure to appreciate that the complex properties of tropical peat soils are unique or at least quite different from those of the temperate regions, account for numerous unjustified simplifications and many past mistakes in attempts to reclaim and use tropical peatland. This lack of recognition of the difference between the properties of mineral soils and peat soils includes the use of analytical procedures. The analysis of peat soils requires a different approach!

The following fundamental issues in characterising lowland tropical peat soils should always be properly recognised: (1) the physical and chemical behaviour of peat soils is very different from that of mineral soils; (2) reclamation and management practices (i.e. drying, or liming) change their physico-chemical properties markedly; (3) moisture content, bulk density and pH largely determine the interpretation of all analytical data. This paper presents a detailed description of the analytical techniques which proved to be reliable for a correct evaluation of the physical and chemical properties of a lowland tropical peat soil.

CLASSIFICATION OF THE PEAT SOIL UNDER STUDY

The upper layer of newly reclaimed coastal tropical peatland was considered as representative material for this study. The peat was sampled in the River Slamet area near Pontianak, West-Kalimantan, Indonesia. The city of Pontianak is located exactly on the equator and the area is subject to a humid tropical climate. The mean air temperature is 26.4°C. Relative humidity remains high throughout the year and rarely drops below 80%. The annual precipitation is about 3200 mm and no month is really dry. The peat soils are influenced by a tidal swamp irrigation-drainage system. Acid groundwater (pH=3) is usually found at a depth of 40 cm while the upper peat soil layer is water-saturated. The thickness of the peat invariably exceeds 2 metres.

The peat soil is classified according to USDA Soil Taxonomy as a Typic Trophemist with a peraquic moisture regime, or as ombrogenous oligotrophic according to Fleischer's classification (Driessen & Soeprathardjo, 1977).

Moist peat was packed immediately upon sampling in double-layered plastic bags for transport to the laboratory. Subsamples for laboratory analysis were prepared by air-drying the peat to a moisture content of about 70-80% (on a wet weight basis). A particle size fraction of $\phi \leq 2\text{mm}$ was collected through manual sieving and stored in plastic containers. This fraction was used in all the experiments of this study.

PHYSICAL PROPERTIES

Moisture Content

Several methods for determining the moisture content of peat soils exist, but few of them offer comparable results. This makes it rather difficult to interpret moisture values from literature. The key problem in peat moisture content determination resides in the definition of the dry state. The organic fraction of peat consists of partly decomposed plant fragments. If subjected to too high a temperature, these materials are strongly oxidised. Where accurate moisture content values are required, precautions must be taken to ensure that losses due to oxidation are minimised. Peat samples should be dried to constant weight or to some arbitrary state of dryness which, by careful timing, can be reproduced.

A common temperature used to dry plant materials is 50°C and is thought by many investigators to be sufficiently low to avoid loss of organic matter by oxidation (James & Wells, 1990). On the other hand, drying temperatures of 100 to 110°C, as commonly used for the moisture content determination of all types of mineral soils or substrates, are well above those regarded safe for organic materials. A low temperature oven-drying procedure is proposed here in order to avoid loss of material by oxidation.

Experiments on the influence of the drying temperature were carried out using a MemmertTM type U-30 drying oven, a desiccator filled with dried silica gel and another filled with a saturated NaOH-solution. The relative humidity of the saturated NaOH atmosphere equals 6%, corresponding to a pF-value of 6.6. Samples (2.000 ± 0.002 g) of moist peat were weighed in a crucible and put in a pre-heated oven for 24 hours at constant temperature. The temperatures examined were: 50, 60, 70, 80, 90, 100, 105 and 110°C. The oven-dried samples were cooled over silica gel. Following weighing, the crucibles were put into the desiccator with a saturated NaOH-solution and further loss of water was determined after 1 day, 1 week and 3 weeks. The saturated NaOH-solution

creates a suction of ± 4000 bar, removing all capillary and film water. The temperature of which an oven-dried sample did not lose any further water when placed in the desiccator with NaOH was selected as the most reliable for the determination of the moisture content of peat.

Table 1. Weight change of oven-dry peat during equilibration over saturated NaOH ($rh = 6\%$).

Oven temp. (°C)	oven-dry (g)	in sat. NaOH atmosphere		
		1 day (g)	1 week (g)	3 weeks (g)
50	0.761	0.704	0.701	0.701
	0.761	0.699	0.695	0.694
60	0.701	0.700	0.700	0.700
	0.703	0.703	0.701	0.701
70	0.701	0.701	0.700	0.701
	0.702	0.702	0.702	0.701
80	0.680	0.714	0.714	0.716
	0.683	0.711	0.709	0.709
90	0.585	0.609	0.609	0.609
	0.673	0.697	0.698	0.698
100	0.659	0.690	0.684	0.684
	0.658	0.686	0.684	0.684
105	0.630	0.663	0.661	0.661
	0.648	0.677	0.677	0.677
110	0.661	0.692	0.686	0.685
	0.657	0.686	0.680	0.674

The average loss of weight after drying duplicate samples was 1.24 g at 50°C, 1.30 g at 60°C and 70°C, and up to 1.37 g at 105°C (Table 1). After drying at 60°C, no more water was lost when the sample was placed in the desiccator with saturated NaOH. On the other hand, drying at temperatures of 80°C or higher could result in an overestimation of the moisture content. The loss of weight at these temperatures can be partly attributed to oxidation of the material. These results are confirmed by Huffman & Stuber (1985), who investigated the loss of weight on drying of humic substances and reported that moisture determinations at 60°C were "safe" and should be promoted as the "most consistent reference point".

Three peat samples with different moisture contents were oven-dried at 60°C for 24 hours. Average results on a percent wet weight basis for three replications were

75.7±0.3, 68.1±0.3 and 57.3±0.2. The reproducibility of the measurements is illustrated by a coefficient of variation (CV) lower than 0.005 (e.g. $CV = 0.3/75.7 = 0.004$).

Bulk Density

Bulk density is perhaps the most important intrinsic characteristic of a peat soil since many other properties are closely related to it. Bulk density depends on the amount of compaction, the degree of decomposition and the ash and moisture content of the peat soil at the time of sampling. Bulk density was determined using the method described for horticultural substrates (De Boodt & Verdonck, 1972). Two copper cylinders were filled with peat and placed in a plastic tank filled with water. Saturation of the peat took 24 hours, after which the cylinders were placed on a sand bed. The peat was subjected to a matrix potential of -10 cm water column. Equilibrium was reached after 24 hours. The peat was oven-dried at 60°C for 48 hours and weighed. The bulk density for the peat soil under study was to 0.148 g cm⁻³.

Water Retention Curve

The characterisation of moisture relationships in tropical peat soils should always include moisture retention values. These are determined using the porous pressure plate technique and presented in a water retention curve, expressing the volume of the pores (i.e. their water content) as a function of the water suction for the low pF-range. Hence the water retention curve for peat soils looks different from the pF-curve for mineral soils (Fig. 1).

Water retention values provide important information for the management of peat soils. As early as 1969, Boelter cautioned that it is necessary to express the water retention values of organic soils on a wet volume basis, as taken in the field, because of their varied bulk densities and because of the volume reduction which occurs upon drying. Nevertheless, there is still much confusion in the literature about the moisture retention values being expressed as a percent by volume, as a percent of the oven-dry weight, or as a percent of the wet weight.

Water retention values were determined using the method described for horticultural substrates (De Boodt & Verdonck, 1972). Porous pressure plates, a precision balance and a drying oven were used. Weighed samples were placed in a filter with a porous plate. After saturation with water for 24 hours, each sample was subjected to a tension of -10 cm water column for 12 hours. Loss of water was determined after drying

at 60°C for 24 hours. Further tensions applied were -20, -30, -50 and -100 cm water column (Table 2).

Water management in agriculture requires information on the difference between the quantity of water retained at field capacity and the water retained at permanent wilting point. Field capacity and wilting point have been defined as the amount of water held at a suction of 1/3 atm (pF 2.54) and the amount held at 15 atm (pF 4.20), respectively. The difference should give an indication of the amount of water available to the plants. In peat soils, however, the amount of available water quantified by this difference seems to overestimate the situation in the field. This clearly indicates that water availability in peat soils and mineral soils are not directly comparable.

Two properties differentiate mineral soils from peat soils. First the volume occupied by the solid particles is much less in peat soils and second, the amount of water retained at very low tensions is much greater for peat soils than for mineral soils. To be able to understand the water availability at low suctions and the nature of capillarity in peat soils above the water table, the concept of the water retention curve as devised for horticultural substrates was thought to be useful. When cultivated, the top layer of the peat soil under investigation has a minimum thickness of 10 cm and the drainage lowers the groundwater level to 40 cm. When the plants are adequately watered, the moisture content is close to saturation in the bottom layer, and gradually decreases from the bottom to the top of the profile, resulting in a well-drained top layer of 10 cm. Therefore, a minimum suction of 10 cm is considered as the requirement for a minimum volume of air.

A second important point to identify is the lowest moisture conditions which will not inhibit plant growth. A water suction of 100 cm might be considered as a maximum for peat as a substrate (De Boodt & Verdonck, 1972; Raviv et al., 1986) as well as under field conditions (Lucas, 1982; Zeitz, 1992).

Figure 1 illustrates the water retention curve using the values from Table 2. Three important parameters for the water management of lowland tropical peat soils are indicated (Raviv et al., 1986). *Air volume* is defined as the total volume of the pores minus the volume of water held at pF 1 (-10 cm water column). It represents the minimum volume of air in the pores available for the plants. Figure 1 gives a value of 15%. Peat with an air content lower than 6% at -10 cm pressure is not suitable for plant growth (van Schie, 1992). An optimum value for horticultural substrates commonly reported is 20%. *Easily available water* is defined as the amount of water held at pF 1 minus the amount held at pF 1.7 (-50 cm water column). It represents the volume of

water which can be taken up by the plant without much energy. It amounts to 13.5% for the peat soil under study, which is rather low. The optimum value for substrates is commonly reported as 20%. *Water buffering capacity* is defined as the amount of water held at pF 1.7 minus the amount held at pF 2 (-100 cm water column). It represents the volume of water that will be taken up under stress conditions and is also called potentially available water. The value of 3% is definitely low and indicates clearly the critical point in water management of the lowland tropical peat soils: the reserve of water for drought periods is very limited.

Table 2. Water retention values in the low pF-range for a lowland tropical peat soil from Pontianak.

<i>h</i> (cm water)	0	10	20	30	50	100
pF	∞	1.00	1.30	1.48	1.70	2.00
water content (vol. %)	88.62	71.65	66.85	64.10	58.18	55.03
	88.53	73.25	64.71	63.39	60.64	57.64
	88.24	75.51	68.42	61.87	61.00	55.79
average	88.46	73.47	66.66	63.12	59.94	56.82

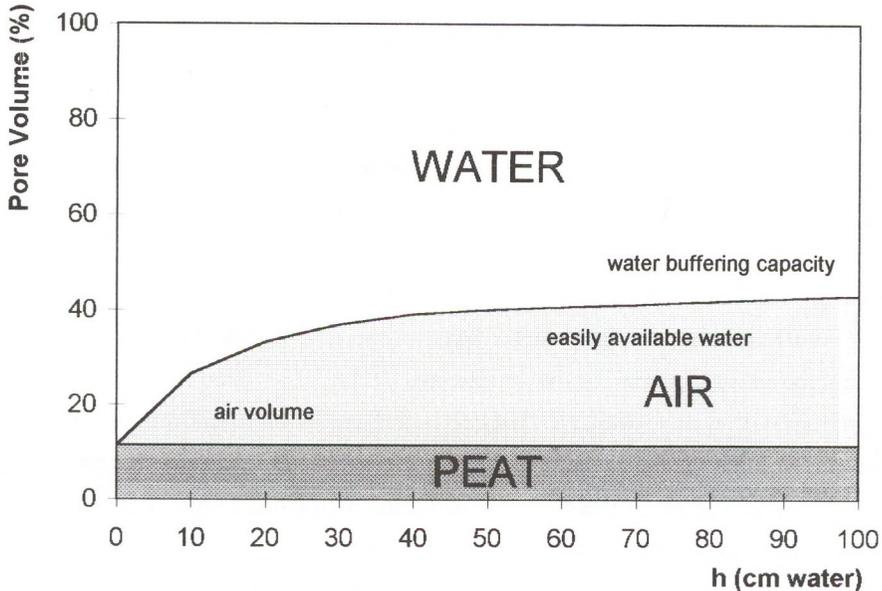


Figure 1. Water retention curve, % pore volume versus cm water, for a lowland tropical peat soil

DRYING AND REWETTING CHARACTERISTICS

Rewetting of lowland tropical peat soils, when dried too extensively, can be difficult or might even be impossible. Normal physico-chemical processes can take place only after a sufficient degree of wetting has been achieved. So far, only bulk properties have been considered in discussing the behaviour of water in lowland tropical peat soils. We will now extend this discussion by investigating the retention of water in the micro- and mesopores, as defined in colloid chemistry.

Relative humidity, bubbling pressure and diameter of the pores

The atmosphere over a saturated aqueous salt solution attains a known constant relative humidity (rh) at a given temperature. Poynting's law describes the relation between the relative vapour pressure and the water tension. When no osmotic phenomena occur, the pF of the soil solution can be derived from:

$$pF = \log \left[- \frac{100RT}{V\rho g} \ln(rh) \right] \quad [1]$$

with R the gas constant, T the absolute temperature, g the gravity constant, ρ the liquid density and V the molar volume of the liquid, or, in the case of water at $T = 303$ K:

$$pF = \log \left[- 3285429 \log(rh) \right] \quad [2]$$

On the other hand, the relation between the diameter of the pores D (nm) and the bubbling pressure Δp (bar) of wet porous material and the surface tension γ of a liquid is given (with $\gamma = 72$ mN/m for water) by:

$$D = 40\gamma \cos\theta / \Delta p \quad [3]$$

Equation [3] was used for the estimation of the pore diameters in the peat soil (see below), assuming that the wetting angle of water in peat can be generalised by a mean contact angle $\theta = 45^\circ$ ($\cos\theta = 0.707$). The different saturated salt solutions that have been used for the drying of the peat are listed in Table 3, together with the

corresponding relative humidity values (Weast, 1983), the water tension [eq.2], the bubbling pressure and the diameter of the pores [eq.3].

Table 3. List of constant humidity solutions (Weast, 1983), with corresponding values for water tension, bubbling pressure and estimated diameter of the pores.

saturated solution	rh (at 20°C)	pF	Δp (bar)	D (nm)
KOH	0.05	6.63	4180	0.5
NaOH	0.06	6.60	3901	1
CrO ₃	0.35	6.18	1483	1
K ₂ CO ₃	0.45	6.06	1125	2
KSCN	0.54	5.94	853	2
NH ₄ Cl/KNO ₃	0.73	5.66	448	5
NaCl	0.75	5.61	399	5
BaCl ₂ .2H ₂ O	0.88	5.26	178	11
ZnSO ₄ .7H ₂ O	0.90	5.18	148	14
KNO ₃	0.94	4.95	87	23
CuSO ₄ .5H ₂ O	0.98	4.46	28	73

All saturated solutions create an atmosphere with a relative humidity that results in a tension of $pF > 4.2$ (15 bar). The D -value (nm) gives the maximum diameter of the pores in which the water can be held at that specific tension.

Three groups of solutions can be recognised: (1) aqueous salt solutions with $rh \leq 0.54$, inducing a tension of $pF \geq 6$, related to pore diameters of $D \leq 2$ nm (micropores); (2) aqueous salt solutions with $0.54 < rh < 0.96$, or a tension of $6 > pF > 4.8$, related to pore diameters in the range of $2 \text{ nm} < D < 50 \text{ nm}$ (mesopores); (3) aqueous salt solutions with $rh \geq 0.96$, inducing a tension of $pF \leq 4.8$, related to pore diameters of $D \geq 50$ nm (macropores).

Preparation of the peat samples

Peat samples were placed in a desiccator over one of the saturated solutions (Table 3). As such, a drying process at different constant water tensions (varying from pF 4.46 to 6.63) was established. Weight loss of the samples was measured weekly and equilibrium was reached after 20 weeks. Five solutions (CuSO₄.5H₂O, KNO₃, NaCl, K₂CO₃, KOH) were selected for an additional experiment on drying and rewetting. Peat samples were dried at a relative humidity of 0.98, 0.94, 0.75, 0.45 and 0.05, respectively (Table 4). When equilibrium was reached, the peat from a lower rh was placed in a

desiccator with a rh one level higher. This process was continued until eventually all the peat samples were placed under a CuSO_4 -atmosphere ($rh = 0.98$).

The drying experiments described above showed that the moisture content of the peat at equilibrium in an atmosphere with $rh \leq 0.54$ (or $pF \geq 6$, related to pores with $D \leq 2$ nm) was 3 to 8% on a wet weight basis. For the peat dried under an atmosphere with rh between 0.45 and 0.75 (or pF between 6 and 5.6, related to pores with D between 2 and 5 nm), the moisture content at equilibrium was 12 to 14%. When dried in an atmosphere with $rh \geq 0.88$ (or $pF \leq 5.2$, related to pores with $D > 10$ nm), the moisture content of the peat was 42% on a wet weight basis. Table 4 gives the results of the drying-rewetting experiment with 5 saturated solutions ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$, KNO_3 , NaCl , K_2CO_3 , KOH). Bearing in mind the D -values in Table 3, the results show that the rewetting of the micropores ($D \leq 2$ nm) is reversible and hence that these pores do not collapse at the high tensions (up to 4000 bar). The mesopores ($2 < D \leq 50$ nm), however, seem to collapse, resulting in a decrease of approximately 50% in volume.

Table 4. Rewetting of dried peat over different saturated solutions: moisture content (% on wet weight basis) after equilibrium at different levels of rh and pF .

series	under KOH $rh=0.05$ $pF=6.63$	under K_2CO_3 $rh=0.45$ $pF=6.06$	under NaCl $rh=0.75$ $pF=5.61$	under KNO_3 $rh=0.94$ $pF=4.95$	under CuSO_4 $rh=0.96$ $pF=4.46$
I	-	-	-	43.1 →	41.9
II	-	-	14.4 →	17.9 →	20.4
III	-	8.3 →	11.2 →	16.3 →	20.1
IV	5.8 →	8.3 →	11.6 →	16.6 →	20.4

The striking conclusion here is that drying-rewetting is reversible for peat with a moisture content between 5% and 20%, but irreversible for peat with a moisture content between 20% and 40%. One can conclude that the large water-holding capacity of the peat is clearly associated with a wide range of pores. The macropores (with $D > 50$ nm) and the micropores (with $D \leq 2$ nm) are dimensionally stable, and can be emptied and refilled reversibly. The behaviour of the mesopores (with D between 2 and 50 nm), however, seems to support a structure described by Farmer (1978) as comprising complex high molecular weight polymers forming a flexible cross-linked framework in which individual chains are hydrated. Even partial dehydration of such a structure can lead to irreversible changes in conformation, and to the collapse of pores which will not refill on rehydration.

Measurement of contact angle (video technique)

In addition to the series of samples prepared in the desiccators, peat in bulk (± 6 kg) was collected from the field in Pontianak for drying in closed containers using the same technique. The following peat materials were prepared: original peat with a moisture content of 76% (w/w wet basis), was kept as such without drying agent (code PO); peat dried over $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ for 49 weeks, resulting in a moisture content of 72% (code PC); peat dried over NaOH for 16 weeks, giving a moisture content of 68% (code PN); peat air-dried in the laboratory for 1 week, resulting in a moisture content of 58% (code AD). Following the drying process, the peat materials were stored in plastic bags, and used for measurement of the contact angle.

Contact angle measurements were performed after dispensing 50 μl drops of distilled water onto pressed peat pellets. Pellets were prepared by pressing the peat to a maximum volume of 25 ml in a chrome steel mould ($\varnothing 1''$) under a laboratory press with maximum capacity of 10 tons. The punches were carefully cleaned and rinsed with distilled water. They were dried with alcohol and ether prior to pellet preparation, in order to obtain a pellet with as smooth a surface as possible. The effect of compression pressure and time was investigated (Lambert, 1995). It was concluded that, within the range 2500 to 10000 kg, the amount of water pressed out of the peat is independent of the pressure and that the total amount of water that is pressed out at a pressure of 7500 kg is independent of the compression time.

A video image analysis technique was adopted using a high resolution B/W CCD video camera connected to image processing and analysis software (FFA PC IMAGE). A laboratory stand was used to hold the camera, which was connected to a computer. The peat pellet was placed on an adjustable laboratory tray to facilitate vertical alignment. Squared paper was positioned above the top centre of the drop to calibrate the system. Measurements of contact angle were made on captured video images, taken about 2 seconds after deposition of the drop onto the pellets. Processing of the captured images included rotating, contrasting, thresholding to reduce data and zooming up. Both advancing and receding contact angles were measured on the monitor for each drop, using triangulate line sampling. Peat was examined at three different moisture contents, from which five pellets each were prepared. The coefficient of variation for the on-screen measurements ranged from 0.01 to 0.04. The contact angle formed by water on pellets prepared from air-dried peat averaged 32.4 degrees. All other contact angles decreased with increasing moisture content of the pellet, showing

greater wettability (Table 5). Further drying of the peat pellets was rejected because cracking of the surface would have led to an overestimation of the contact angle (Valat et al., 1991). As such, the technique is limited for peat pellets with a moisture content on a wet weight basis of approximately 48% or more.

Table 5. Advancing contact angles for water on peat pellets for three different moisture contents (m.c.).

peat (m.c.)	pellet no.	m.c. pellet (%)	θ_a (degrees)
AD (58%)	1	47.4	32.9 ± 0.5
	2	47.7	32.7 ± 1.1
	3	48.5	31.6 ± 1.0
	4	49.3	32.1 ± 1.2
	5	48.1	32.5 ± 0.4
PN (68%)	6	58.9	26.5 ± 0.4
	7	57.7	27.7 ± 0.3
	8	59.8	26.8 ± 1.1
	9	60.2	27.0 ± 0.7
	10	58.1	26.0 ± 0.2
PO (76%)	11	64.9	17.3 ± 0.3
	12	65.7	16.4 ± 0.4
	13	65.8	17.2 ± 0.4
	14	n.d.	14.2 ± 0.7
	15	66.2	17.6 ± 1.0

CHEMICAL PROPERTIES

Loss on Ignition

A rapid method to establish the amount of organic matter in a peat soil is through loss on ignition. The oven-dried sample was ashed in a furnace for 2 hours at 200°C, 1 hour at 400°C and finally 3 hours at 550°C (Sanchez, 1990). The ash content of the peat under study was only 1.7% on a dry weight basis. Microscopic evidence showed that the ash is composed of so-called biogenic opaline silica from phytoliths.

Degree of Decomposition

While the degree of decomposition appears to be a key property of peat soils, it is not clearly defined and therefore difficult to quantify. It is a relative value that is usually approximated by a measure of one of the chemical or physical properties that change with advancing decomposition, such as bulk density, ash content, cation

exchange capacity, C/N ratio, cellulose content (Boelter, 1969; Levesque & Diné, 1982; Mathur & Farnham, 1985; Malterer et al., 1992). The lack of a quantifiable degree of decomposition is illustrated by the two systems for peat soil classification, i.e. the von Post humification method and the analysis of rubbed fibre in USDA Soil Taxonomy. Both systems use the degree of decomposition as the single most important criterion for classification, but use of the methods depends largely on experience, i.e. operator training, rather than on measurement.

The von Post humification method, as introduced in the 1950's and still advocated by the International Peat Society, relies on the squeezing force of the human hand. The rubbed fibre content, used in USDA Soil Taxonomy for the classification of organic soils at suborder level (Nichols & Boelter, 1984), is estimated by rubbing small portions of peat 10 times between the thumb and fingers, using moderate pressure. We appraised both methods as too subjective. Moreover, a variety of peat properties were not considered during the initial development of the von Post method, as for instance the very woody peat and tropical peat soils (Malterer et al., 1992). As a matter of fact, rubbing destroyed the fibres in the peat soil under study. Consequently, it was decided not to use either of these techniques for the characterisation of a lowland tropical peat soil.

Instead, the *R*-value, originating from the German Bureau for Normalisation (DIN) for the standardisation of horticultural substrates was considered an objective measure of the degree of decomposition of the peat material. It gives the amount of peat that is hydrolysed by 72% H₂SO₄ under standardised conditions (DIN 11542). A 0.500±0.001 g sample of air-dried peat of known moisture and ash content was taken. Five ml 72% H₂SO₄ were added and the mixture was stirred every 30 minutes. After 5 hours, 10 ml water were added and the mixture was allowed to stand overnight. It was then diluted with 200 ml water in a round-bottom flask, boiled with reflux for 5 hours and cooled. The solution was poured onto a pre-ashed porcelain filter (ø 2 mm); the filter was washed until free of sulphate, tested using 1% BaCl₂. The residue on the filter was dried for 4 hours at 105°C and weighed after cooling over dried silica in a desiccator. It was subsequently ashed for 2 hours at 550°C, cooled and weighed again. The *R*-value (%) was calculated as follows:

$$R = \frac{(K-L) 10^6}{w(100-M)(100-a)} \quad [4]$$

where $(K-L)$ is the loss of residue through ashing (g), w is the sample weight, a the ash content and M the moisture content of the air-dried peat (g).

The R -value for the tropohemist under study was 74 ± 2 %. A value of 60.3% was found for woody (fibric) peat from the same area, indicating a lower degree of decomposition. We also propose the R -value as a measure for lignin and lignin-derivatives. A value of 74% falls within the range of 56 to 76% reported by Lucas (1982) for the coastal lowland peat soils of South-East Asia.

Total Nutrient Content

For the determination of the total nutrient content in peat soils, both wet and dry digestion procedures, as described for plant analysis, can be used. Dry ashing is more commonly used, as it is simpler, safer and more economical than wet ashing. However, some elements, such as P and K, volatilize during ashing at temperatures above 550°C (Christian, 1986).

Total Ca, K and Na were determined by flame photometry and total P by colorimetry, after digestion of the samples with 18% HClO₄. Total contents of Mg, Fe, Cu, Mn and Zn were determined by atomic absorption spectrophotometry after digestion of the pre-ashed samples with 1 M HNO₃. Total N was determined using the salicylic acid-thiosulfate modification of the Kjeldahl method (Bremner & Mulvaney, 1982). Total C was measured by combustion of the peat, capturing the CO₂ in 1 M NaOH and quantifying it through titration with HCl. Results are presented in Table 6. The figures based on dry weight basis are recalculated on a wet volume basis (kg/ha), assuming a top layer of 25 cm with a bulk density of 0.148 g cm⁻³ and a moisture content on wet weight basis of 78.3%. It is clear that only these figures have a real practical value.

Table 6. Elemental composition of a representative peat sample from Pontianak.

element	mg/100g dry peat	kg/ha
C	43915	35259
N	1638	1314
P	67	54
Ca	79	63
Mg	54	43
K	77	62
Na	29	23
Fe	107	85
Cu	1	0.8
Mn	2	1.6
Zn	4	3.2

Most information on the C content of peat soils in the literature is based on the Walkley & Black wet oxidation method, which is not a correct measure when the total organic carbon content is higher than 10% (Lambert et al., 1993). As such, it is difficult to make some general comparisons with reported carbon contents. Of more interest is the relation between loss on ignition and the amount of organic carbon. Values for a ratio of percentage loss over percentage carbon of approximately 2 seem most common (Andriessse, 1988). The ratio for the peat under study is 2.2 (98.3 over 43.9). This indicates that a ratio of 2 or more probably reflects the actual situation in an oligotrophic tropical peat soil better than the value of 1.67 used in USDA Soil Taxonomy to distinguish organic soils from mineral soils.

The total N content is also of considerable importance to agriculture. It is assumed that all the nitrogen is in the organic form here. A total N content of 1.6% on a dry weight basis appears to be regarded as "high" to "very high". However, taking moisture content and bulk density into account, a much lower value of 1300 kg N/ha is obtained. Similar misinterpretations of analytical results are repeatedly made in the literature, giving rise to incorrect assessments of the required nitrogen levels for crop production.

The total macronutrient content of the peat soil is very low. With P less than 0.07% on a dry weight basis, N less than 2.5%, K less than 0.1% and Ca less than 2%, it can be classified as oligotrophic peat (Andriessse, 1988).

The micronutrient status of the peat soil is also very low. The values for total Cu, Mn and Zn are less than those reported as deficient for a deep tropical peat soil (Ambak

et al., 1991). However, too little detailed information on micronutrient requirements for crops growing on these soils is available at present. First of all, a consensus in the use of analytical methods is urgently needed, since it is still unclear which extractant will be preferred by international peat experts for the estimation of available micronutrients in tropical peat soils. Such a consensus is especially needed for the problem element Cu. Although it has been suggested that HCl is an appropriate extractant for Cu in peat (Haynes & Swift, 1985), it is also important to consider the effectiveness of the extractant over a reasonably wide pH range. Careful consideration must be given to the conditions under which the analysis is carried out if results applicable to natural conditions are to be obtained. Actually, the chemical method to be selected is important only to the extent that it should distinguish between deficient and non-deficient peat soils. Extraction with 0.05 M NH_4OAc + 0.02 M EDTA at pH 4.65 could be an appropriate method. At this pH and concentration, the complexation ability of EDTA towards ionic Cu^{2+} is 100%, whilst the risk of overestimating the available copper by extracting non-ionic forms is limited.

Acidity and Lime Requirement

The pH is another very important property of a tropical peat soil, influencing or controlling its chemical behaviour. Lowland tropical peat soils of oligotrophic and ombrogenous nature are commonly strongly acid. The top layer is very poor in cations, possessing a high amount of exchangeable hydrogen and thus extreme acidity.

A peat/water-mixture was prepared at a weight/volume ratio of 1/2.5. After the mixture had been allowed to stand for 2 hours, the $\text{pH}(\text{H}_2\text{O})$ was measured by means of a glass electrode and a Ag/AgCl reference electrode. The mixture was gently stirred just prior to immersing the electrodes. The $\text{pH}(\text{H}_2\text{O})$ of the top layer of the peat soil under study was 3.2. Exchangeable aluminum was negligible. Exchangeable hydrogen was determined by titrating the 1 N KCl-extraction solution with NaOH (endpoint pH = 8.25). A value of 14.7 meq H^+ per 100 g dry peat was found, which is equal to 5 meq $\text{Ca}^{2+} \text{ dm}^{-3}$ wet peat.

As the natural pH of the peat soils under study is always very low, liming is a prerequisite action for reclamation. For the acid tropical peat soils, however, information on lime requirement is still lacking. Optimum CaCO_3 -values in the literature are often confusing because the exchange properties of the peat soil are rarely given when results are discussed. In order to obtain figures which are applicable to the

natural conditions of the tropical peat areas, it is proposed here that lime recommendations for tropical peat soils are estimated following incubation with CaCO_3 .

When 0.5 g CaCO_3 was added to 100 g moist peat, which is roughly equal to 1850 kg CaCO_3 per ha, the pH is raised after 2 months incubation to 4.5 (Table 7). An increase up to a higher pH is undesirable and cannot be justified. The stimulative effect of pH amendment by the addition of CaCO_3 on the decomposition rate of tropical peat soils was ascertained by Murayama & Zahari (1992). As a result of the very high mineralisation and solubilisation at this pH, in combination with a high temperature, the peat would finally disappear.

Table 7. pH of the peat soil after incubation with CaCO_3 .

CaCO ₃ added (g/100g) (t/ha)		incubation time		
		1 week	1 month	2 months
0	0	3.20	3.20	3.20
0.5	1.85	4.60	4.65	4.50
1	3.70	4.95	5.05	4.75
1.5	5.55	5.80	5.80	5.80
2	7.40	6.60	6.60	6.60
3	11.10	7.70	7.70	7.50
4	14.80	7.70	7.75	7.80

Redox Potential

By determining the standard redox potential (E_o) of the peat-water suspension, the inter-relation of the peat/water-system with other redox systems can be stated numerically. By comparing the standard redox potential, the possible reduction properties of the peat soil under natural conditions could be assessed. However, the determination of redox potentials is not always easy, simple or unequivocal. Instantaneous measurements with Pt-calomel-electrodes do not express real equilibrium potential differences. This is especially the case in reactions where O_2 plays an important role, which makes one wonder whether the $\text{O}_2/\text{H}_2\text{O}$ -system instead of the peat/water-system is examined. As such, we must here ascertain that all information obtained from these experiments has mere qualitative value.

It has been established that the peat/water-system can be regarded as a reversible one (Szilagyi, 1971). A reversible redox system can be most generally characterised by the formula:

$$Eh = Eo - \frac{mRT}{nF} \text{pH} + \frac{RT}{nF} \ln \frac{[ox]}{[red]} \quad [5]$$

where n is the number of electrons participating in the electrochemical equilibrium and m the number of protons in the redox reaction. Eh is the redox potential, Eo the standard redox potential and $[ox]/[red]$ represents the concentration of the ion forms that are poorer or richer in electrons.

The $[ox]/[red]$ ratio in the peat material under study is given, and affects the pH of the peat/water mixture at equilibrium. As such, it is impossible for both $\ln\{[ox]/[red]\}$ and pH to have a zero value simultaneously. Therefore the Eo value cannot be determined by a single measurement ($Eo = Eh$ when $[ox]=[red]$ and $\text{pH}=0$). The standard redox potential of the peat/water-system was determined by an indirect experimental method (Szilagyi, 1973). Six series of peat/water suspensions were prepared by mixing 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8 and 2.0 g peat with 20 ml H_2O . Each member of one series was set for an identical pH value by addition of NaOH or HCl. The Eh was measured with a Pt-calomel electrode for the pH values 1.8, 3.0, 5.0 and 7.0 (Fig. 2). Each of the curves represents relationships of the same type between the logarithm of the peat concentration and the Eh value for a given pH, or:

$$Eh = A + B \ln(C) \quad [6]$$

where A is the ordinate of the intercept at $\ln(C) = 0$, B the slope of the curve, and C the concentration of the peat in 20 ml H_2O (g).

Since $\ln\{[ox]/[red]\}$ in equation [5] and $\ln(C)$ in equation [6] are proportional, it can be established that:

$$A = Eo - \frac{mRT}{nF} \text{pH} \quad [7]$$

The change of the ordinate intercept A is a linear function of the pH. The ordinates A of Figure 2, together with the experimentally obtained Eh values for $\ln(C)=0$ at pH 2.4, 3.8 and 6.0, are plotted in Figure 3 as a function of pH. Extrapolation to $\text{pH}=0$ gives the standard redox potential. For the peat under study a standard redox

potential of 650 mV was found. As such, the peat/water-system can be characterised among other redox systems: the value of 650 mV reflects the reducing capacity of the peat with respect to the redox systems $\text{Fe}^{3+}/\text{Fe}^{2+}$, $\text{MnO}_2/\text{Mn}^{2+}$ and $\text{NO}_3^-/\text{HNO}_2$.

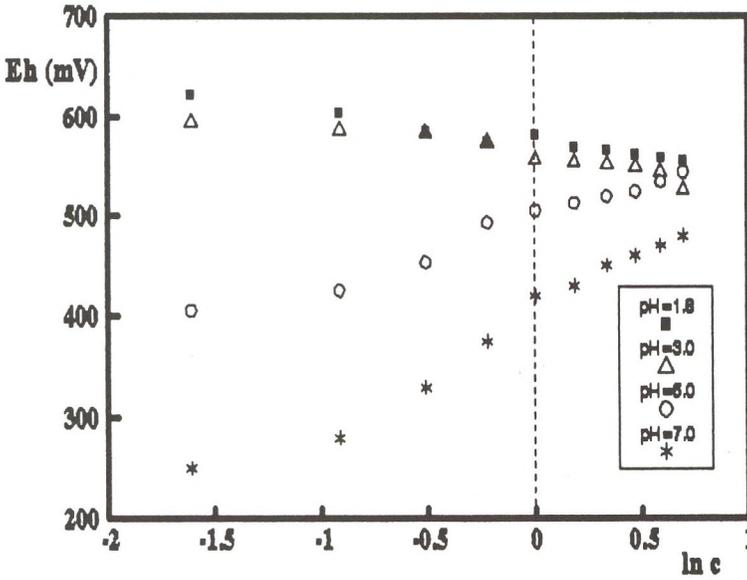


Fig.2. Relationship between Eh and peat concentration (log scale) at different pH values

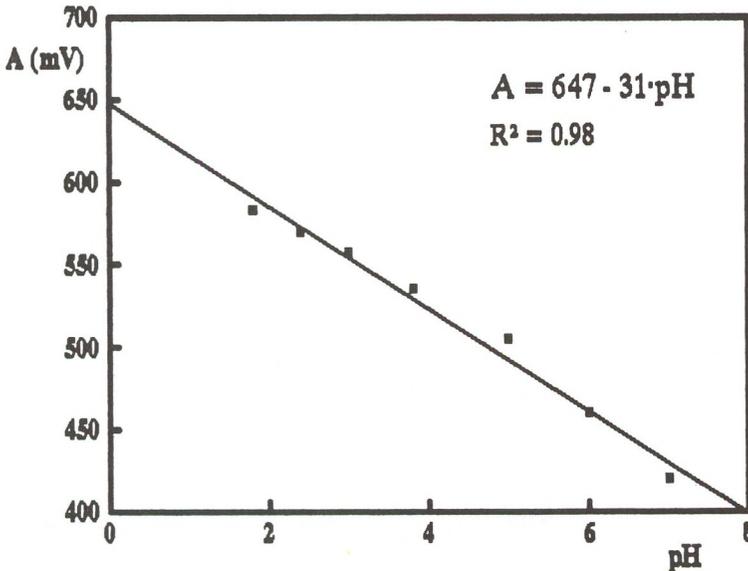


Figure 3. The ordinates A for $\ln(C)=0$ in Fig.2 as a function of pH.

EXCHANGE PROPERTIES

Cation Exchange Capacity

There are various methods to determine the cation exchange capacity (CEC) of soils and hence it is sometimes difficult to compare results. Estimation of the CEC of soils is commonly obtained by the ammonium acetate method, buffered at pH 7. Although the method has major advantages, it is doubtful whether it has significance for tropical peat soils. The CEC of a peat soil is highly pH-dependent. Estimation of the CEC at a pH different from the one in the field can produce misleading results. An unbuffered method for the determination of the CEC of peat soils is proposed (Lambert et al., 1988). The major advantage of the proposed method is that subtle variations in the CEC, due to the changes in pH, can be detected. The influence of the exchange pH-values was elaborated with a BaCl_2 - $\text{Ba}(\text{OH})_2$ -mixture as extraction solution. Ba was exchanged from the complex using MgCl_2 .

Two grams of moist peat were weighed into centrifuge tubes and 20 ml 0.1 M BaCl_2 was added. The suspensions were shaken for 3 hours and poured onto a preweighed glassfilter-system, equipped with a 0.45 mm plastic filter, and connected to a water vacuum pump. The pH of the filtrate was measured and used as a reference, the so-called "exchange-pH". Next, and in order to decrease the Ba-content of the interstitial solution, two times 20 ml of 0.025 M and four times 20 ml of 0.01 M BaCl_2 were poured onto the peat. The last 20 ml filtrate was kept for determination of the Ba-concentration and for pH-measurement. The glassfilter containing the moist peat was weighed and subsequently leached with four times 20 ml 0.5 M MgCl_2 . The filtrate was collected, made up to 100 ml with H_2O , and analysed for Ba with a flame photometer. After correction for the Ba content of the interstitial solution, the CEC was calculated.

The peat soils under study had an exchange pH of 2.9 ± 0.1 . Triplicate determinations estimated the CEC at 37.5 ± 2.2 meq per 100 g dry peat. Once again this value has to be considered in the light of a low bulk density of the material. When calculated on a volume basis, the CEC of the peat is only 12 meq dm^{-3} moist peat. The influence of the exchange pH can be investigated using a mixture of $\text{Ba}(\text{OH})_2$ and BaCl_2 (Table 8). As such, the CEC was monitored for increasing pH of the extraction solution. A linear relationship between pH and CEC was obtained (Fig. 4). The regression line ($R^2 = 0.97$) has a slope of 33.0 meq per pH unit. At pH 7, the CEC is estimated at 180 meq per 100 g dry peat, equal to 58 meq dm^{-3} moist peat.

Table 8. Exchange-pH as a function of the amount of $Ba(OH)_2$ added to the $BaCl_2$ extraction solution.

ml $BaCl_2$ 0.1 M	20	19	18	17	16	15
ml $Ba(OH)_2$ 0.1.M	0	1	2	3	4	5
exchange-pH	2.8	2.9	3.8	5.0	6.7	7.6

As mentioned above, it is difficult to compare results from the literature. Using the ammonium acetate method, Suhardjo & Wijaja-Adhi (1977) found CEC values of 125 to 140 meq per 100 g dry peat. Driessen (1978) even reported values up to 270 meq per 100 g for deep peat soils under forest. Figure 4 shows that these high CEC values do not reflect the real situation. This is confirmed by the field observations in the same area. For these lowland tropical peat soils Lambert & Staelens (1993) reported a maximum value of 106 meq per 100 g dry peat at an exchange-pH of 7.2.

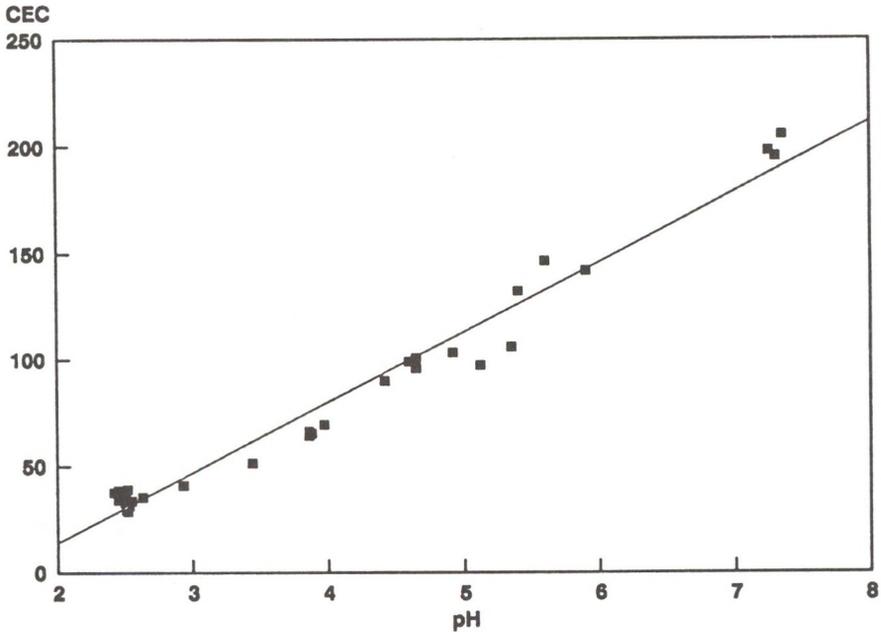


Figure 4. CEC of the peat soil as a function of the pH.

Potentiometric titration

In order to be able to examine the functional groups involved in the ion exchange, a titration at very low speed was conducted. The humic substances in peat possess an extremely high surface area and are the major source of pH-dependent

charge. The functional groups which interact with cations include the acidic groups, carbonyl groups and the alcoholic hydroxyls. Each of these groups interacts with cations in a different manner (White & Zelazny, 1986). As the peat material is a natural product, there is no clear cut boundary between the functional groups present. Hence titration curves with inflection points and plateaus attributed to a particular surface charge reaction cannot be produced. Still, one good measure for the comparison of different peat soils can be extracted from these curves. It concerns the amount of base needed for the neutralization of the material between natural pH and pH 7. An estimation of the apparent pK_a was introduced by White & Thomas (1981). This is based on the pH related to 50% of the total amount of base added, or the pH at midpoint of the titration. The pK_a ranges from 4.0 to 5.0 for carboxyl groups on a long chain or benzene ring, and from 6.5 to 7.5 on average for soil phenolic hydroxyls (White & Zelazny, 1986).

Three grams of moist peat and 25 ml H_2O + 5 ml 0.1 N HCl were poured into a centrifuge tube. NaOH (0.2 N) was added to this solution at a rate of 3ml h^{-1} using a peristaltic pump and under continuous stirring. The pH was recorded as a continuous mV-signal using a datalogger. The potentiometric titration curve is presented in Figure 5. The following information can be deduced: (1) the first and most distinct inflection point is situated at a pH of 3.4; this means that strong acidic groups do not occur, so the weak acid groups are of a carboxylic nature; (2) a second, less important inflection point is found at pH 8, so the very weak acidic groups are of phenolic origin; (3) the curve shows a continuum of functional groups involved in the deprotonation reactions; the apparent pK_a is estimated at 6.4; (4) at pH 6, the DpH/base -ratio has fallen from 0.9 to 0.4, showing the low buffering capacity in the higher pH range; (5) the amount of base added for the neutralisation of 3 g peat between pH 3.4 and pH 7 amounts to 1.69 meq. This is equal to about 140 meq per 100 g dry peat, which is in accordance with the CEC at pH 7, as derived from Figure 4.

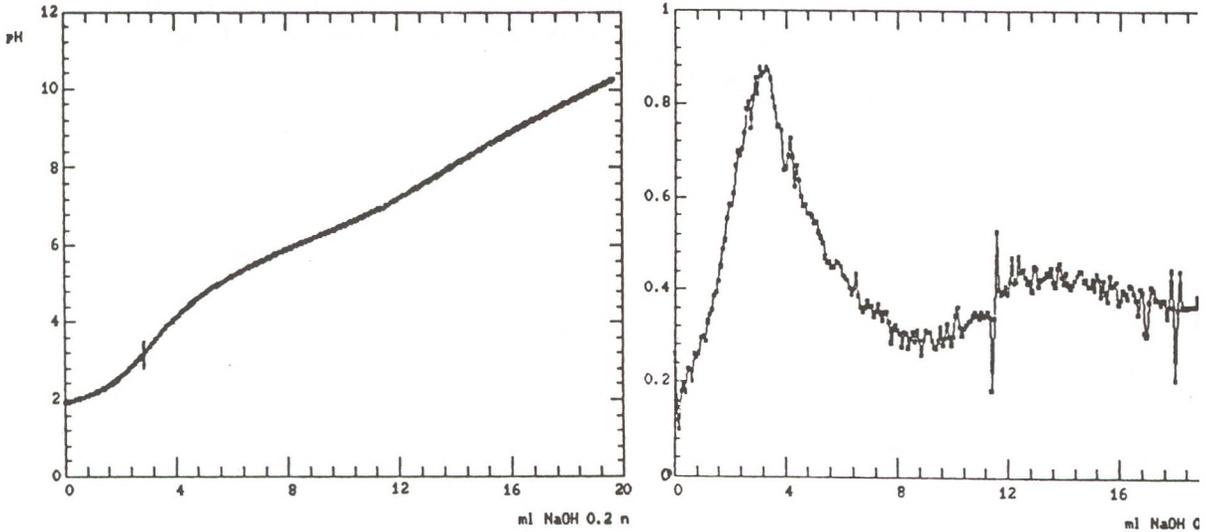


Fig. 5. Potentiometric titration curve for peat (XY and XdY plot).

CONCLUSIONS

In this study, special attention has been given to a detailed description of the methodology which proved to be appropriate for a correct and complete physico-chemical characterisation of lowland tropical peat soil.

It is recommended that the moisture content be determined at a drying temperature of 60°C for 24 hours. Under these conditions, an overestimation due to oxidation of the peat material is avoided and the drying to constant weight provides the most reproducible results. Bulk density is of extreme practical importance in interpreting analytical data. Analytical values, particularly those indicating fertility levels, must be recalculated on a weight per volume basis, using bulk density as a correction factor. The concept of the water retention curve proved to be appropriate for the characterisation of the water availability at low tensions. Three parameters can be obtained from the water retention curve: air volume, easily available water and water buffering capacity. The latter indicates the critical point in water management: the reserve of water for drought periods is very limited.

Drying-rewetting is reversible for moist peat with a moisture content between 5% and 20% (on a wet weight basis), but irreversible when the moisture content is between 20% and 40%. The large water holding capacity of the peat is clearly associated with a wide range of pores. The micropores and the macropores are

dimensionally stable, and can be emptied and refilled reversibly. It has generally been recognised that the methods for the assessment of the contact angle of water on peat are imperfect, due to both practical and theoretical limitations. In this study, contact angles have been measured using the sessile drop approach. It has been acknowledged that the process of forming a pellet could cause surface deformation and, consequently, alter the contact angle such that results may not reflect the properties of the original peat. Despite these reservations, compressed peat pellets offer the quickest and most straightforward approach to the assessment of the wettability of peat. With the image processing hardware & software available at present, we believe that the sessile drop method overcame most of its practical limitations and became less imperfect among the available techniques for the characterisation of peat wettability.

The *R*-value (DIN 11542) is proposed as a measure for the lignin fraction of a lowland tropical peat soil (of fibric, hemic, sapric type) and as a quantified expression of its degree of decomposition. As such, it could serve as an objective parameter for the decomposition classification of tropical peat soils. The total macronutrient content of the peat soil is very low. With P less than 0.07% on a dry weight basis, N less than 2.5%, K less than 0.1% and Ca less than 2%, the material can be classified as oligotrophic peat. These traditional classification boundaries can be easily converted to more practical values on a wet volume basis, using: 1% = 800 kg/ha. No consensus could be found in the literature on the use of extractant to determine the availability of micronutrients. The element Cu deserves special attention because of the assumed link between its deficiency and plant sterility. Extraction with 0.05 M NH₄OAc + 0.02 M EDTA at pH 4.65 is appropriate for the assessment of plant available Cu in tropical peat soils.

The soil reaction of the peat soil when drained is always strongly acid; pH(H₂O) was 3.2. Lime requirement was calculated at 1850 kg CaCO₃ per ha to raise the pH(H₂O) to 4.5. This pH value is suggested to reduce costs, and to suppress mineralisation and solubilisation. An refined technique is presented for an indirect, experimental determination of the standard redox potential for lowland tropical peat soils. *E_o* was 650 mV, expressing the reducing capacity of the peat soil with respect to the Fe³⁺/Fe²⁺, Mn⁴⁺/Mn²⁺ and NO₃⁻/NO₂⁻ redox systems.

A method for the determination of the Cation Exchange Capacity (CEC) of acid tropical peat soils is proposed. A linear CEC-pH relationship is obtained using a 0.1 M BaCl₂-Ba(OH)₂ mixture as extraction solution. The relation $CEC = -52 + 33 \times pH$ can be used to estimate CEC-values at a given pH for the peat soil under study.

Potentiometric titration curves revealed a continuum of functional groups involved in the protonation reactions; the most distinct inflection point is found at pH 3.4, and the apparent pK_a is estimated at 6.4.

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PEAT PRODUCTION AND OTHER SOURCES IN THE LOADING OF WATER COURSES

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INTRODUCTION

In the western part of Oulu County in Finland, where the area for peat mining is currently about 15 000 hectares, the solid matter and nutrient loading of the water courses due to peat extraction has been observed systematically since 1986. The effects of other sources of loading have also been monitored and this, together with estimations based on the results of different research projects, has enabled an overall assessment of nutrient and solid matter loading in eight different river catchment areas

In the most southern parts of the study area, farming is strongly represented and is the main source of the nutrient load. The northern catchments, on the other hand, contain large areas of peatland and forest, which means that natural run-off is a significant loader. In any event, peat production only contributes up to a maximum of 3 per cent and 6 per cent of the total loadings of phosphorus and nitrogen, respectively.

During the study period (1986-1994), the peat mining area has doubled but loads have remained about the same, allowing for variations caused by annual rainfall. This has been made possible by the construction of more effective water purification systems at production sites. The overland flow field is most common of these new systems, by means of which reduction in solid matter and nutrient loads has improved considerably compared with that achieved by the sedimentation basin.

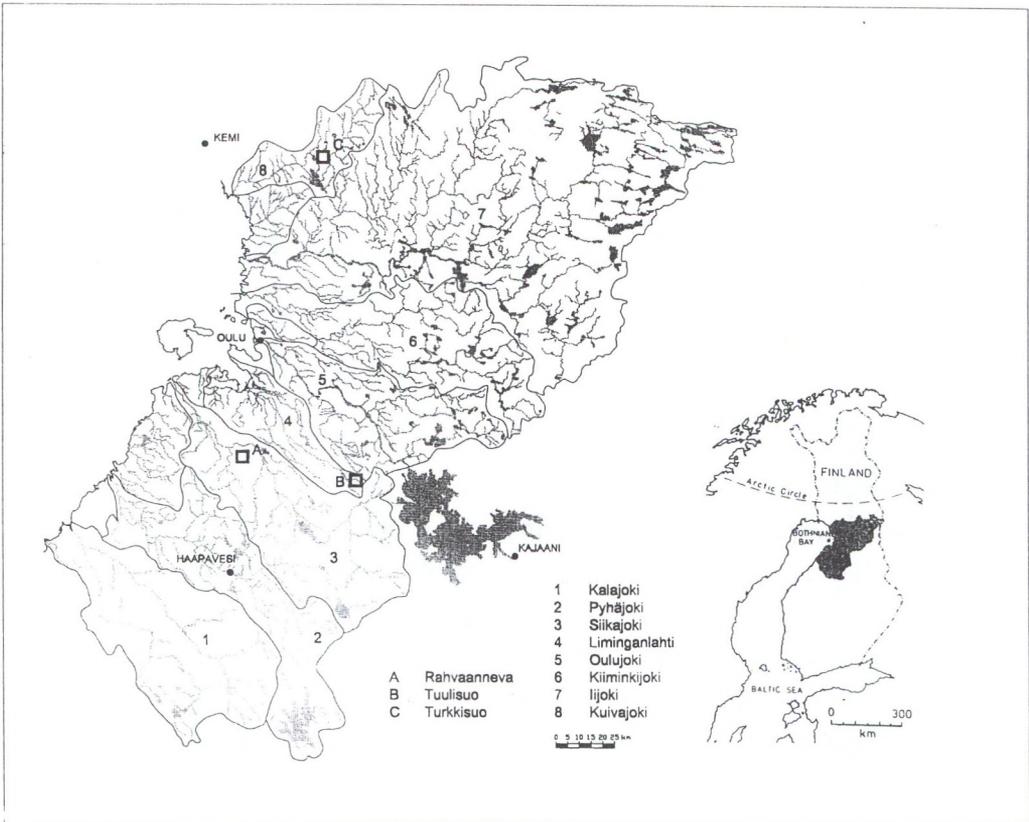


Figure 1. Location of catchments and river systems in the study area. The most important peat power plants are marked by dots.

LOADING OF WATER COURSES

Sources of loading

Loading can be divided into two categories, diffuse and point source. Diffuse loading takes place directly from the atmosphere, and includes industrial and other emissions, and also directly and indirectly from the ground, mainly as a result of agriculture, forestry and input from scattered settlements.

Point loading covers activities which have a specific point of discharge into the water system and a periodically regulated load. These include industry, mining, fish farms and urbanisation. Peat producers also have their unloading sites, but periodic discharge is less well regulated, as with diffuse loads. Loading caused by the peat production results from ditching as well as from mining.

The research area is one of intensive peat production because many large peat-fired heat and power plants are located in Northern Ostrobothnia (Fig. 1.). Here, peat production increased at the beginning of 1970s due to a greater use of domestic energy in Finland. The previous peak in peat production occurred during and immediately after the Second World War. The use of peatlands for other purposes, such as farming and forestry, has been encouraged since 1740, when a law guaranteed an exemption of taxes for new farms on cleared peatland.

PRINCIPLES OF LOAD EVALUATION

The loading effect of different land use activities has been evaluated in a report on the state of the water systems in Oulu County (Pohjois-Suomen vesitutkimustoimisto 1995a). The loading figures for built-up areas and industry are based on statutory measurements. Figures are also available from most of the fish farms but are in most cases restricted to the measurement of annual loads calculated on the basis of feed input.

Estimations of diffuse loads associated with different forms of land use are based on the results of previous research. Loadings due to agriculture were determined using figures obtained by Rekolainen (1989); those due to forest drainage and fertilizing are based on research undertaken by Ahtiainen (1988). Calculation of diffuse loads derived from scattered habitations are based on the results of Viitasaari (1990).

The loading caused by peat production was monitored mainly during the production period. It is estimated that 70 per cent of the phosphorus and 80 per cent of the nitrogen loads occur in the summertime (Vodata 1993).

PROPORTION OF NUTRIENT LOAD FROM DIFFERENT LAND USE SOURCES IN DIFFERENT CATCHMENT AREAS

Table 2 shows the loadings of phosphorus and nitrogen (kg/d) from different sources for the eight catchment areas in Northern Ostrobothnia (Pohjois-Suomen vesitutkimustoimisto 1995a). The largest loader of phosphorus in the southern areas is agriculture, which contributes 58 per cent of the total in the Kalajoki catchment but has a decreasing effect towards the north. Most of the phosphorus load in the areas north of Oulujoki comes from natural run-off. Farming and natural run-off constitute the two main sources of phosphorus loading over the research area as a whole. Forest drainage and fertilization together with isolated settlements are the second most

important sources. The settlements include both permanent and leisure- time residences. Fish farming has relevance only in the water catchment area of Iijoki.

Although peat production takes place in all the areas studied, its contribution to the total phosphorus load is relatively insignificant (less than 3 per cent) compared with that from some other sources. In the southern areas, farming is relatively intensive and densely populated areas also contribute significantly to the phosphorus load. In the north, catchment areas are large and inputs are derived mainly from forest drainage and natural flow.

The most significant impact of peat production occurs in the Kuivajoki area where it contributes 3 per cent of the overall phosphorus load. Contributions to the phosphorus load from other than natural sources in Kuivajoki are low (Granberg & Sundell 1992). Here, as in the other river catchments, there are no important industrial plants. In the Oulujoki catchment, only the lower part below the Oulujärvi lake was included in the study, which means that the effect of Kajaani city and its industry was not discernible.

Half of the nitrogen load from the research area emanates from natural flow and atmospheric sedimentation. At Kalajoki, however, some 50 per cent of the nitrogen load is due to agriculture, which is also a significant source of nitrogen in other southern river areas. The fourth most important source of nitrogen is liquid sewage from densely populated areas. At Kuivajoki and Kiiminkijoki, however, the contribution from built-up areas is small.

Peat production plays a slightly larger role as a nitrogen than as a phosphorus loader, contributing between 1 and 6 per cent in different catchment areas. As with phosphorus, the highest percentage was recorded in the Kuivajoki area.

LOADING CAUSED BY PEAT PRODUCTION

Results of systematic observations 1986-1994

The systematic joint observation of loading caused by peat mining in the study area began in 1986 (Pohjois-Suomen vesitutkimustoimisto 1995b,c). Altogether the quality of water at 27 sites was monitored and absolute loadings calculated. The average run-off from peat mining areas varied from 10-30 l/s/km² in different years depending on rainfall. Differences between the mining areas were also large.

Figure 2 shows the relationship between the total peat production area and the loadings of phosphorus, nitrogen and solid matter for the period June to September 1986-1994 in the Environment Centre area of Northern Ostrobothnia. In terms of peat production, this area is practically the same as that of the river catchments previously mentioned. The figure shows that although peat production has doubled over the nine year period, the total annual loads of phosphorus and nitrogen have remained about the same level overall, despite the peaks in years of higher rainfall. The results indicate that it is possible to improve production methods and water control measures to the extent that the total load does not increase with respect to production area. Figure 2 also shows that, compared with P and N, the input of solid matter to the water systems has actually fallen over the study period.

Effect of water control structures

All peat mining areas under observation since 1986 have utilized sedimentation basins, sized in order to slow down the flow of water from production sites so that most of the solid matter sinks to the bottom. These basins are emptied once a year or more frequently should the need arise. The sedimentation basin provides a practical solution to the problem of retaining solid matter but it has no effect in the case of soluble substances. Therefore other methods have been introduced. In increasing numbers and in association with sedimentation basins, overland flow fields have been constructed on mining sites. By this means, water emanating from the production site is directed to an area of natural peatland at a lower level. Since 1991, it has been possible to compare water system loads from peat mining areas with sedimentation basins and overland flow fields (Fig. 3). It should be noted that other improvements for the purification of run-off water have been used simultaneously at the working sites.

Based on the average figures for the whole of the study period, it can be seen that the solid material by-passing the overland flow fields is only about a quarter of that passing the sedimentation basins. The corresponding amounts for phosphorus and nitrogen are under one third and a half, respectively. The effect on chemical oxygen consumption was variable and less significant. So far, the number of observations has been fairly small but research continues. In 1995, five peatland sites with overland flow fields were under observation.

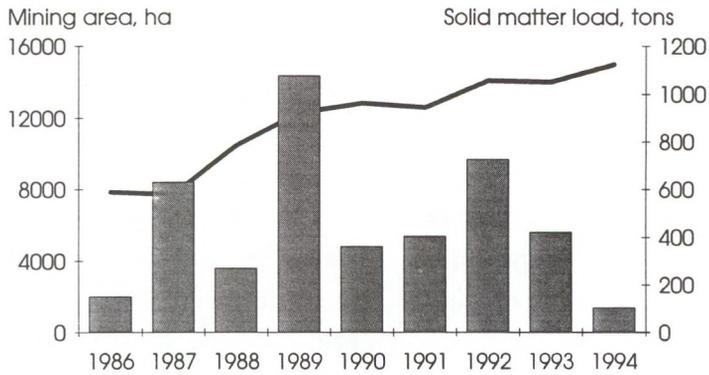
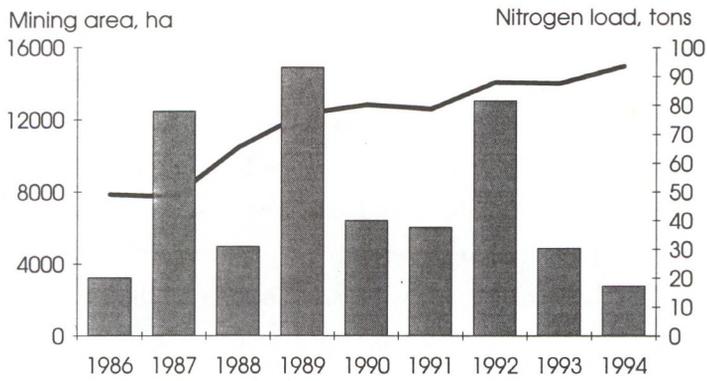
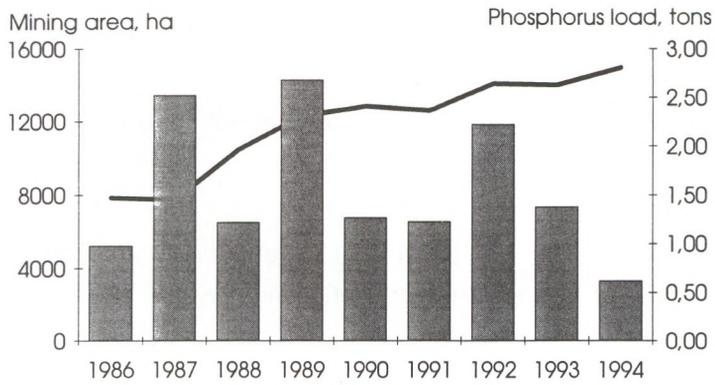


Figure 2. Relationship between mining areas and nutrient and solid matter loadings during the years 1986 - 1994. The mining areas are shown by the black line.

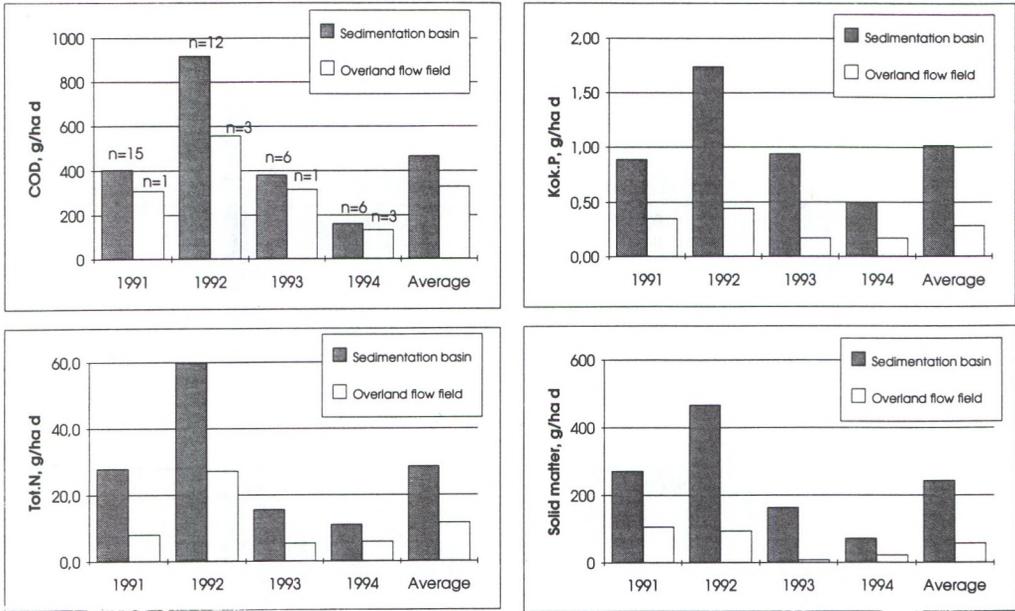


Figure 3. Comparison of specific load figures for mining areas with sedimentation basins and overland flow fields, n = number of studied peatlands. Location presented in Fig. 1.

In 1994, the purifying effect of overland flow was compared at three different mining areas by taking water samples from upper and lower sections of the fields (Fig. 3). Although considerable variation occurred in the amounts of solid matter, nitrogen and phosphorus removed at each production site, the average reduction figures were promising. Similar results have been obtained from previous studies on overland flow areas (Ihme 1994).

Table 3. Reduction in nutrient and solid matter loads due to overland flow fields in three different peat production areas as measured by the quality of water in the upper (A) and lower (B) field areas in summer 1994 (Pohjois-Suomen vesitutkimustoimisto 1995b).

Mining Area		COD mg/l O ₂	Tot.P µg/l	Tot.N µg/l	Solid matter mg/l
Rahvaanneva	A	98	120	2861	19
	B	63	54	1712	2
	Reduction (%)	36	55	40	89
Tuulisuo	A	39	81	2753	12
	B	52	60	2354	11
	Reduction (%)	-33	26	14	10
Turkkisuo	A	23	281	1517	78
	B	35	82	815	9
	Reduction (%)	-56	71	46	89

SUMMARY

The area under observation is marshy and fairly sparsely inhabited. The impact of man as a nutrient loader of water systems is notable only as a result of farming in the southern river areas and in some other places as a consequence of population density and forest drainage. Calculation of the relative contribution of different loading sources is based mainly on research estimations. Results of statutory observations are available for densely populated areas, industry and peat production sites. The contribution of peat production as a source of nitrogen and phosphorus amounts to only a few per cent.

Monitoring the nutrient load due to peat production showed that there has been no change in the total load during the study period of nine years, although the total mining area has doubled. The load calculated per production hectare has thus halved.

One can expect the load diminish further as the proportion of mining sites with overland flow fields increases. This is because research results presented here and those published previously show that the fields can hold a considerable amount of nutrients as well as solid material.

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WATER STORING AND RELEASING PROPERTIES OF PEAT

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SUMMARY

Microscopy, electron microscopy and gravimetry were used to study the exchange of water in peat. Slightly decomposed *Sphagnum* peat exhibits the original cellular structure of the plants, with hollow spaces within the cells of about 0.01 mm in diameter (macropores) connected to each other and to the outside by "windows" in defective cellular membranes. In addition, water absorption produces under swelling a micro- and mesopore system with diameters between 2 and 200 nm within and between the cellular membranes. Two water exchange mechanisms can be distinguished: sorption from the vapour phase within the swelling membranes and filling of the hollow cells from the liquid phase. The macropore filling process is used in horticulture to reach several day's water storage. A thermal swing process including sorption within the membranes may be applied for catching water from the atmosphere. For effective water uptake and release in arid regions, however, a material may be required with a pore system covering the whole range from micro- to macropores without interruption.

INTRODUCTION

One of the big unsolved world projects is the amelioration of the desert soil. Several techniques of water supply are available: distribution of desalinated water from the sea or pumping of groundwater. Both methods are economically viable in restricted regions only. In addition, the soil can be improved using water-retaining agents. By means of such soil conditioners, water provided by occasional rain or irrigation is protected from immediate evaporation and percolation and held available

for an extended period of time. In regions of periodically moderate or high air humidity, in particular near the coast, when during the night at reduced temperature the humidity increases or mist is generated, soil conditioners may be applied which are able to collect water from the atmosphere. The process includes water absorption at reduced temperature from the air, transition from the absorbed phase to a liquid condensate, storage and slow release directly to plants or to the soil at elevated temperature and low soil humidity as depicted in Figure 1. This is a simple example of temperature swing absorption as used today increasingly in industry (Mersmann & Scholl, 1991). Of course, this process may be difficult to realize under the given environmental conditions. The material needed to cover the soil must be non-toxic for plants, animals and human beings, readily available and cheap. A variety of materials are proposed for improving water retention in soils (Askar, 1992) including minerals like gypsum, superphosphate, bentonite, natural organic materials e.g. farmyard manure, sewage sludge, rice straw, as well as hydrophylic polymers: hydrogels, e.g. polyacrylamide, urea formaldehyde and hydrophobic polymers like bitumen emulsion. In order to collect water from the atmosphere, black plastic foils are applied partially to cover the ground or in the form of artificial palm trees.

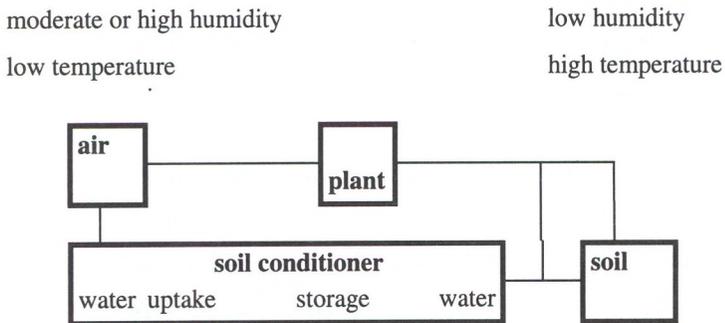


Figure 1. Requirements for humidifying arid soil from air.

Peat is widely used in horticulture for water storage. In granulated form it has been proposed as a possible material to improve soils in subtropical regions (Lüttig, 1980), it is also occasionally used in tropical regions (Ismail *et al.*, 1990, Robens 1991). For the peat/water system, several equilibrium data are available (Reeker & Springer, 1973; Grumpelt, 1983). However, to assess the possibility of the use of peat for water collection, storage and concentration, knowledge is required about the

kinetics of water exchange for the whole range from very dry up to saturated peat. The present study is based on results of an investigation performed at the Battelle-Institute, Frankfurt am Main (Hampel *et al.* 1973), supplemented by gravimetric measurements. The measuring data were evaluated and presented using the programs EqPlot and LineTrace (Reichert, 1993).

PROPERTIES OF PEAT

The composition of peat varies considerably depending on the nature of its plant components, but the chief constituent is moss of the genus *Sphagnum*. The genus *Sphagnum* comprises a number of species (Fig. 2) which are able to grow under acid conditions, exhibiting pH values of 2.5 to 4.5 and containing little nutrient matter. The leaves are formed of a cellular tissue containing macropores up to 0.01 mm in diameter. The water content of the plants ranges from 75 to 94 percent. Peat forms because the decomposition of these plants is restricted by the exclusion of air. In contrast to the succeeding product lignite, peat contains a large amount of cellulose and exhibits the original pore structure of the plants.

The slightly decomposed white moss peat of the upper layers in the peat bog is used mainly for horticulture. It is almost sterile on account of its acidity. The dried peat as delivered in bales exhibits a apparent bulk density of round 160 kg m^{-3} and contains about 30 volume percent water. It may retain more than the double this amount of water (Fig. 3). Even when wet-through it contains about 30 percent air. In its use in horticulture, peat decomposes very slowly depending on the type and humidity of the soil to which it is added. The main peat deposits are situated in Russia, Canada, the USA including Alaska, Northern and Central Europe and, in particular, Finland. In subtropical and tropical regions only few deposits of this type of peat are found.

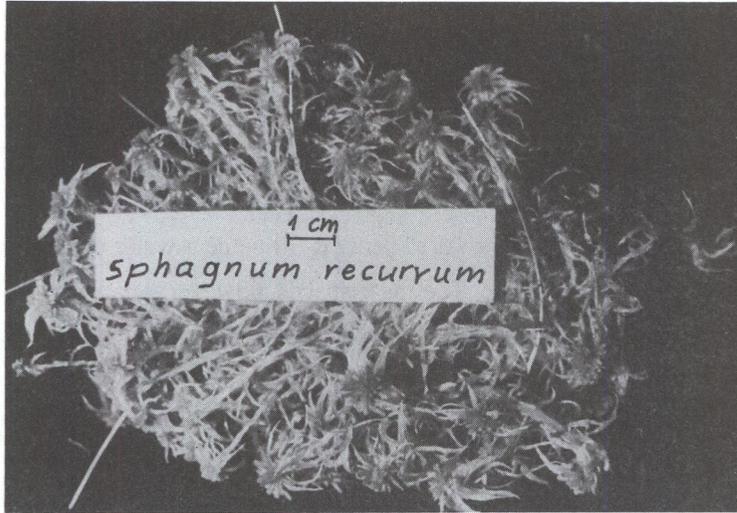


Figure 2. *Sphagnum recurvum*.

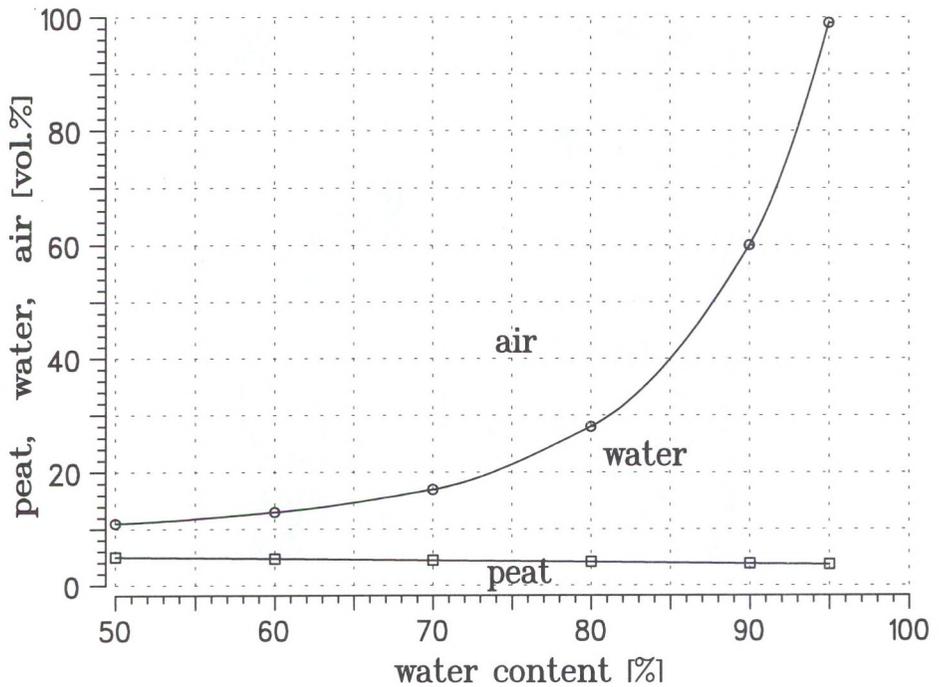


Figure 3. Volume of water and air in peat as a function of water content, according to Reeker & Springe, (1973).

MICROSCOPIC INVESTIGATION

Transmitted light microscopy (Leitz Panphot) shows a structure of veins and hollow cells mostly of magnitude $10\ \mu\text{m}$ in diameter (Figs. 4,5). The scanning electron microscope (Cambridge Stereoscan) reveals large "windows" in several membranes, which provide connections to adjoining spaces and to the outside (Fig. 6).

After immersion of the "dry" peat (\approx 30 percent water content) only a few air bubbles adhere to the outside. The inner spaces, however, retain air bubbles for hours and days (Fig. 5). Adhering air bubbles exhibit contact angles between 80 and 120° measured through the liquid phase. By addition of a surface active agent the contact angle decreases below 20° . Then, bubbles detach and air escapes from the interior. This is in accordance with experience: Normally peat needs to be through-wetted for more than 24 hours, but after adding some surface-active agent the time is reduced to less than one hour.

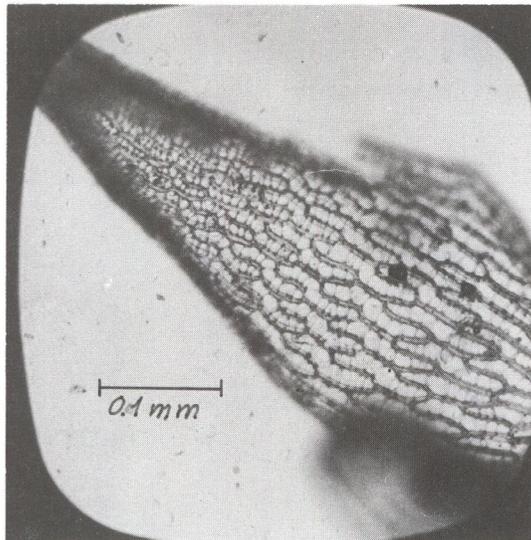


Figure 4. Sphagnum peat under the transmission light microscope.

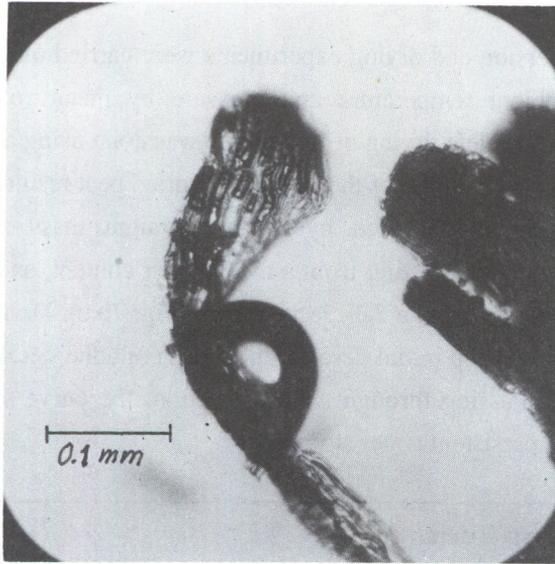


Figure 5. Adhering air bubble and trapped air in peat immersed in water.

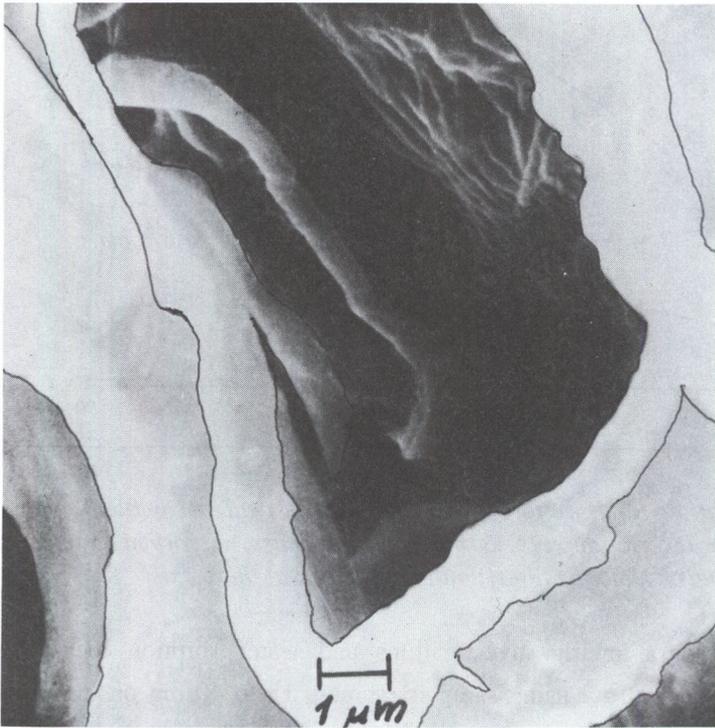


Figure 6. *Sphagnum* peat under the scanning electron microscope. Interior of the hollow spaces of the original cellular tissue with connections through the membranes. (External contours are retraced.)

GRAVIMETRIC INVESTIGATION

Wetting, immersion and drying experiments were carried out using samples of about 100 g at ambient temperature and pressure by means of a conventional inclination balance. Complete drying of the sample was done using a microwave oven (end of curve Fig. 7c). Immersion of the completely dried peat results in a initial steep increase in water content followed by a slow straight mass ascent (Fig. 7a). Immersion as well as drying starting from a mean water content, as is usual in stored peat, leads to a slow linear rise or fall, respectively (Fig. 7b,c). Drying of completely moistened peat shows a steep initial descent due to loss of adherent water between the aggregates (Fig. 7d). Passing through a linear section, the curve show a flat, slow decrease, confirming persistent water storage

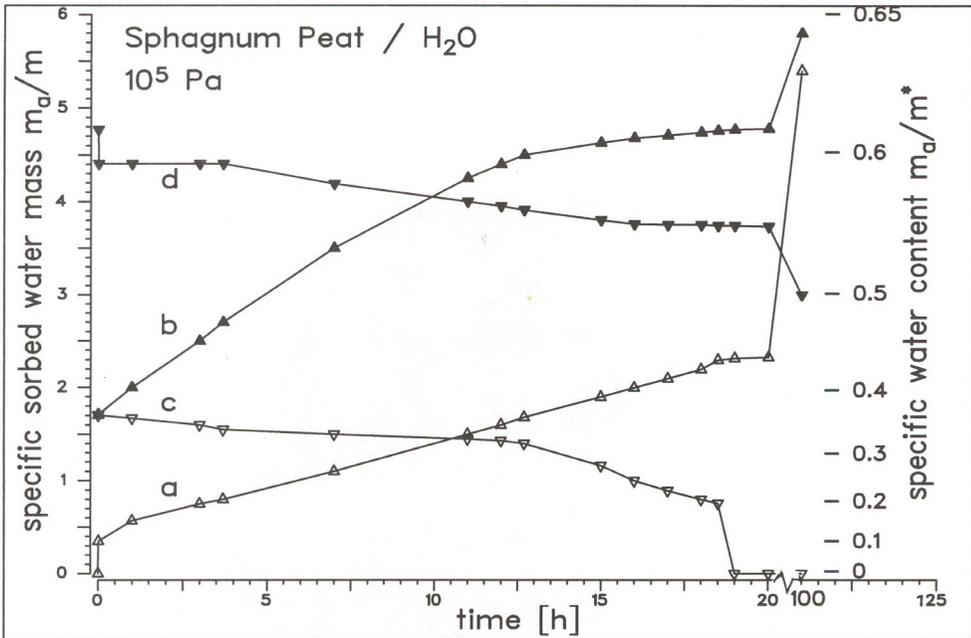


Figure 7. Drying and wetting by immersion of peat at ambient temperature and pressure. For description see text. m dry sample mass, m_a sorbed water mass, $m^* = m_a + m =$ total mass. Note the interruption at the end of the x-axis.

Thermogravimetric investigations and water sorption measurements (Gal, 1967) were carried out using samples of mass 15 to 40 mg on a Sartorius vacuum microbalance (Gast *et al.*, 1995). The vapour pressure was controlled by means of a temperature-controlled water reservoir (Fig. 8). In Figure 9 a thermogram of peat is

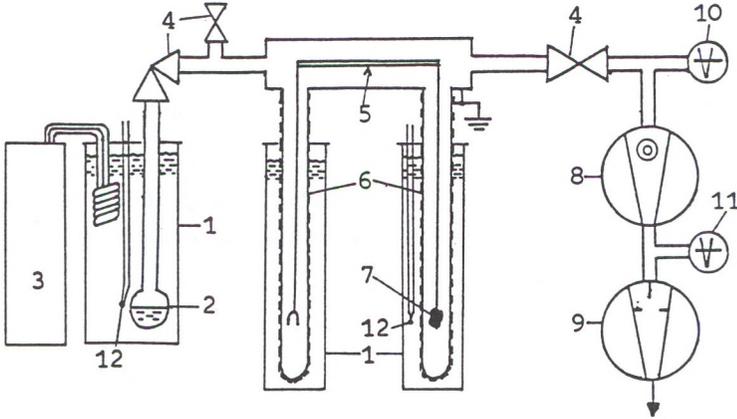


Figure 8. Microgravimetric apparatus.

1 refrigerator, 2 water reservoir, 3, Dewar vessels, 4 valves, 5 Gast microbalance, 6 quartz tubes with metal stockings, 7 sample, 8 turbo molecular pump, 9 rotary vane pump, 10 Penning gauge, 11 Pirani gauge, 12 thermocouples.

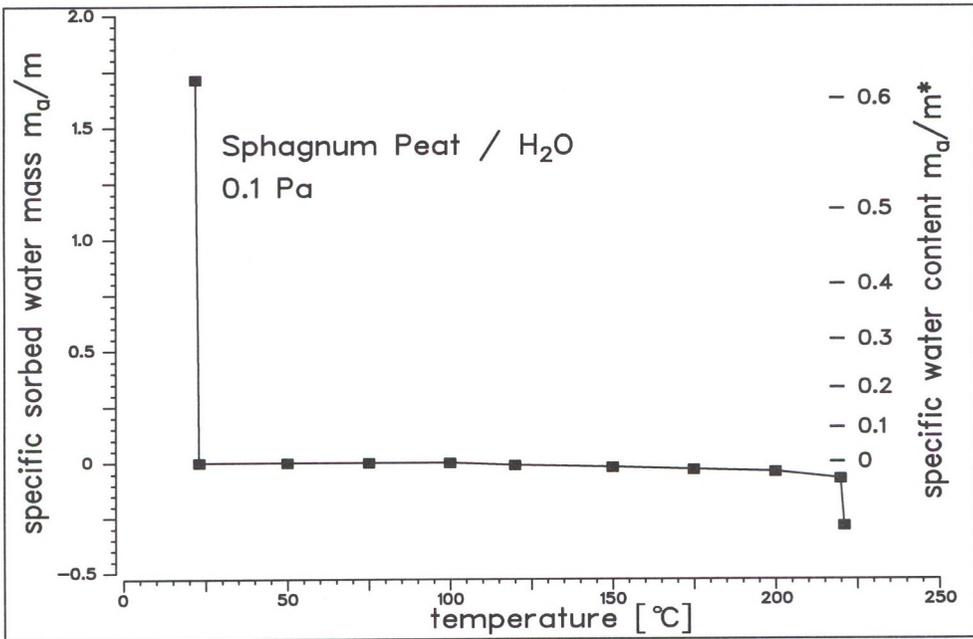


Figure 9. Thermogram of Sphagnum peat. m dry sample mass, m_a sorbed water mass, $m^* = m_a + m =$ total mass.

depicted. The very first decrease is due to the loss of absorbed water. During heating up to + 220 °C in vacuum, an insignificant mass loss occurs; subsequently there is a slow, continuous decrease due to decomposition. This treatment did not affect the structure of the material as determined under the transmitted and the reflected light microscope.

Figure 10 demonstrates that drying depends strongly on air pressure. At ambient temperature and pressures above 0.1 kPa drying takes hours. By application of a moderate vacuum, the sample is dried completely within a few minutes. Figure 11 shows a stepwise measured water vapour absorption and desorption isotherm at ambient temperature. Equilibrium after uptake of water vapour was obtained within 15 to 30 minutes and after desorption within 30 to 60 minutes. The isotherm corresponds with the types H3/H4 of the IUPAC classification (Sing *et al.*, 1984; Rouquerol *et al.*, 1994) as is typical for wetting substrates (contact angle below 90°). In its lower part, it is reversible and exhibits above the relative pressure 0.4 a hysteresis loop as produced by meso- and macropores and/or by swelling (Willems *et al.*, 1989). This hysteresis loop represents a region of thermodynamic instability

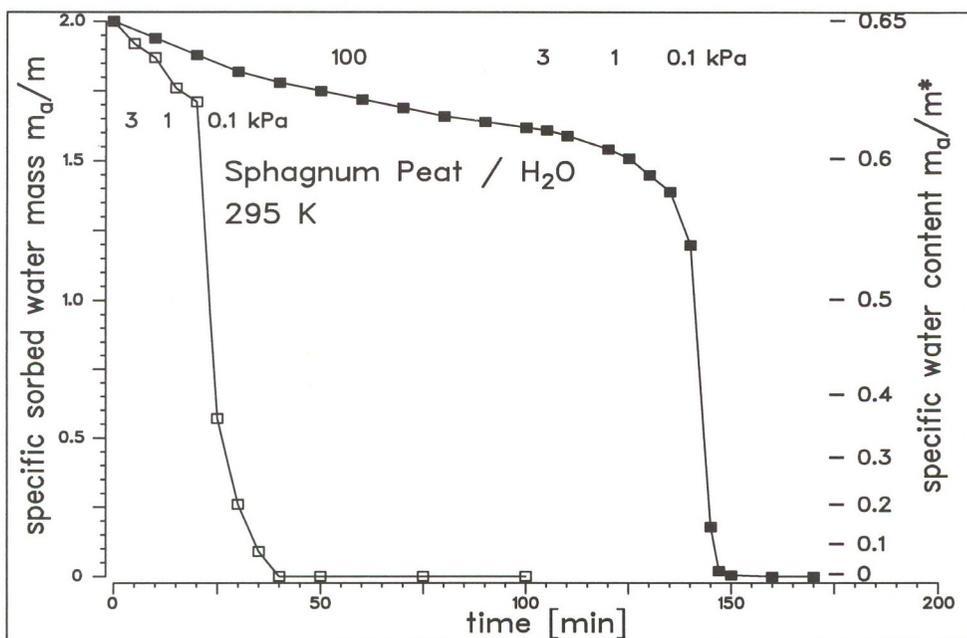


Figure 10. Drying curves of peat at ambient temperature and varied air pressure in vacuum, ■ at initially atmospheric pressure. m dry sample mass, m_a sorbed water mass, $m^* = m_a + m = \text{total mass}$.

(Mikhail & Robens, 1983): If, during measuring the desorption branch, the vapour pressure is increased, the absorbed mass remains constant and the region within the hysteresis loop is entered. Subsequent desorption produces a deviant course of the desorption isotherm as is demonstrated by some points in Figure 11. Similar things occur when the pressure is lowered during absorption. It may be emphasized, that the water vapour isotherm covers just the steep increase at the very beginning of curve (a) in Figure 7.

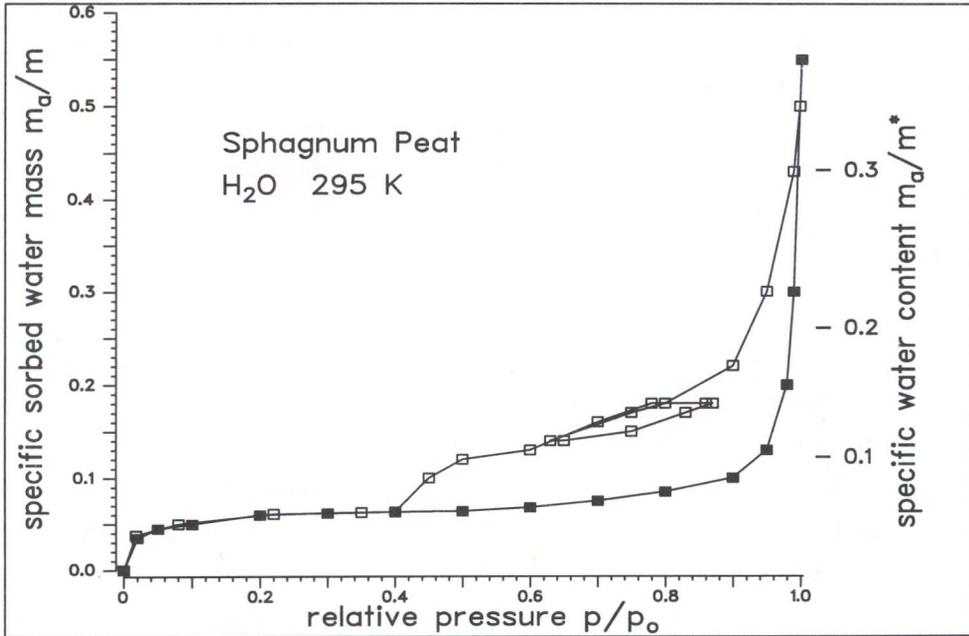


Figure 11. Water sorption isotherm of peat at ambient temperature. p pressure, p_0 saturation vapour pressure, m dry sample mass, m_a sorbed water mass, $m^* = m_a + m =$ total mass, \blacksquare absorption, \square desorption. process. The dark colour of peat accelerates equalization to ambient temperature and favours, therefore, water sorption at reduced temperatures.

DISCUSSION

The results of our experiments demonstrate two independent water exchange mechanisms: sorption from the vapour phase in swelling membranes and hollow cell-filling from the liquid phase. Cell-filling and slow water depletion are applied conventionally in horticulture. Both, cell-filling by displacement of trapped air bubbles and release of water can take from hours to days. Peat is able to store a large amount of water for days, but if insufficiently moistened it dessicates the surrounding

soil and can damage plants. Among other factors, this effect contributes to weed-prevention by covering plant beds with dry peat.

The impediment by air pressure of the moistening and drying process from and to the atmosphere, respectively, is obviously caused by diffusion through the cellular structure. This effect may diminish the efficiency of a thermal swing absorption process. The dark colour of peat accelerates equalization to ambient temperature and favours, therefore,

The transition from the sorbed to the condensed phase of water as a necessary concentration process is obstructed by the wide gap between pore diameters of the micro-/mesopore structure and the macropore dimension of the large cellular spaces. Neimark *et al.*, (1994) showed recently, that on swelling, peat exhibits an extended region of surface fractality. This fractality is due to a continuous "roughness" of the swollen structure over a wide order of magnitude that could favour the phase transition.

CONCLUSIONS

Filling of the hollow cellular structure of peat by water, as conventionally used in horticulture, can be remarkably accelerated by addition of a tenside. In turn, however, this will affect likewise the water release and may shorten the storage period. Also at low humidity, peat can be used as a water-storing soil conditioner. In this case, however, the desiccative effect must be taken into account. The hollow cells and the swollen membranes may be used to incorporate fertilizers and pesticides. After distribution in the soil and moistening, the ingredients are slowly released within periods of days or weeks.

For effective water uptake from a humid atmosphere by means of a thermally stimulated absorption swing process, a material containing a pore system covering the whole range from micro- to macropores without interruption, could be more favourable.

Peat being a natural but nevertheless resistant material, offers some unique features for use as a soil conditioner. However, in arid, high temperature conditions, a fast decomposition (humification, mineralization) could take place. Peat deposits occur far from arid regions and, thus, noticeable transportation costs should be considered. As peat is a light and fluffy material, some pretreatment, e.g. compaction, may be required to prevent loss by windblow.

ACKNOWLEDGEMENT

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GERMAN MIRES - UTILISATION AND PROTECTION

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SUMMARY

Mires in Germany are mainly used for agriculture. Peat mining is important regionally, but forest utilisation less so.

Twenty years ago in the former West Germany, the first steps from peatland utilisation to peatland protection were taken. Bog protection programmes were developed first. Nowadays research directed towards fen protection has begun, prompted by the decreasing importance of agriculture in central Europe and an increasing environmental awareness.

The situation regarding mire protection in Germany is presented for each Federal State individually. A rough estimate suggests 45,000 ha of protected bogs and 25,000 ha of protected fens. These areas include natural and semi-natural mires as well as rewetted mires.

INTRODUCTION

In Germany, the area originally covered by mires was 1 625 000 ha, before being reduced to an extent not completely known at present.

The main bog region is northwest Germany (Lower Saxony and Schleswig-Holstein), where the most important prerequisite of bog development was the strong influence of an oceanic climate. A second region of bog concentration is the Alpine foreland (mainly Bavaria), which is affected by a very high rate of precipitation. However, small bogs are also found in many other mountainous regions (Fig. 1). The extent and distribution of fens is greater than that of bogs because their development depends largely on the topography.

In the Federal Republic of Germany each state has its own geological survey as well as its own administration for land surveying, nature protection and management

of protected areas. Laws concerning those matters also differ from state to state. The following descriptions and statistical data are therefore divided according to the 16 states and reflect the status in 1993.

The mire areas of the various states of Germany are shown in Table 1. A mire is defined geologically as a site where the peat layer is thicker than 30 cm (Fig. 1) The following accounts are for those states with a considerable area of mires

Tab. 1: Distribution of mires in Germany (partly after Schneider & Schneider 1990).

State	Mire-unit-type		
	Bog (ha)	Semi-natural or natural bog (ha)	Fen (ha)
Lower Saxony/Bremen	249 00	28 120	85 100
Schleswig-Holstein/Hamburg	34 000	9 760	125 000
Bavaria (bogs include transitional mires)	40 000 -50 000	20 000 -25 000	80 000
Baden-Württemberg	3 400	-	32 400
North Rhine-Westfalia	5 000	-	60 000
Brandenburg/Berlin	-	-	190 000
Mecklenburg-Vorpommern	6 000	-	230 000
Thüringen	-	-	700
Sachsen	few	-	6 000
Sachsen-Anhalt	-	-	50 000
Hesse	1 000	-	4 000
Saarland/Rhineland-Palatinate	2 000	-	3 000
Sum	ca 350 000	60 000	870 000

LOWER SAXONY

Bogs And Fens

In Lower Saxony, bogs originally covered an area of about 330 000 ha of which 249 400 ha remain. It can be divided into two regions of bog formation; the more continental eastern region and the more oceanic western region. While in the northwestern area the composition of the younger, so-called white peat is dominated by sphagna belonging to the section *Sphagnum* (*S. papillosum*, *S. imbricatum*), the peat in the southwestern area consists of sphagna of the section *Acutifolia*. The boundary is quite distinct, indicating the different climatic conditions during the last two thousand years, the phase when the accumulation of white peat took place (Overbeck, 1975)

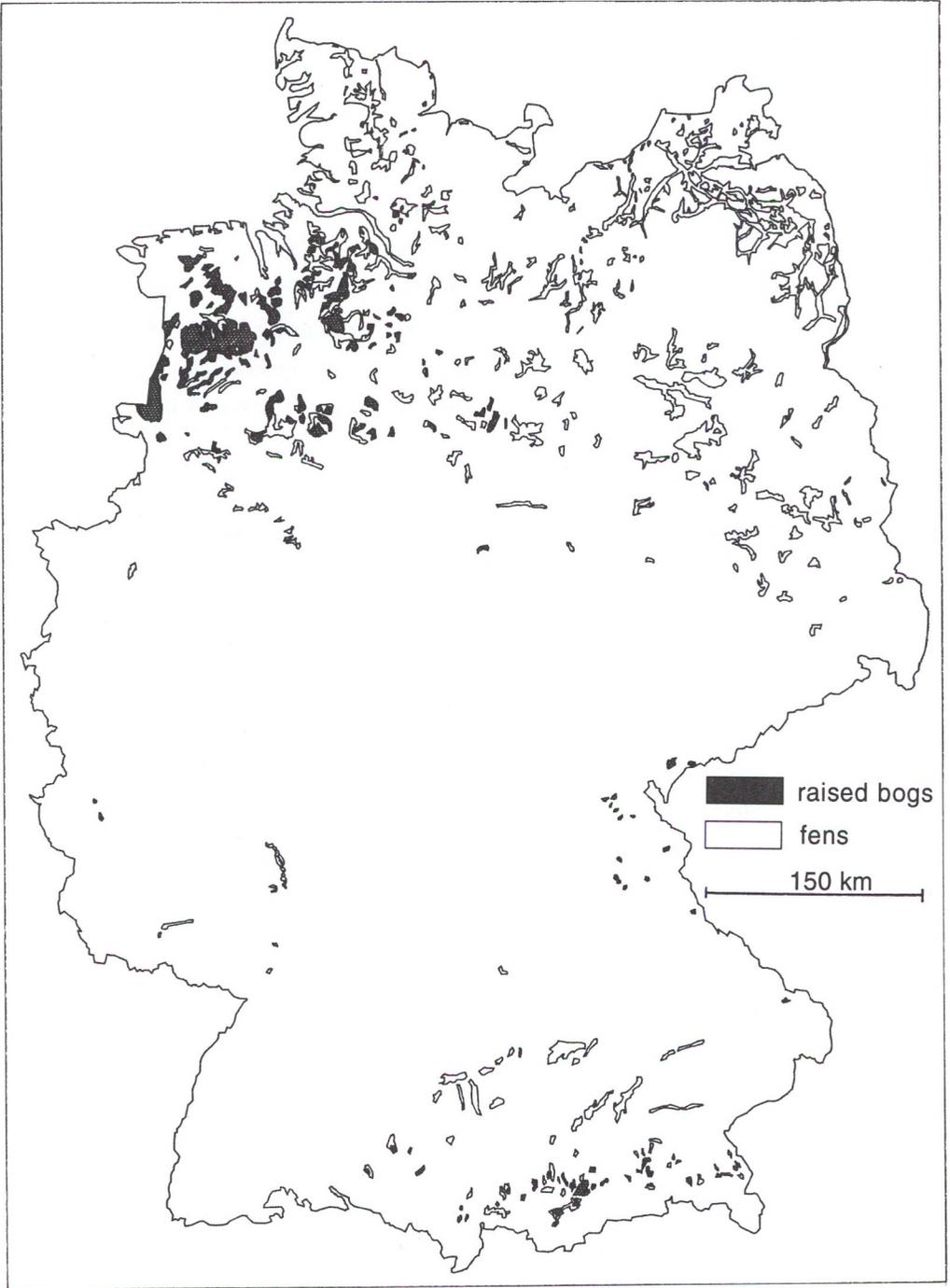


Figure 1: Distribution of bogs and fens in Germany.

Originally fens covered an area of 300 000 ha, which has since decreased to 185 100 ha. Fens developed mainly in the wide valley lowlands through paludification and nowadays almost all of them are in agricultural use except 2 334 ha of natural fens, which are protected (Göttlich & Kuntze, 1990).

The bogs of Lower Saxony are plateau bogs with a raised central area. They are treeless and are surrounded by a marginal slope and a lagg. The marginal slope is partly covered by birches and pines. The underlayer (sand or minerotrophic peat) is either almost flat or slightly depressed. The main feature of plateau bogs in Germany is the alternation of hummocks and hollows and their different plant communities.

Many of the raised bogs are "wurzelechte Hochmoore", which means that peat formation started directly on the mineral sublayer (mostly sand with an almost impermeable ortstein or ground moraine) without an intermediate minerotrophic phase.

Mire Utilisation

Pliny the elder (23/24-79 AD.) was the first to report on the extraction of peat as a source of fuel in northern Germany. However, it was not until the end of the 16th century that raised bogs were used intensively by Dutch-inspired Veen cultivation and peatland burning (Overbeck, 1975). At the beginning of the 20th century peatland burning was replaced by the German raised bog cultivation (*Deutsche Hochmoorkultur*), developed and tested by the Mire Experimental Station in Bremen since 1877. In order to leave the stratigraphy undisturbed and to prevent peat losses by decomposition and mineralisation, these are managed mainly as grasslands (110 000 ha), and only 15 000 ha as arable land (Schmatzler, 1991).

The importance of peat mining of raised bogs as well as their agricultural importance has fluctuated with the economical and political circumstances. Nowadays about 32 000 ha are used or will still be used for peat mining. Both white peat and increasingly black peat are harvested for horticultural purposes.

The 18th century was the era of intensive fen cultivation, applying various agricultural methods. Either the stratigraphy was left intact and the fen was drained, or the stratigraphy was disturbed so that sand from the sub-peat layer could be transferred on the surface in order to minimise peat wastage (Göttlich & Kuntze, 1990).

Fen Protection And Fen Regeneration

The ground-water relation, the main prerequisite of fen formation is mostly linked to that of the neighbouring mineral soils. Therefore the protection and the

restoration of this relation within the mire affects the surrounding areas. The following matters thus have to be taken into consideration:

- The mire type (hydrologically and genetically),
- the oxygen content of the water feeding the mire,
- the establishment (conservation or restoration) of the ground-water level near the surface,
- maintenance or renewal of water input from the surrounding areas,
- calculation of hydrological buffer zones (Eggelsmann, 1989).

Some trials concerning the regeneration of fens are in progress in Lower Saxony and the Netherlands. However, those trials have only been in progress for a few years, and cannot yet be evaluated. A large federal project on ecosystem management of fens was therefore started in 1992.

Recently, it was acknowledged that less intensively used fen grasslands are also very valuable for species protection, e.g. characteristic bird species. In order to keep the ecological values of agriculturally managed fens at levels suitable to the requirements of endangered species, the extent of utilisation has to be reduced. Drainage has to be limited to a certain depth and N-fertilisation and liming also have to be reduced.

Raised Bog Regeneration

The first steps towards peatland protection instead of peatland utilisation were not taken until the beginning of the 1970's (Kuntze, 1973; Eggelsmann, 1975). In 1980, a complete survey of bogs including evaluation of their importance with respect to mire protection was carried out (Birkholz *et al.*, 1980). This served as a basis for the mire protection programme (Ministerium Ernährung...1981) whose aims have been enshrined in law. This investigation showed that the following areas are valuable in terms of nature protection: 28 000 ha, which are still in a natural or semi-natural state; another area of 25 580 ha, consisting mostly of formerly drained sites, covered by heathland vegetation, and 30 000 ha, which are going to be rewetted after peat harvesting.

The first field trial in raised bog regeneration after peat harvesting was started in 1976 (Kuntze & Eggelsmann, 1981; Blankenburg & Eggelsmann, 1990). In the meanwhile many new trials have been established on industrially harvested sites as well as on manually cut-over sites.

Raised bog rewetting demands:

- a humid climate,

- a rise in the water-level up to the surface (prevention of too deep inundation),
- blocking and sealing the ditches in order to stop runoff (above and below ground) (Schäfer *et al.*, 1987),
- construction of an artificial microrelief (Eggelsmann 1987, 1988),
- calculation of hydrological buffer zones (Eggelsmann 1977, 1982),
- a minimum thickness and essential properties of the remaining peat layers (Roderfeld, 1992, 1993).

In 1990, 5 436 ha of harvested peatland were rewetted, of which 70% is already protected under the nature protection law (Blankenburg & Schmatzler, 1991).

Furthermore, there are about 150 small bogs which will also be protected (Ministerium Ernährung...1986). Altogether, 25 072 ha of raised bogs are already protected by the nature protection law (Schmatzler, 1991).

SCHLESWIG-HOLSTEIN

Bogs And Fens

The distribution of mires in Schleswig-Holstein is closely associated with its various glacial deposits. In the hilly eastern landscape, formed during the last glaciation (Weichsel) there are hardly any bogs to be found, only small fens, which developed in glacial depressions are present. Bogs occur more frequently on the low Sandur area to the west of the terminal moraines (Weichsel). However, in the most westerly part of Schleswig-Holstein, where the topography is determined by the penultimate glaciation (Saale), bogs are only found on the sandy lowlands. Here also fens are more abundant in the low and wide river valleys. Fens formerly covered 150 000 ha, but have now decreased to 125 000 ha.

Bogs covered originally an area of 45 500 ha, of which 30 000 ha remain. As a prerequisite for former bog growth in this region climatic conditions (a precipitation rate exceeding 700 mm/a) were as important as the features of relief (Eigner & Schmatzler, 1991; Eigner pers. com., 1993)

Mire Utilisation

The utilisation of mires in Schleswig-Holstein is almost the same as in Lower Saxony. Agricultural use, nearly all as grasslands, accounts for 19 530 ha of bogs and 121 268 ha of fens. About 1 000 ha support man-made forests.

The major disturbances to mires are created by drainage. Furthermore, the lack of buffer zones as well as the increasing nitrogen and sulphur concentrations in the air lead to eutrophication. Peat mining takes place only on an area of less than 500 ha.

Mire Protection

Since 1973 each mire has been protected by law against any man-made change.

Nowadays 31 bogs (2 950 ha) are protected as nature conservation areas. Plans have been put into effect for an additional 37 bogs (5 296 ha). Measures aimed at bog regeneration have been introduced at 62 bogs and are planned for 20 bogs. Conservation management concepts for more than 240 mires, have still to be developed (pers. com. Eigner, 1993).

BAVARIA

Bogs And Fens

Because the annual precipitation ranges between 1 000 to 2 000 mm in the Alpine foreland, Bavaria is a southern state with many ombrotrophic mires. Formerly their total area was about 59 000 ha, whereas nowadays it is about 40 000 to 50 000 ha (Schuch, 1993). Bogs developed in the area of morainic accumulations dating from the last glaciation (Würm), when the annual precipitation was above 800 mm. Bogs are also located in the mountain ranges both near the Czech border and in northern Bavaria. As in north Germany, the raised bogs in Bavaria are plateau bogs, but here bog formation took place following the accumulation of minerotrophic peat.

The original size of the fen-covered area in Bavaria was 141 000 ha, which has now decreased to about 80 000 ha (Schuch, 1993). One of the main regions of fen formation is situated near the northern margin of the Alps. The ground-water flow originating in the high mountains towards the north caused a rise in the water level and the formation of fens (Dachauer Moos, Erdinger Moos). Other large fens developed alongside rivers and in the lowlands (Donaumoos, Isarmoos, Donauried) (Schuch, 1986, 1990).

Mire Utilisation

Very early, before proper research concerning mires was conducted, Bavarian mires were used for agriculture and fuel production. At first farmers harvested the peat. This kind of manual peat cutting was followed later by large-scale industrial fuel

peat mining until it was replaced by oil. Nowadays peat is harvested only for horticultural and balneological purposes on an area of about 1 000 ha.

It is known that the cultivation of small fens started very early. However, the larger fen areas were not cultivated until 200 years ago. In order to intensify the agricultural use of mires, a Bavarian research institute (Landesmoorkulturkommission) was founded in 1895. Its duties, apart from mapping, were the investigation of peat properties and mire hydrology in order to acquire knowledge of peatland cultivation. Considerable success in fen cultivation was achieved only after the end of the First World War.

Nowadays 70% of the fens are still used for intensive farming, while 30% are used as wet grasslands and litter meadows (*Streuwiesen*).

Fen Protection And Fen Regeneration

The decreasing importance of agricultural use of peatlands nowadays offers many opportunities for nature protection, including the rewetting of fens after agricultural use has ceased. Field trials (Donaumöös) show that those measures lead to re-colonisation by typical fen vegetation. Any attempt at protecting and regenerating fens has to be effected according to the laws (Schuch, 1991).

Bog Protection

About 20 000 ha of raised bogs are protected against any change.

Bogs which were or are still used for peat mining have also been rewetted or will be rewetted (about 1 000 ha). Peat harvesters have to apply methods which take the purpose of rewetting into account in order to provide the best initial conditions for the regeneration process.

BADEN-WÜRTTEMBERG

Mires And Their Utilisation

In Baden-Württemberg 3 400 ha of bogs and 32 400 ha of fens are to be found in the Pleistocene and Holocene landscapes. Extensive mires are situated on the end moraines of the Würm glaciation whereas small-sized mires occur frequently on the ground moraines of both the Würm and Riss glaciations. Raised bogs occur mainly in the Allgäu and the Black Forest.

Mires (here: mires and peaty soils) in Baden-Württemberg are mostly used as grasslands (22 000 ha). About 7 000 ha are managed as litter meadows (*Streuwiesen*),

2 500 ha as arable land and 3 300 ha are used for forestry. The remaining areas consist of 4 000 ha of nearly natural forests, peat mining sites (1 600 ha) and mountain forests (2 000 ha) (Briemle, pers. com. 1993).

Mire Protection

Since 1992, endangered biotopes like mires have been protected by law. Some mires have been proclaimed nature conservation areas. At the moment, information on the number and the areas of protected mires in Baden-Württemberg is not available (Briemle, pers. com. 1993).

NEW FEDERAL STATES OF GERMANY

Bogs And Fens

The situation regarding fens and bogs in the former GDR (New Federal States) will be described as a whole, since the survey is not yet complete (1993).

The topography of northeastern Germany is characterised by the last glaciation (Weichsel), which created an uneven relief favourable to fen formation, e.g. in the main glacial melt-water channels, through paludification.

The mire-covered area covered 550 000 ha in 1950, only a small part of it (1%) being raised bogs. Most of the bog area (6 000 ha) is to be found in Mecklenburg-Vorpommern and only a small part in the Saxonian Erzgebirge. Nowadays 478 000 ha of the approximately 500 000 ha of fen areas remaining are used mainly as grassland. Probably the true size of the cultivated area is smaller because of the peat loss due to subsidence, decay and mineralisation under agricultural use. In fens with a shallow peat layer (55 000 ha), its thickness may have decreased to such an extent (< 30 cm) that they are no longer considered as peatlands. Exact data will be available only when the current survey is complete (Lorenz *et al.*, 1992). The greater part of the fens have been formed by paludification mires, but there are also numerous kettle-hole mires, many inundated fens and the so-called "Durchströmungsmoore" which have formed on very slight slopes fed by the particular water movement through the whole peat area (Succow, 1988).

Mire Utilisation

From the beginning of the 18th century, fens in central Germany were systematically drained and used for agricultural purposes, usually as grasslands. The increasing demands of the more commercial agricultural production over the last 30

years have caused an increase in utilisation intensity, fens were drained to considerable depths, treated with heavy machines causing soil compaction, cultivated with grass species developed to be very productive, influenced by too-frequent ploughing in order to prevent weed growth, and fertilised with large amounts of nitrogen and the form of utilisation was often not appropriate to the site type. The peat soils in the fens have been degraded and production has decreased (Lorenz *et al.*, 1992).

Of the bogs in Mecklenburg, 90% have been intensively used either for agricultural or peat mining purposes. Only the remaining 10% are still in a semi-natural or natural state. The development of a bog protection programme is ongoing.

Fen Protection And Fen Regeneration

Great efforts are made nowadays to manage degraded fens according to their site type. A less intensive utilisation of fens has been prescribed to some areas as well as the rewetting of fens for regeneration. Many investigations and projects to implement these plans have been begun (Landesumweltamt Brandenburg, 1993).

Until now there has been only a little knowledge about fen regeneration, but the first approaches also have been made in the new states (Zeit, 1993). About 5 000 ha of fens are still regarded as undisturbed, these being under the nature protection law. Another 20 000 ha are still in a semi-natural state.

The small kettle-hole mires also have an important ecological value. It is estimated that there are about 1 000 kettle hole mires still in a natural state, averaging about 3 ha (Succow, 1986).

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SEASONAL RESPONSES OF HERBAGE TO N FERTILIZER AND CHANGES IN PEAT NUTRIENT CONTENTS ON POORLY DRAINED RESEDED BLANKET BOG LIMED AND FERTILIZED WITH P AND K

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SUMMARY

Herbage yields and nutrient content following April and June applications of P+K and N+P+K (2 applications of 30 kg P and K and 112.5 kg N ha⁻¹) were measured on an area of poorly drained, reseeded blanket bog where the response to N applied in April showed a progressive decline. During a 6 year period, clover re-established in the sward in P+K treatments and annual yields increased from 0.9 to 2.3 Mg DM ha⁻¹. In N+P+K plots, clover was absent and the total yield ranged from 2.2 in 1985 to 4.1 Mg ha⁻¹ in 1987. Averaged over 6 years, DM yield was significantly ($P < 0.001$) lower in June than in September

Uptakes of N, P and K were all small during June and increased on average three to four-fold in September. In 1987, herbage N in June was equivalent to 25% of that applied compared with 50% in September. Aeration as measured by air volume and air filled porosity was less than 10 per cent on most occasions except when periods of low rainfall occurred during the growing season. However, poor aeration was insufficient to explain the differences in growth between April and June. Over a four year period the mean total N content of the peat in P+K and N+P+K plots appeared to increase at an average rate of 288 kg N ha⁻¹ yr⁻¹ which was partly explained by decomposition of organic matter. It was concluded that a combination of low temperature and poor aeration during spring impaired root uptake which could not then compete effectively with microbial assimilation of N in the peat.

INTRODUCTION

In the north west Highlands of Scotland, peatlands account for up to 21 per cent of the land area (Robertson, 1971) and reseeded to improve grazing has been common practice. Drainage on these areas is infrequent (Younie and Black, 1979) and even when peatland is drained the results are frequently unsatisfactory (Speirs, 1982). Maintenance dressings of lime and fertilizers are not regularly applied (Younie and Black, 1979) and inputs are generally low. Early applications of fertiliser N to upland areas to stimulate grass growth for lambing ewes is recommended (Jarrett, 1986), but this is not common practice on peatland where responses to N can be variable (Rangeley, 1988). The reasons for this are not known, but transformation of the applied N by soil microorganisms is implicated (Rangeley and Knowles, 1988).

An area of blanket bog in the north of Scotland which had been improved in 1982 began to give diminishing responses to spring applications of NH_4NO_3 within 2 years of reseeded, yet growth following N fertilization in summer was visibly greater and more satisfactory. Experimental plots were laid out on the site in 1985 to investigate the poor response to spring applications of N and in this paper the response of herbage to N-fertilizers is presented. The dynamics of the available N at this site have already been reported (Williams and Wheatley, 1992).

MATERIALS AND METHODS

Experimental Site

The experiment was located on a sloping area of blanket peat (average depth 60 cm) at Sletill, Forsinard, Highland Region (Nat. Grid Ref. NC 924 464), 200 m above sea level. Mean daily temperature is 8°C and the average annual rainfall is approx. 850 mm (Meteorological Office, 1987). The original vegetation on the virgin blanket bog included *Trichophorum caespitosum* (L.) Hartm., *Eriophorum vaginatum* (L.), *Molinia caerulea* (L.) Moench and *Sphagnum* spp. In 1982, the vegetation was cut and redistributed using a screw-leveller and the area treated with 1t ha^{-1} ground magnesian limestone, 56 kg ha^{-1} basic slag and 50 kg N ha^{-1} ammonium nitrate. The peat was reseeded with a mixture of timothy (*Phleum pratense* L.), ryegrass (*Lolium perenne* L.), rough and smooth stalked meadow grass (*Poa trivialis* L. and *Poa pratensis* L., respectively) and white clover (*Trifolium repens* L.). At the start of the experiment in spring 1985 the grass sward consisted mainly of smooth and rough stalked meadow grass, with some white clover and pearlwort (*Sagina* spp. L.).

Twelve experimental plots, 2m x 2m, were laid out in an area fenced to exclude grazing animals, mainly sheep, rabbits and deer. The plots were split into two sets of six, one of which was used for destructive sampling of the peat and the other maintained for the measurement of grass yield. Each plot was isolated on three sides from the surrounding buffer strips by inserting polythene sheet to 50 cm depth so that runoff water samples could be collected on the downslope edge (Williams and Young, 1994)

Fertilizer treatments

From 1985 to 1990, plots received two treatments comprising P+K and N+P+K applied in two equal additions in April and in June (Table 1). For 1987, annual rates of P and K were increased to 120 kg element ha⁻¹, and then the original rate restored in 1988. Each set of six plots was treated as a randomized block design and half of them initially received N applications as NH₄NO₃. In 1987, urea replaced NH₄NO₃, because of the activity of denitrifying organisms in the peat (Wheatley and Williams, 1989), and from 1988 to 1990 the annual rate of N addition was reduced to 150 kg N ha⁻¹ applied in two equal dressings, an amount consistent with current management practice. In November 1988, all plots were treated with ground limestone at a rate equivalent to 5 tonnes ha⁻¹.

Fertilizers were broadcast over the plots by hand and the first application was made during the third week of April when the mean daily temperature at 5 cm depth reached 5.5°C. Herbage was cut during the first two weeks in June except in 1988 when the harvest was delayed until the end of the month. The second fertilizer treatment was applied immediately after the first harvest. The second harvest was usually cut during the last week of August and the first week of September. From 1986 onwards a third cut was taken at the end of October.

Table 1. Annual applications of N, P and K (kg ha⁻¹) applied in two dressings to P+K and N+P+K treated plots

		N	Granulated superphosphate	Potassium chloride
1985	NH ₄ NO ₃	250	60	60
1986	NH ₄ NO ₃	250	60	60
1987	Urea	250	120	120
1988	Urea	150	60	60
1989	Urea	150	60	60
1990	Urea	150	60	60

Physical properties

Peat was sampled on 22 dates between April 1985 and January 1988. Sampling points were selected using random coordinates for each plot and cores removed with a cylindrical pvc tube (diam.10 cm, length 30 cm) fitted with a band-saw blade around the bottom edge. Grass was removed from cores prior to transportation to the laboratory. The upper 10 cm of each core was retained and cut into 5cm lengths corresponding to 0 to 5 and 5 to 10 cm depths. The cores were weighed fresh and subsamples dried at 70°C to determine moisture content. The specific gravity of dried peat was measured in ethanol (Segeberg, 1955) and used to calculate the volume of peat solids. Pore volume and then air volumes were calculated by difference and aeration was expressed as air-filled porosity.

The acidity of the peat was determined by measuring pH of a suspension in 0.01M CaCl₂, at a solution:sample ratio of 5:1, after overnight shaking.

Harvesting and chemical analysis

Herbage was cut in June, August and October, except in 1985 when only two harvests were taken. Total analyses of peat cores were carried out on cores taken on 6 sample dates between August 1985 and February 1988. Samples were dried at 70°C to determine moisture content of the peat and dry matter (DM) content of the herbage and then ground for chemical analysis. Total N, P, K, Ca, Mg and Na contents of the grass and peat were measured on duplicate samples by digesting dry ground sub-samples (150 mg) with a 1:1 mixture of conc. H₂SO₄ containing 0.1% (w/v) Se and 30% (v/v) H₂O₂ (Wall *et al.*, 1975). Ammonium-N and orthophosphate in the acid digests were measured using colorimetric methods (Crooke and Simpson, 1971; Murphy and Riley, 1962). Calcium, Mg, K and Na were determined spectrochemically.

Statistical analysis

The two treatments, P+K and N+P+K, were randomised between 3 blocks in each set of 6 plots. Values for DM yields and N, P and K contents of herbage were subject to an analysis of variance for individual harvests (Ryan *et al.*, 1985) and also for June and August harvests combined for all six years (Genstat, 1987). The results of the measurements of pore and air volumes in the cores were analysed by analysis of variance using values from 22 sampling occasions during the period of the experiment (Genstat, 1987). The same procedure was used for the total contents of N, P, K, Ca, Mg and Na in the peat, based on the analyses of cores sampled on six sample dates.

RESULTS

Dry matter yields

Yields of DM in June increased steadily in P+K plots during the 6-year period although the pattern was interrupted by the delayed larger harvest in 1988 (Fig. 1). This steady increase in yield was accompanied by a noticeable improvement in the growth of white clover in P+K plots (results not shown). In the N+P+K treatment, the yield in June improved for the first three years, but in 1988 the amount of N applied as urea was reduced from 112.5 to 75 kg N ha⁻¹ and there was no further increase after 1988. Yields in August showed no trends with time except for a general increase in P+K plots during the last two compared with the first two years.

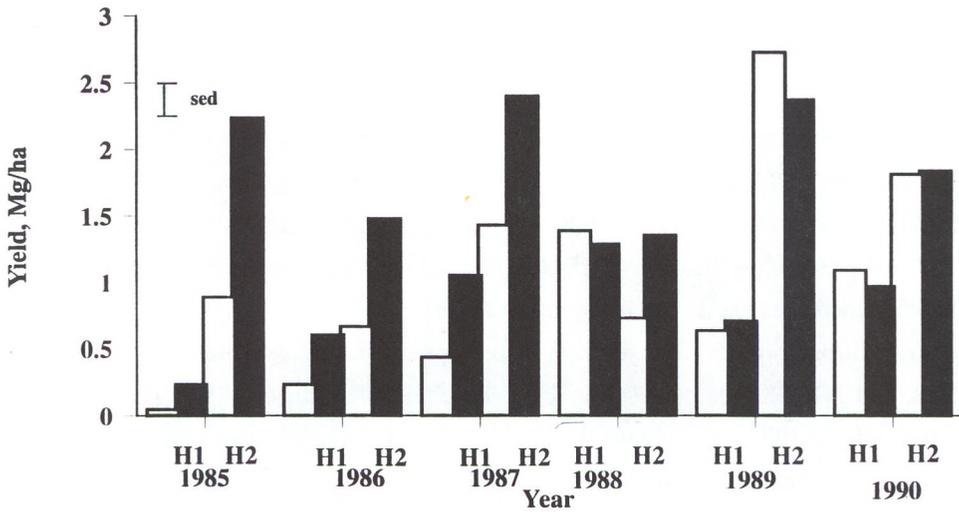


Figure 1 Yields of DM (Mg ha⁻¹) in June (H1) and August (H2) in P+K (•) and N+P+K (n) treatments, respectively, from 1985 to 1990. sed = standard error of difference.

Averaged over all harvests and years, N fertilization increased mean DM yield from 0.7 to 1.1 Mg DM ha⁻¹ ($p < 0.01$), but as the yield in P+K plots increased so the benefit of adding N decreased (Fig. 1). Application of fertilizer-N significantly ($p < 0.05$) increased the yields in June only during the first three years, 1985 - 1987. The yield in August fluctuated between years and was increased significantly by the addition of N only between 1985 and 1987. In 1987, there was also a small, but significant ($p < 0.01$) increase in the DM yield of a third cut during October, from 0.44 to 0.68 Mg DM ha⁻¹ in

response to N addition (not shown). In 1985, the first year, the yield per kg N applied was 1.6 and 12 kg DM kg N⁻¹ for June and August harvests, respectively. In subsequent years, growth of white clover in P+K, but not N+P+K plots, accounted for approximately 30 per cent of the area and DM production and exceeded the dry matter yield of the sward with added N. Hence, measures of fertilizer N efficiency became invalid because of the potential for N fixation by clover.

The yield was consistently greater ($p < 0.001$) in August than that in June when the first cuts were equivalent to less than 1.5 t DM ha⁻¹. When the first harvest was delayed for two weeks until the end of June in 1988 the difference between the two harvests was not evident (Fig. 1).

Nutrient content of herbage

Concentrations of N in the P+K treated herbage in June averaged 22.4 g N kg⁻¹ DM and did not vary greatly during the first 3 years. In August, values were lower than in June and increased by 35% from 15.6 in 1985 to 21.1 g N kg⁻¹ DM in 1987. Fertilizer-N significantly ($p < 0.05$) increased N concentration of herbage in June 1986 from 20.2 to 25.6 g kg⁻¹ DM, but by 1987 P+K and N+P+K values were similar at 24 and 27 g N kg⁻¹ DM, respectively. In August, herbage-N was significantly ($P < 0.01$) increased from 15.6 to 27.3 g N kg⁻¹ DM by NH₄NO₃ in 1985, but thereafter values for P+K treated herbage increased and N had no significant effect.

Nitrogen removed in herbage in June progressively increased each year in both P+K and N+P+K treatments (Fig. 2). The effect of fertilizer-N was significant ($P < 0.01$) only in 1987. Each year, the August harvest removed more N than that in June, though fertilizer N had no significant effect on the amounts at the second cut. The fertilizer-N recovery in 1985 was calculated from:

$$\frac{(N+P+K \text{ Herbage-N} - P+K \text{ Herbage-N}) \times 100}{\text{Fertilizer-N}}$$

and some 5.5 and 37.3% of fertilizer-N were removed in June and August, respectively. Amounts of herbage-N totalled for each cut over 3 years (Table 2) were again greater in August than in June, but whereas the first cut showed no response to fertilizer-N, the second was significantly ($p < 0.05$) increased.

Table 2. Removal (kg ha^{-1}) of N, P and K during (April-June) and (June to August) accumulated over 3 years on reseeded blanket bog treated with P+K and N+P+K. Total fertilizer additions (kg ha^{-1}) in parentheses

FERTILIZER		APRIL - JUNE			JUNE - AUGUST		
		P+K	N+P+K	se	P+K	N+P+K	se
NITROGEN	(675)	29	38	7.3	77	140	5.0
PHOSPHORUS	(240)	5	6	1.2	14	20	1.8
POTASSIUM	(240)	17	21	4.2	50	72	8.7

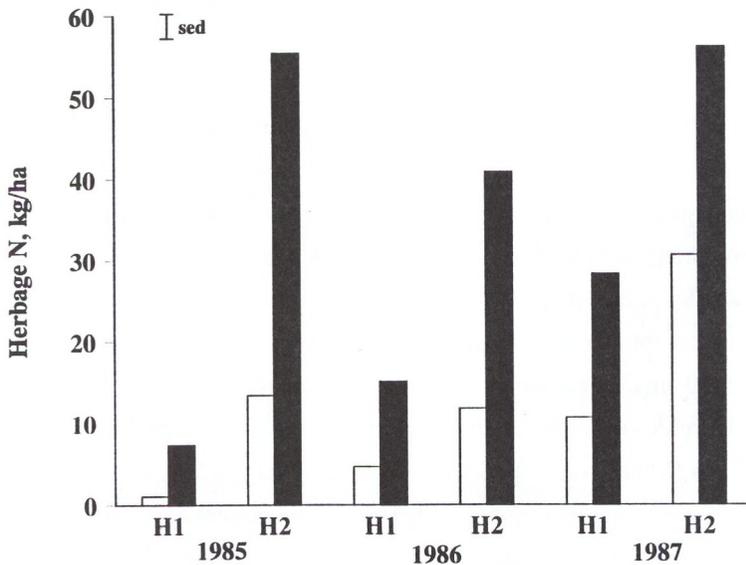


Figure 2 Nitrogen (kg ha^{-1}) removed in herbage during the first three years, 1985 - 1987, in June and August (H1, H2) from P+ K (•) and N+P+K (n) treatments. sed = standard error of difference.

Concentrations of P and K in herbage showed small variations between harvests and years. Phosphorus ranged from 2.6 to 4.8 g P kg^{-1} DM and was significantly ($p < 0.01$) increased by N fertilizer in June of the first year only, from 2.6 to 3.5 g P kg^{-1} DM. The total amounts of P removed in herbage in June over the 3 years (Table 2) was only 5 % of that added in both P+K and N+P+K plots. Greater amounts of P were removed in August, equivalent to between 11 and 16% of that added.

Potassium concentrations in herbage ranged from 13 to 16.6 g K kg⁻¹ DM in June and 11.9 to 15.0 in August without showing any increase with the amounts of either KCl or N fertilizer added. The amounts of K removed in herbage were greater in August than in June, corresponding to almost 60% of fertilizer K in the N+P+K plots.

Nutrient content of peat

The mean total quantity of N in the surface 10 cm of peat was 2.3 Mg ha⁻¹ (Table 3) at the start of the experiment and the amounts were similar at both 0-5 and 5-10 cm depth. Values increased between sample dates and increased during the 4-year period 1985 to 1988 (Table 3). Total N as per cent of dry matter increased and averaged over P+K and N+P+K plots at both depths there was a significant ($p < 0.01$) linear correlation between time and the mean total N%;

$$N\% = 1.79 + 0.0184 * \text{month} \quad (R^2 = 0.866)$$

There was no significant difference in the slope of the regression between either depth in the peat or treatment with N. The rate of increase in N% was equivalent to a mean annual increase of 288 kg N ha⁻¹ yr⁻¹.

For P, the total contents were significantly ($p < 0.001$) greater in the surface 5 cms than at 5-10 cms. There were no significant changes with either N treatment or time despite regular additions of P fertilizers and values in the surface 5 cm remained in the range 63 to 88 kg P ha⁻¹ compared with 35 to 58 kg ha⁻¹ at 5-10 cms depth. The total K contents of the peat were also significantly ($p < 0.001$) greater at 0-5 than 5-10 cms depth and steadily increased in the upper layer with time from 36 to 113 kg K ha⁻¹, reflecting the regular applications of K as fertilizer.

The total contents of both Ca and Mg were significantly ($p < 0.01$) greater in the surface 5 cm than at 5-10 cm depth and while Ca levels showed no consistent trend Mg increased at both depths during the 3-year period (Table 3). Sodium contents showed a small increase with applications of N in the surface 5cm and with time (Table 3).

Aeration and pH

The overall mean pore volume was 906 cm³ dm⁻³ (standard error of the mean (s.e.) = 1.9, n = 132) and values for 0 to 5 and 5 to 10 cm depth were not significantly different. Pore volume was very similar throughout and only showed changes with time for sample dates where some drying and shrinkage of the peat had occurred. The

Table 3. Total contents(kg ha⁻¹) of N, P, K, Ca, Mg and Na in the peat from P+K and N+P+K plots at two depths, 0-5 and 5-10 cm depth, sampled in May 1985 and in July 1988. Sed = standard error of difference.

	1985		1988		
	P+K	N+P+K	P +K	N+P+K	sed
NITROGEN					
0-5cm	984	1074	1473	1345	106.7
5-10cm	1275	1419	1681	1405	
PHOSPHORUS					
0-5 cm	64	62	74	74	5.6
5-10 cm	57	60	47	45	
POTASSIUM					
0-5 cm	47	25	106	121	8.7
5-10 cm	36	31	51	39	
CALCIUM					
0-5 cm	375	374	432	441	47.3
5-10 cm	184	356	282	356	
MAGNESIUM					
0-5 cm	73	86	146	156	12.9
5-10 cm	55	81	115	133	
SODIUM					
0-5 cm	20	27	50	54	3.1
5-10 cm	25	22	35	32	

mean bulk density was 133.1 g dry matter dm⁻³ (s.e. = 2.69, n = 132) and was unchanged by application of N fertilizer and was similar at both depths. There were fluctuations between sample dates, but no overall trend. Peat cores taken at different dates differed in the mass of dry matter per unit volume with greater values occurring during spring and summer when moisture content was lower and some shrinkage had occurred. Water occupied more than 90 per cent of the pore volume on the majority of sampling dates particularly at 5 to 10 cm depth. Hence, air volume was significantly ($p < 0.001$) greater at 0-5 than at 5-10 cm depth (Table 3) and fluctuated between sample dates depending on rainfall (Fig. 3). Increases in air-filled porosity followed low values in the mean monthly rainfall and the highest air volume recorded occurred after a period of low rainfall during June 1986. In general, aeration in the surface peat was poor and air filled porosity averaged only 11.8 per cent (s.e.= 0.27) in the surface 0-5 cm layer. There were no consistent differences in aeration between April and June during 1985 and 1987 that would account for the improved responses to the second application of N.

colder but drier podzols and brown earths in north-east Scotland, yielded 4.7 and 5.8 Mg DM ha⁻¹, respectively (Riley and Macleod, 1980). The very small yield and response of 1.6 kg DM kg N⁻¹ to fertilizer applied in April is comparable with those reported for brown earth and peaty gley soils in upland conditions (Davies and Munro, 1974). These poor yields during spring appear to be associated with the wetter areas of Britain and Munro and Davies (1974) reported little benefit from applying fertilizer N to increase early spring growth above that achieved by mixed swards containing clover. The reasons for the poor response to N applied in April are not clear though the wet conditions and poor aeration prevailing in the peat probably affect root growth and uptake (Boggie, 1968). Criteria for the timing of N application based on the temperature in the peat and on the accumulated temperature value of 200°C from 1 January had been satisfied, but these may not be applicable to very wet soils. Rangeley and Knowles (1988) reported on microbial processes in peaty soils such as denitrification and immobilization which could compete with plant roots for available N.

Previous studies (Williams and Wheatley, 1989) have shown that reseeded had reduced the pore volume and increased bulk density compared with that of the unimproved blanket bog. However, the changes were small and the occupation of more than 90 per cent of the pore volume in the peat by water on most occasions would suggest that aeration is probably limiting. There were no consistent differences in aeration between April and June to indicate that this was solely responsible for the poor uptake of N, P and K in the first cut of herbage. Monthly rainfall distribution in the area is evenly distributed across the growing seasons (Meteorological Office, 1988) and the improved growth between June and August was not necessarily accompanied by improved aeration. Temperature probably has an important influence and, in spring, growth and uptake may be limited by a combination of high moisture and low temperatures.

The apparent increase in total N concentration and N content in the peat was equivalent to an input to the surface 10 cm of approximately 288 kg N ha⁻¹ yr⁻¹. Known inputs to P+K plots at this site included 5 kg N ha⁻¹ yr⁻¹ in wet deposition (Williams and Young, 1994) and unknown amounts as dry deposition and biological N fixation by clover. Heil *et al.* (1988) reported that dry deposition was relatively small in cut swards whereas biological N fixation can account for as much as 130 kg N ha⁻¹ annually on improved deep peats (Newbould, 1982). Net gains of 70 - 80 kg N ha⁻¹ yr⁻¹ were reported for improved blanket bog in the Western Isles of Scotland and ascribed to biological N fixation (Williams *et al.*, 1985). Assuming comparable rates of N fixation at

the present site still leaves $\sim 200 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ unaccounted for on P+K plots. An apparent increase in total N content could arise from the decomposition and loss of carbonaceous organic matter as CO_2 (Damman, 1988). From the regression (Equation 1) the mean annual increase in N concentration was 0.22 per cent which could be achieved by a decomposition loss of $10.5 \text{ g organic matter } 100 \text{ g}^{-1}$ or approximately $0.3 \text{ mg g}^{-1} \text{ day}^{-1}$. This maximum value compares with rates of decomposition of mixed litter in montane grassland on mineral soils of $1.3 \text{ mg g}^{-1} \text{ day}^{-1}$ during the winter (Perkins *et al.*, 1978). The increased decomposition is consistent with liming having a stimulating effect on microbial activity which was greater in the reseed than in adjacent unimproved blanket bog (Williams and Wheatley, 1989). Under these conditions assimilation and immobilization of N by microorganisms would be greater, resulting in increased competition for available N between plant roots and microbial populations.

Total P contents in the peat did not increase significantly despite regular applications of superphosphate confirming that the capacity of peats to retain P is small compared to mineral soils (Cuttle, 1983). Losses of inorganic P in runoff at the site were small and increased by the addition of N (Williams and Young, 1994) so that if P is lost it is removed in some other form or else by another pathway. From the amounts removed in herbage it is evident that K must be applied at the same time as N, and that grass growth cannot be sustained on this peat without additions of K. The application of N did not cause changes in pH in the peat, but the gradual fall in pH indicated acidification in both P+K and N+P+K treatments. Williams and Young (1994) reported that the pH of runoff waters was greater than that of the incoming rain at this site and the decline in pH in the peat probably reflects this buffering effect.

CONCLUSION

The poor usage of fertilizer N by the sown species on this poorly drained blanket bog was not the result of low temperature alone as first harvests on colder mineral soils can be greater. The poor aeration in the peat prevailed for most of the year except during periods of low rainfall in the growing season yet the growth response of herbage to N applied during June was initially much greater than to that added in April. Hence, impaired root uptake caused by a combination of waterlogging and low temperatures is probably to blame for poor yields during spring. In addition, the peat appeared to accumulate N which could have been the result of organic matter decomposition stimulated by liming. Increased microbial activity in the peat would result in greater competition for nitrogen between plant uptake and microorganisms. Phosphorus and Ca

contents in the peat showed no increases with time despite regular additions whereas K, Mg and Na increased.

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