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265

SUBSIDENCE OF LOW MOOR PEAT SOILS IN THE WESTERN NETHERLANDS

C.J. SCHOTHORST

Institute for Land and Water Management Research, Wageningen (The Netherlands)

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ABSTRACT

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Three experimental fields were laid out to study the effects of deeper drainage on the processes of subsidence. It was found that 6 years after ditchwater levels had been lowered, surfaces had subsided 6—10 cm. Of this subsidence, 65% could be ascribed to shrinkage and oxidation of organic matter in the layer above the groundwater level and 35% to compression of the layer below groundwater level. Compression accounted for 1—4 cm of subsidence after 6 years. Because the deep peat is affected only very slightly by deeper drainage, it may be assumed that compression of it caused little or no subsidence over the past 1000 years in areas with high groundwater levels.

By comparing the bulk density of organic matter in the layers above and below groundwater level, it was found that about 0.30 m, or approximately 15% of the total subsidence of 2 m in the past 1000 years, could be ascribed to shrinkage of the upper layer. This leaves 85% to be ascribed to the oxidation of organic matter. If it is assumed that higher contents in mineral elements in the upper layer result from oxidation of organic matter, the rate of oxidation can be calculated by comparing the bulk density of mineral elements in the layers above and below groundwater level. In this way oxidation of 1.75 m was estimated which would explain surface subsidence of about 1.75 mm per year.

This theory is supported by the fact that organic soils supply more nitrogen to the crop than mineral soils. At deeper drainage of organic soils this additional N-supply increases considerably.

The additional N-supply is calculated from the N-content of the dry matter yield of grass of the experimental fields. The loss of organic matter can be calculated from the additional N-supply, taking the N-supply of mineral soils as a reference level. According to this calculation, the annual losses of organic matter per hectare are 4 tons in shallowly drained and 12 tons in more deeply drained (0.5 m more) peat soils.

With a bulk density of organic matter of the toplayer of 0.2 g cm^{-3}, the rate of loss of organic matter is 2 mm per year at shallow drainage and it increases to 6 mm per year after 0.5 m deeper drainage. These rates of 2 and 6 mm per year are in good agreement with the soil losses above groundwater level measured by means of disks placed at various depths in the profile, some years after drawdown of the ditchwater levels.

In this manner a plausible explanation can be given for the surface subsidence of the low moor peat soils in the western Netherlands.

INTRODUCTION

The process of subsidence has been studied in an investigation of the optimal depth of drainage in low moor peat soils under grass in the polders of the western Netherlands.

The traditional system of shallow drainage by means of ditches with an open water level at 0.20 to 0.50 m depth seriously impedes the intensification and mechanization required for modern livestock farming because of the insufficient bearing capacity of the sod layer of grassland. The bearing capacity can be improved by deeper drainage (Schothorst, 1965, 1974).

Some Netherlands' investigators fear this would increase the rate of subsidence and might cause lower gross yields of grass resulting from irreversible desiccation of the root zone of soil profiles (Hudig and Duyverman, 1950; Hooghoudt et al., 1960). In contrast, German investigators do not share the fear of excessive drying (Baden, 1963).

The general opinion in The Netherlands is that subsidence of peat soils permanently under grass occurs mainly through decreasing volume by shrinkage above groundwater level and by compression below (Bennema et al., 1953). In peat soils under grass with shallow drainage oxidation of organic matter was regarded to be not important, though it has been observed after very deep drainage (Schothorst, 1967). Many studies outside The Netherlands have ascribed subsidence of peat soils largely to oxidation of organic matter (Neller, 1944; Skoropanow, 1961; Van der Molen and Smits, 1962; Baden, 1963; Okruszko, 1969; Stephens and Speir, 1969). The rate of oxidation depends on many factors, including climate, cultivation, chemical and physical composition. In subtropical areas cultivation of peat land can lead to an oxidation rate of 10 cm per year (Levin and Shoham, 1972).

Another cause for concern over the effects of deeper drainage is subsidence of old farm buildings, bridges and of other structures with consequent severe damage.

Before applying deeper drainage to low moor peat soils in the old polders, more information was needed on the probable effects. For this purpose, three experimental fields with drainage ditches at different depths were laid out in 1969. Relations between depth of ditch- and groundwater level, moisture and air content in spring and summer, bearing capacity, grass production and the process of subsidence were studied during the investigation. In this paper only the process of subsidence will be considered and a possible explanation given.

HISTORY OF SUBSIDENCE

The low moor peat soils in the old polders of the western Netherlands were reclaimed in a period between the 9th and 14th centuries. Under the influence of drainage and agriculture, the peat began to subside. Initially, the elevation of the soil (peat) surface must have been equal to or somewhat above mean sea level (Bennema, 1954). At low tides excess water could then be discharged by means of sluices into the sea or into rivers. This system of gravitational discharge was possible until the beginning of the 16th century, when the surface had subsided to such an extent that excess water had to be discharged artificially by means of windmills. This continued until about 1870, when steam pumps began to replace windmills. Although throughout the centuries only shallow drainage was applied, the soil surface nevertheless subsided to about 1—2 m below sea level over a period of 8—10 centuries.

Because of the low elevations of these peat soils, they now are mainly used as pasture. At present the water level in the ditches generally is maintained 0.20 to 0.50 m below surface.

After steam-pumping stations began controlling water levels in winter about a century ago the process of subsidence was accelerated (Duyverman, 1948). Details of this process can be followed from the records kept of the polder Zegvelderbroek situated west of Utrecht. The present soil profile in this polder consists of 7 m of eutrophic wood-sedge peat. In 1873 a steam-pumping station was constructed and began operations. At that time the polder water level was 1.60 and the land surface 1.50 m below mean sea level. Since that time, according to available records, the water level has been lowered repeatedly. Subsidence of the soil surface ensued, as shown in Table I.

In the period of 1877—1965, the polder water level was lowered by 0.5 m. During the same period the surface subsided an equal amount. The rate of subsidence was 6 mm per year in spite of the very shallow drainage, only 0.10—0.20 m below the surface.

Before drainage in winter was made possible by a steam-pumping station, the total subsidence in the past amounted to at least 1.50 m, assuming that the initial elevation was equal to or somewhat above sea level. According to historical sources (Van Doorn, 1942; Van der Linden, 1956) the polder Zeg-

TABLE I

Elevations of peat surface and ditchwater level during the past century in the polder Zegvelderbroek, with mean sea level as reference point

	Elevation below mean sea level (m — O.D.) *		
	soil surface	ditchwater level	
1877	−1.50	−1.60	lowered to: −1.68
1907		−1.68	−1.71
1925		−1.86	−1.94
1943	−1.80	−1.94	1 cm per 2 years
1965	−2.05	−2.10	−2.35
1969 **	−2.10	−2.35	−2.85
1975 **	−2.20	−2.85	

* O.D. = Ordnance Datum.
** concerns experimental fields for drainage.

TABLE II

Elevation of soil surface (m — mean sea level) of an experimental field in Zegvelderbroek in the period 1952 through 1973

Month	May	Sept.	Mar.	Jan.	Mar.	Mar.	Apr.	Oct.	Apr.
Year	1952	1954	1955	1956	1960	1962	1967	1970	1973
Elevation	−1.88	−1.98	−1.98	−2.01	−2.01	−2.04	−2.02	−2.08	−2.11

velderbroek was reclaimed round 1000 A.D. The subsidence during the subsequent 9 centuries thus amounted to 1.7 mm per year. After water control in winter was introduced, the subsidence accelerated from 1.7 to 6 mm per year. It obviously was necessary to continue to lower the water table to keep it below the continuously subsiding land surface.

More detailed data have been obtained from an experimental field (Hooghoudt, 1950) laid out in 1952 for water control in the polder Zegvelderbroek. By means of an intensive system of tile drains with a spacing of 5 m, groundwater levels ranging from 0.30 to 0.70 m below the surface were maintained. After the experiment was completed in 1962, the average water level in ditches was 2.60 m below mean sea level (O.D.). The ditchwater level before 1952 was 2.20 m — O.D. or 0.30 m below the surface.

The 0.40 m drawdown of the ditchwater level over a period of 20 years resulted in a total surface subsidence of 23 cm (see Table II). The data in Table II represent the mean values of 200 measurements made over the experimental field.

In the first two years the subsidence proceeded very rapidly, constituting 44% of the total for the 20-year period. Subsequently, the subsidence rate decreased to a constant 7 mm per year, which is, according to Table I, approximately equal to the subsidence of the entire polder.

The subsidence mainly seems to be caused by changes in the top layer, the one above groundwater level. This could follow from the elevation of the tile drains, which were placed on wooden laths to prevent their subsidence when they were installed in 1952. Initially the depth of the tiles was 0.80 m below the surface (2.70 m — O.D.) and this had decreased to 0.60 m in 1973. The elevation of the tiles with regard to the reference level (O.D.) remained the same.

It can therefore be concluded provisionally that the surface of the polder Zegvelderbroek subsided about 1.7 mm per year before water control was applied in winter. Afterwards, the subsidence increased to 6 to 7 mm per year (in the last century) in spite of high water levels in the ditches.

DESCRIPTIONS OF THE EXPERIMENTAL FIELDS

The experimental fields are located in the polder Zegvelderbroek, west of the town of Utrecht, in the polder Hoenkoop (Lopikerwaard) and in the pol-

TABLE III

Organic matter content (weight percentage) by tiers of the peat profiles of the experimental fields

	Depth (cm — surface): 0—10	10—20	20—30	30—40	40—50	50—60	60—70	70—80	80—90	90—100
Zegvelderbroek	52	59	74	78	81	84	83	84	82	81
Bleskensgraaf	37	29	31	57	81	85	84	84	84	87
Hoenkoop	34	24	19	27	53	70	70	71	77	76

der Bleskensgraaf (Alblasserwaard). Their total area is 120 ha.

The soil profile consists of eutrophic wood-sedge peat (*Carex* and *Alnus*) with a thickness of 5 to 8 m. According to the American classification system (Soil Survey Staff, SCS, 1975), the peats are in the great group of Medihemists and order of Histosols. The organic matter content in the 0—0.30 m surface layer roughly ranges from 20 to 35% in the Hoenkoop and Bleskensgraaf fields and from 50 to 70% in the Zegvelderbroek field, as shown in Table III. The top layers of the first two fields have received fluvial sediments from rivers. With a marked change from the clayey top layer to pure peat, the organic matter content gradually increases to 80—85% at a depth of 0.80 m below the surface as the degree of decomposition decreases. The peat profile of Zegvelderbroek is homogeneous to the sand 7 m below the surface in contrast to the Hoenkoop and Bleskensgraaf fields. Here, clayey layers of various thicknesses and composition due to fluvial action appear in the peat profile at depth.

The deep groundwater flow consists of a negative subsurface inflow in the polder Zegvelderbroek and a positive inflow in the polders of Bleskensgraaf and Hoenkoop.

METHOD OF INVESTIGATION

The experimental fields were laid out within existing farms with ditch spacings from 30 to 60 m.

To study the effects of differing water levels on subsidence each of the Bleskensgraaf and Hoenkoop fields was divided into five parts. In three parts the water levels were maintained at depths of 0.40, 0.70 and 1.00 m below the surface, respectively. In two parts the water levels in the ditches did rise from 0.70 and from 1.00 m to 0.40 m below the surface in the period from May to August when evaporation exceeded precipitation. That is possible by supplying water from adjacent high water ditches. The Zegvelderbroek field was divided into four parts. Water levels were maintained within 0.25 m of the surface in two parts and 0.75 m below the surface in the other two parts.

Surface elevations were measured three times per year (spring, summer and autumn) at 50 fixed points in each of 22 parcels. These were compared to reference levels established by iron tubes 10 m in length inserted through the peat and clay layers into the sand bottom below. In addition, metal disks were placed in an undisturbed peat profile at vertical intervals of 0.20 m at depths ranging from 0.20 to 1.40 m below the surface. Elevations of these disks were then recorded periodically to measure the subsidence of the various tiers within profiles.

By 1972, it had been found that placement of disks within profiles provided a satisfactory method for measuring subsidence of individual tiers. Moreover, it had also been noted that subsidence occurred even if water tables were maintained near the peat surface. Disks were therefore installed in three of the test plots with high water levels.

Depth to groundwater was continuously registered in 16 test plots by recorders.

Entire peat profiles were sampled to determine bulk density, moisture content, and organic matter content. Samples were also taken in the spring and in dry summer periods down to groundwater levels to determine moisture withdrawal.

The gross yield of dry matter of grass was determined in duplicate on 20 test plots so as to cover the different depths of drains and three levels of nitrogen fertilization, namely 0, 150 and 300 kg of N/ha. Because of indications that drainage to greater depths affected nitrogen utilization by plants, the dry matter of the harvested grass was analyzed for nitrogen in 1973 and 1974. Thus, the nitrogen uptake from the peat and the yield of protein could be calculated.

RESULTS

Surface subsidence in relation to ditchwater and groundwater levels

Mainly depending on precipitation in winter and evaporation in summer, the groundwater level fluctuates as compared to ditchwater level (see Fig. 1). In dry summer periods, the groundwater subsides to a maximum depth of about 0.70 m below the surface at high and to 1.00 m below the surface at low ditchwater levels. Even if ditchwater levels are kept as high as 0.20—0.40 m from the surface in dry summers, the groundwater level drops 0.30—0.50 m below ditchwater level.

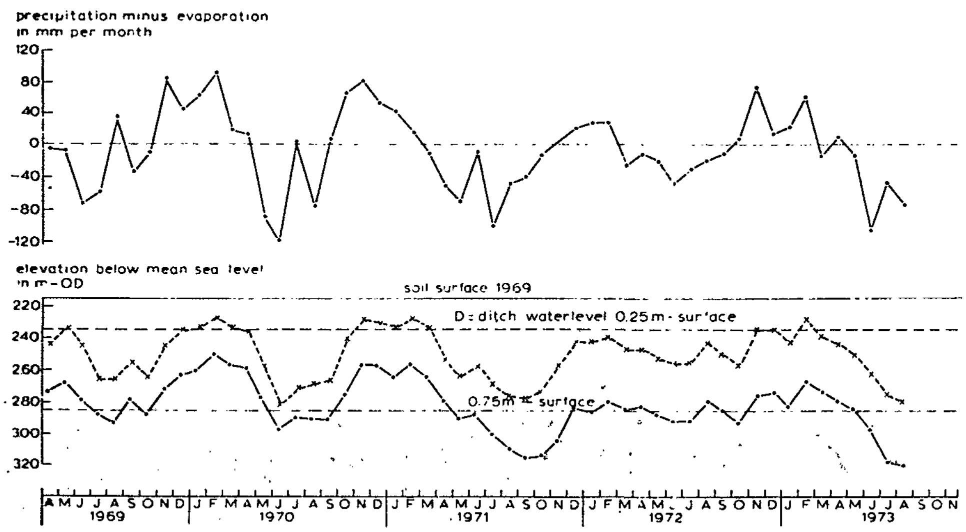

Fig. 1. Precipitation surplus and groundwater levels at ditchwater levels of 0.25 m and 0.75 m below the surface in the period 1969 through 1973 in the Zegvelderbroek field.

The infiltration from the ditches is insufficient to replenish the moisture withdrawn from the soil profile in spite of the high permeability of the peat. This is a general phenomenon in peat areas (Sonneveld, 1954). Due to permanently high ditchwater levels and trampling of the ditch slope by drinking cattle, a strip about 3 m wide along each ditch has a low permeability of 0.05—0.15 m/24 h. At greater distances from ditches, the permeability increases to values of 3—4 m/24 h because of many fissures in the peat above groundwater levels. These fissures are lacking close to the ditch because the soil remains permanently wet, except for the root zone (0—0.20 m beneath surface). This is the so-called "ditch bank effect".

In winter the groundwater level fluctuates from 0.15 m at shallow to 0.40 m below surface at 0.5 m deeper drainage. A permanent drawdown of the ditchwater level results in a lower mean groundwater level both in winter and in summer.

The lowering of the mean groundwater level amounts to roughly 50% of the drawdown of the ditchwater level. With the fluctuation of the groundwater level the surface elevation of the peat also fluctuates (see Fig. 2). The same was found earlier in German experiments (Eggelsmann, 1960). The sur-

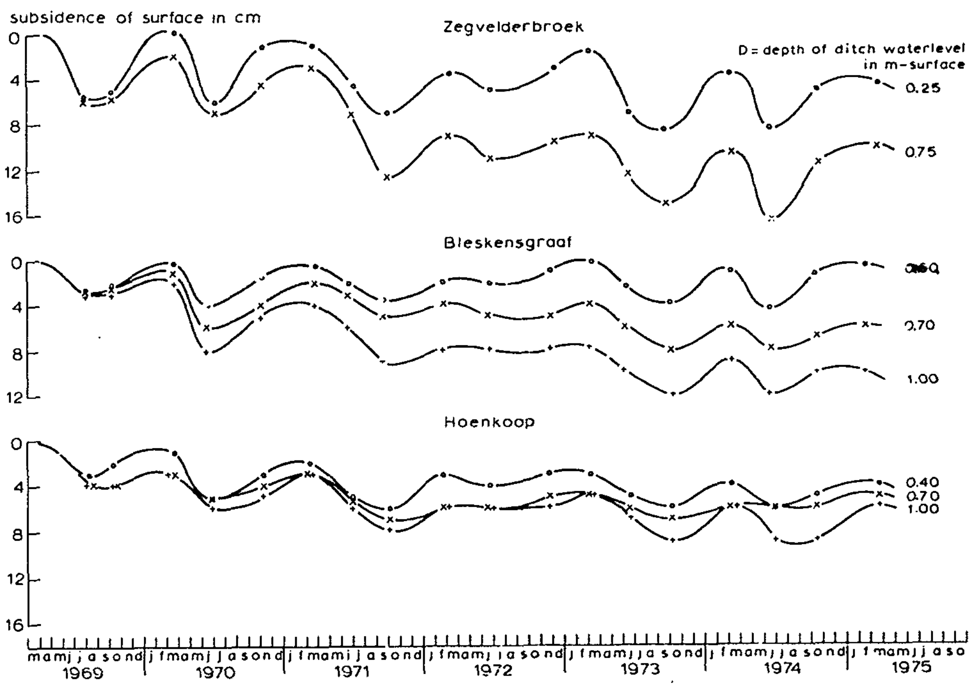

Fig. 2. Subsidence of the soil surface in the period 1969 through 1975 in the experimental fields of Zegvelderbroek, Bleskensgraaf and Hoenkoop at different depths of ditchwater levels.

TABLE IV

Surface subsidence at different ditchwater levels from the spring of 1969 to the spring of 1975

Exper. field	Zegvelderbroek:						
Parcel nr.	13	8	3	16	19	20a	20b
Depth of ditchwater level (m — surface)	0.20	0.30	0.70	0.80	0.80	0.80	0.50
Subsidence (m)	0.05	0.04	0.10	0.10	0.11	0.09	0.05

Exper. field	Bleskensgraaf:					
Parcel nr.	I	II	III	IV	V	VI
Depth of ditchwater level (m — surface)	1.00	1.00/0.35	0.70	0.70/0.40	0.35	0.35
Subsidence (m)	0.09	0.06	0.06	0.01	0.01	0.01

Exper. field	Hoenkoop:									
Parcel nr.	A_o	A_w	B_o	B_w	C_o	C_w	D_o	D_w	E_o	E_w
Depth of ditchwater level (m — surface)	0.70	0.70	1.00	1.00	0.70/0.40		1.00/0.40		0.50	0.40
Subsidence (m)	0.05	0.05	0.06	0.06	−0.02		0.02	0.02	0.03	0.04

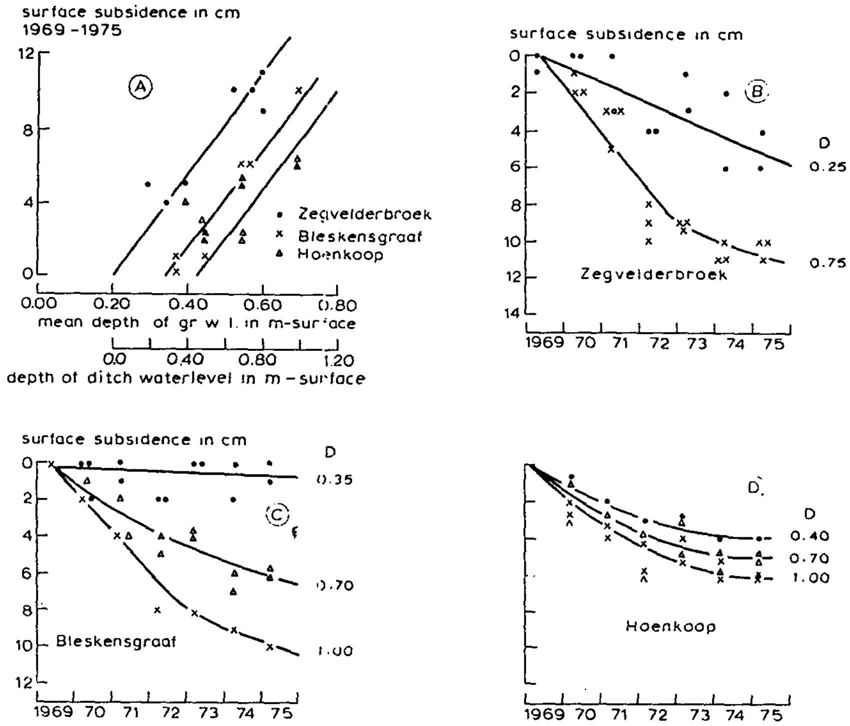

Fig. 3. Surface subsidence (cm): A. as a function of the depth of ditch- and of groundwater level; B. as a function of time at different depths of ditchwater levels in the Zegvelderbroek field; C. as B in the Bleskensgraaf field; D. as B in the Hoenkoop field.

face subsides only in dry periods of summer, at deep groundwater levels, apparently due to shrinkage. The extent of subsidence is mainly determined by the amount of evaporation. Deeper drainage causes somewhat more subsidence. Depending on the organic matter content of the 0—0.30 m surface layer, the surface subsidence may range from 0 to 2 cm in a wet summer (1972) to 4 to 8 cm in a dry one (1973). In winter at high groundwater levels the peat swells and the surface rises. The extent of the swelling is determined by the amount of precipitation in winter. With deeper drainage there is less swelling. The resulting surface subsidence after 6 years is given in Table IV, which gives mean values of 18 measurements of surface elevation at distances of 7 to 13 m from the ditches. Fig. 3A shows the subsidence as a function of the depth of the ditchwater and groundwater levels. The mean depth of groundwater level is correlated with depth of ditchwater level as given along the abscissa of Fig. 3A.

In Figs. 3B, C and D the surface subsidence is given as a function of time, namely from spring to spring eliminating the reversible subsidence during the summer period. The subsidence occurred more rapidly during the initial years as could be expected. After the end of 3 years (1972), the subsidence seemed to decrease. There also seemed to be subsidence at permanently high ditchwater levels of 0.20—0.30 m below the surface in Zegvelderbroek. This subsidence amounted to 4—5 cm in 6 years or 7,5 mm per year, agreeing with subsidence over the past century as given in Tables I and II.

In Bleskensgraaf the surface scarcely subsided at high water levels, whereas in Hoenkoop a low rate of subsidence was found. At the same depth of ditchwater level the peat soil of Zegvelderbroek, with an organic matter content of 50—75% in the 0—0.30 m layer (Table III) is more susceptible to subsidence than the peat of the other two polders. At a drawdown of the ditchwater level from 0.25 m to 0.75 m from the surface the subsidence increased from 4 cm to 10 cm in 6 years. In Bleskensgraaf and Hoenkoop polders, the surface subsided 10 cm and 6 cm, respectively, with the ditchwater level 1 m below the surface.

Components of subsidence

Subsidence consists of the following components.

(1) Shrinkage due to physical processes. The withdrawal of moisture from the surface layers by evapotranspiration may cause high moisture tensions in the root zone resulting in a decrease in volume of those layers (above the phreatic surface).

(2) Oxidation of organic matter through biochemical processes. The entry of air into the soil seems to cause increased activity of micro-organisms which consume organic matter.

(3) Compression due to a mechanical process. When the groundwater level is lowered, the buoyant force of water is lost in the upper layers. The deeper layers then have to bear an increased weight of 1 g cm^{-2} per cm of drawdown of the groundwater level. This will cause compression of the soil layers below the phreatic surface.

To get more insight into the processes of subsidence, disks were inserted into some peat profiles, as mentioned previously. By this method the course of subsidence of individual tiers could be measured, given in Fig. 4.

From the difference in subsidence of the top and bottom of a tier the volume change of the layer can be calculated (see Table V). This table gives an example of the changes in tiers with the seasons. The reswelling in 1971—1972 was limited because of a dry winter. In spite of the limited reswelling, the root zone (0—0.20 m) of the profile still shows the largest reversible shrinkage.

A rise of the tiers below groundwater level (1.00 m — surface) is observed in winter. Apparently the soil below groundwater level is soft and buoyant enough to act as a sponge when the groundwater level rises and the load decreases. This phenomenon is known in soil mechanics from "elastic" solids (Terzaghi, 1956). A further indication of the soft character of the deeper peat appears in subsidence of the initial surface near farm buildings after it is covered with 1 m of sand. The total subsidence of the original surface amounted to roughly 0.75 m.

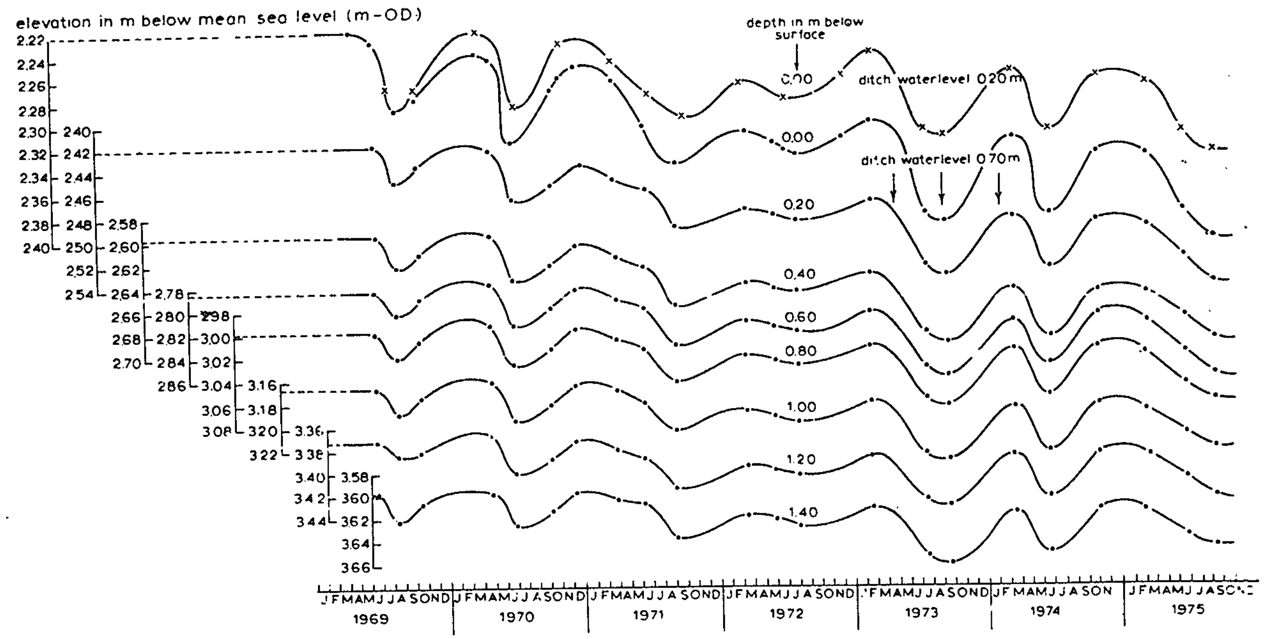

Fig. 4. Elevation changes in profile tiers in the experimental field Zegvelderbroek at a depth of ditchwater level 0.70 m below the sur-face in the period from 1969 through 1975, and the subsidence of soil surface at depth of ditchwater level 0.20 m.

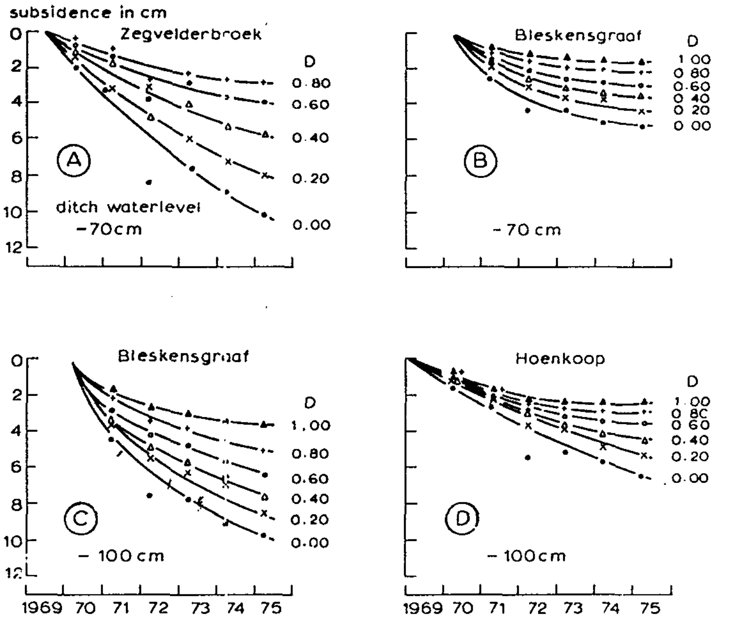

Fig. 5. Subsidence of profile tiers (depth D in m — surface): A. at a depth of 0.70 m — surface in Zegvelderbroek; B. at 0.70 m in Bleskensgraaf; C. at 1.00 m in Bleskensgraaf; D. at 1.00 in Hoenkoop.

drainage with 0.5 m shows a low rate of some centimetres can be explained by a low increased rate of the pressure on the subsoil below groundwater level.

As previously mentioned the lowering of the mean groundwater level amounts to about 50% of that of the ditchwater level. The pressure on the subsoil below groundwater increases by 1 g cm^{-2} per 1 cm groundwater level

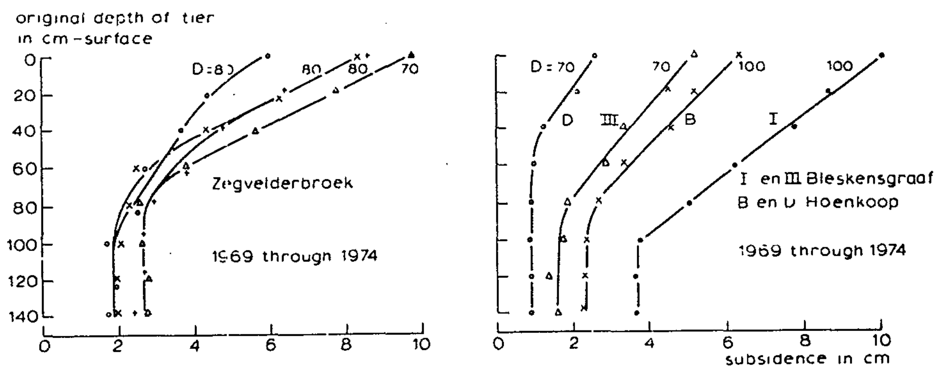

Fig. 6. Subsidence of profile tiers after 6 years of lowered ditchwater levels as a function of the original depth of tier below surface. D = depth of ditchwater level in cm.

TABLE VI

Decrease in thickness of the profile tiers, total shrinkage including oxidation of organic matter (S_{sh}), total compression (S_c) and total surface (S) in the period spring 1969 through spring 1975 in mm; between brackets the figures for 1973—1974 are given

Depth in m — surface	Zegvelderbroek				Bleskensgraaf		Hoenkoop	
	20b	20a	3	16	III	I	D	B
0—0.20	16(3)	21(0)	20(3)	22(1)	7(0)	13(2)	5(1)	11(2)
0.20—0.40	8(2)	20(2)	21(2)	16(2)	9(3)	12(3)	9(5)	9(2)
0.40—0.60	8(2)	18(4)	19(7)	11(5)	8(2)	13(2)	2(0)	10(3)
0.60—0.80	6(2)	3(3)	11(6)	8(4)	8(2)	12(3)	1(0)	7(2)
0.80—1.00	3(3)	2(2)	0(0)	2(0)	4(0)	13(6)	0(0)	3(0)
1.00	19(3)	20(10)	27(4)	27(11)	16(2)	38(6)	9(0)	24(3)
S_{sh}	41(12)	64(11)	71(13)	59(12)	36(7)	63(16)	17(6)	40(9)
S_c	19(3)	20(10)	27(4)	27(11)	16(2)	38(6)	9(0)	24(3)
S	60(15)	84(21)	98(22)	86(23)	52(9)	101(22)	26(6)	64(12)
Depth ditchwater level in m — surface	0.50	0.80	0.70	0.80	0.70	1.00	0.70	1.00

drawdown. After 0.5 m deeper drainage the mean lowering of the groundwater level amounts to 0.25 m. So the pressure on subsoil increases by 25 g cm^{-2}. An intensified compression occurs after exceeding a confined pressure of about 50 g cm^{-2} according to the "stress—strain" characteristics of elastic solids (Terzaghi and Peck, 1956). Much higher rates of compression can be expected after lowering of the groundwater level with more than 0.5 m.

Table VI also gives the thickness decreases over the period from spring 1973 to spring 1975. In this period compression is still observable at a rate of 4 or 3 mm per year, on the average. The shrinkage in the Zegvelderbroek and Bleskensgraaf fields with a drawdown of the ditchwater level of 0.5 m amounts to 7 or 8 mm.

In 1972 the disk measuring method was extended to a trial plot with a high ditchwater level in each experimental field. In these cases the thickness changes from spring to spring were too small and the period too short for reliable conclusions. Therefore the thickness changes within the seasons of the years 1973 and 1974 were used to calculate the mean subsidence in summer and the mean reswelling in the next winter with the figures given in Table VII. The difference between subsidence and rise can be considered as the mean thickness decrease per year in this period. For the same period this calculation was applied to the all trial plots.

According to Table VII, the mean subsidence ranges from 30 to 40 mm in Hoenkoop and Bleskensgraaf fields and to 75 mm in the Zegvelderbroek field in summer. For the greatest part, 85% on the average, the subsidence due to

TABLE VII

Measured shrinkage and reswelling above groundwater level (1.00 m — surface), compression and rise of the peat below groundwater level and total subsidence and rise, as the average of summer and winter of 1973 and 1974 (Z = Zegvelderbroek; B = Bleskensgraaf; H = Hoenkoop), all in mm

Plot nr.	Depth ditch-water level m — surface	Shrinkage	Reswelling	Thickness decrease	Compression	Rise	Total subsidence	Total rise
Z—13	0.20	18	14	—4	40	36	58	50
Z—20b	0.50	22	15	—7	47	46	69	61
Z—20a	0.80	31	23	—8	39	34	70	57
Z—3	0.70	31	23	—8	44	42	75	65
Z—16	0.80	29	23	—6	48	43	77	66
B—V	0.35	34	32	—2	21	21	55	53
B—III	0.70	22	18	—4	8	7	30	25
B—I	1.00	28	21	—7	12	9	40	30
H—E	0.40	20	16	—4	10	7	30	23
H—D	0.70	26	24	—2	9	9	35	33
H—B	1.00	20	15	—5	13	11	33	26

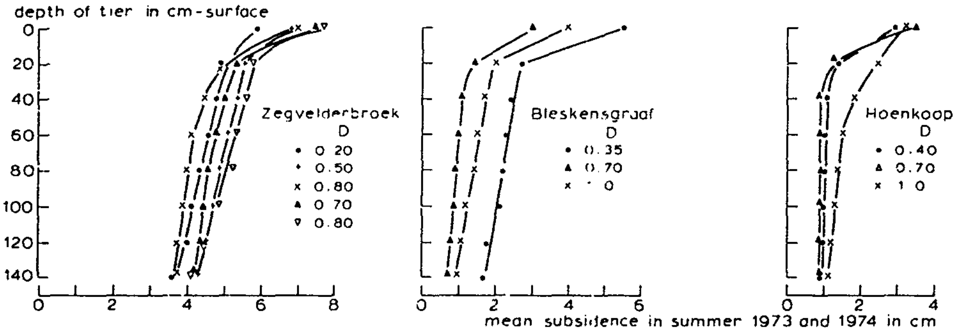

Fig. 7. Mean subsidence of the summers of 1973 through 1974 as a function of the depth below surface.

shrinkage and compression is compensated for reswelling and rising of the soil layers in winter.

In Fig. 7 the summer subsidence is given as a function of depth below surface. It appears that the reversible shrinkage is mainly restricted to the root zone of 0 to 0.20 m surface layer. It amounts to 20 mm, on the average, for this layer.

In the Zegvelderbroek field an irreversible shrinkage at a rate of 2 mm per year was observed with shallow drainage and 7 mm per year at low ditchwater levels. In the Bleskensgraaf field 7 mm and in the Hoenkoop field 5 mm were found at deep drainage. This agrees with the data in Table VI, covering the period from the spring of 1973 to the spring of 1975. In the Zegvelderbroek field the high rate of surface subsidence in summer is largely caused by elastic compression of the peat below groundwater level. The permanent compression amounts to 4 mm per year, on the average, for both high and low ditchwater levels. In the other two fields it ranges from 0 to 3 mm. A total mean subsidence of 8 mm per year at shallow drainage in Zegvelderbroek field agrees with the data in Tables I, II and IV, giving a mean subsidence of 6 to 8 mm per year.

Shrinkage and bulk density

In the previous sections, the amount of shrinkage has been derived from changes in thickness of the layers, but decreasing thickness may be due to increasing bulk density. Soil samples were therefore taken from the top layer of the experimental field of Zegvelderbroek in the spring and in a dry period of the summer of 1973. The bulk densities are given in Table VIII.

Shrinkage between spring and summer was calculated according to the formula:

$$S_s = dW_2/W_1 - d$$

TABLE VIII

Bulk density in spring and summer (g cm^{-3}) and shrinkage (cm) in the top layer of the experimental field of Zegvelderbroek with high and low ditchwater levels (m—surface) in 1973

Layer m—surface	Ditchwater level					
	0.20 m			0.70 m		
	spring	summer	shrinkage	spring	summer	shrinkage
0.00—0.05	0.43	0.57	1.6	0.49	0.57	0.8
0.05—0.10	0.51	0.60	0.9	0.53	0.58	0.5
0.10—0.15	0.49	0.55	0.6	0.4	0.47	0.6
0.15—0.20	0.39	0.39	0	0.31	0.36	0.8
0.20—0.25	0.30	0.32	0.3	0.22	0.26	0.9
0.25—0.30	0.26	0.26	0	0.20	0.21	0.2
Total			3.4			3.8

where S_s = subsidence due to shrinkage in cm; W_2 = bulk density in dry summer in g cm^{-3}; W_1 = bulk density in spring in g cm^{-3}; d = actual thickness (= 5 cm). The shrinkage of the upper layer of 0 to 0.20 m is in good agreement with the shrinkage measured by the disk method (Table V). Below 0.20 m the difference in bulk density from shrinkage is too small to be measured reliably. The bulk density is consistent with the findings from the disks. Reversible shrinkage in summer mainly occurs in the root zone (0—0.20 cm) subject to high moisture tensions.

Causes of subsidence in the past

Shrinkage

As mentioned earlier in this paper, the surface of the peat soils in the polder Zegvelderbroek subsided approximately 2 m in the past 1000 years. Today the deeper peat is still very soft and buoyant. The results of this study on subsidence indicate that peat below groundwater level is scarcely influenced by deeper drainage (see Table VI). The compression rate still ranges from 1 to 4 cm. Since its reclamation in the Middle Ages the land was never drained as deep as it is now in the experimental fields. Therefore, it is plausible to assume that the bulk density of the peat below groundwater level has scarcely increased since reclamation. Assuming that compression of the deep peat played no part in surface subsidence in the past, we must ascribe such subsidence to shrinkage and oxidation of organic matter in the layer above groundwater level.

The shrinkage of that layer can be calculated by comparing the bulk densities of the layers above and below groundwater level. This was done for eight

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profiles of the experimental field of Zegvelderbroek and the figures are given in Table IX. Because the oxidation of organic matter will cause a relative increase in mineral content only the bulk density of organic matter has been considered.

Deeper than 0.80 m below the surface, the bulk density of the eutrophic wood-sedge peat is 0.145 g cm^{-3} at an organic matter content of 80—85%. The bulk density of the organic matter is 0.12 g cm^{-3} and that of the mineral elements 0.025 g cm^{-3}.

Shrinkage was calculated according to the formula:

$$S_s = dW_{h2}/W_{h1} - d\ ,$$

where S_s = subsidence due to shrinkage in cm; W_{h2} = actual bulk density of organic matter in g cm^{-3}; W_{h1} = initial bulk density of organic matter (= 0.12 g cm^{-3}); d = actual thickness (= 10 cm).

The total shrinkage amounts, on the average, to 28 cm, most of which occurred in the top 0 to 0.30 m layer. Therefore for total subsidence in the past only for a small part can be explained by shrinkage. There remains the oxidation of organic matter.

Oxidation of organic matter

As already mentioned in the Introduction, many authors have stated that the surface subsidence of peat soils is mainly caused by oxidation of organic matter. The general opinion in The Netherlands, however, was that oxidation is not important in peat land under grass. From the present study it appears that the explanation for the subsidence of low moor peat in the western part of The Netherlands, even when under grass, must be found chiefly in the oxidation of organic matter.

When it is assumed that the higher content of mineral elements in the top layers is due only to oxidation, it is possible to estimate that oxidation by comparing the bulk density of mineral elements in the top layer with that in the peat below groundwater level because when organic matter oxidizes the total quantity of mineral elements will remain the same but the weight percentage will increase. As mentioned earlier the bulk density of mineral elements in the soil below the groundwater level is 0.025 g cm^{-3}.

The total subsidence can be computed according to the formula:

$$S = dW_{m2}/W_{m1} - d$$

where S = total surface subsidence in cm; W_{m2} = actual bulk density of mineral elements in g cm^{-3}; W_{m1} = initial bulk density of mineral elements (= 0.025 g cm^{-3}); d = actual thickness of layer (= 10 cm). This calculation was applied to the soil profiles covered in Table IX, giving the results in Table X.

According to Table X the mean subsidence is 204 cm with a range of 164—248 cm. This represents the entire subsidence, including shrinkage. Because shrinkage amounts to 28 cm, total oxidation amounts to 176 cm. The present

TABLE IX

Bulk density of organic matter (g cm^{-3}) above the maximum depth of the groundwater level and the derived shrinkage (S_{sh}) in cm

Layer m—surface	Profile number								Mean	S_{sh}
	3	4	12	13	16	17	7	8		
0.00—0.10	0.25	0.24	0.24	0.24	0.25	0.27	0.24	0.24	0.24	10
0.10—0.20	0.21	0.22	0.22	0.24	0.22	0.24	0.21	0.22	0.22	8
0.20—0.30	0.16	0.16	0.17	0.19	0.19	0.22	0.19	0.20	0.18	5
0.30—0.40	0.14	0.15	0.13	0.16	0.15	0.17	0.14	0.15	0.15	3
0.40—0.50	0.13	0.13	0.12	0.12	0.14	0.16	0.13	0.14	0.13	1
0.50—0.60	0.13	0.14	0.13	0.10	0.13	0.13	0.11	0.13	0.13	1
0.60—0.70	0.12	0.12	0.12	0.10	0.13	0.11	0.12	0.13	0.12	0
0.70—0.80	0.12	0.11	0.11	0.12	0.13	0.11	0.12	0.11	0.12	0
Shrinkage S_{sh}	25	27	23	26	32	37	25	30	28	28

TABLE X

Bulk density of mineral elements (g cm^{-3}) above groundwater level and the derived thickness decrease (ΔV in cm)

Layer m—surface	Profile number								Mean	ΔV
	3	4	12	13	7	8	16	17		
0.00—0.10	0.27	0.26	0.21	0.25	0.24	0.26	0.24	0.28	0.25	90
0.10—0.20	0.17	0.15	0.25	0.20	0.17	0.18	0.20	0.19	0.19	66
0.20—0.30	0.06	0.04	0.09	0.12	0.07	0.06	0.10	0.07	0.08	22
0.30—0.40	0.05	0.03	0.05	0.09	0.04	0.08	0.04	0.06	0.05	10
0.40—0.50	0.03	0.04	0.03	0.04	0.03	0.04	0.03	0.06	0.04	6
0.50—0.60	0.03	0.04	0.02	0.03	0.04	0.04	0.05	0.05	0.04	6
0.60—0.70	0.02	0.03	0.03	0.02	0.05	0.04	0.03	0.06	0.03	2
0.70—0.80	0.02	0.03	0.04	0.02	0.03	0.04	0.02	0.05	0.03	2
ΔV (cm)	184	164	208	228	188	216	204	248	204	204

surface elevation of 2.20 below mean sea level can thus be explained as 85% due to oxidation of organic matter. From this it follows that during a period of 900 years the subsidence by oxidation amounted to 2 mm per year. In this manner an initial peat formation with a thickness of 1.5 m was reduced to 20 cm muck soil with a present mineral content of 50%.

Nitrogen supply from soil and loss of organic matter

The conclusion that oxidation of organic matter of the peat soil plays an important role in the process of subsidence is supported by the evidence of gross yields of grass.

According to Dutch authors (Minderhoud, 1960; Jachtenberg and De Boer, 1967; Hoogerkamp and Woldring, 1965; Boxem, 1973) the gross yield of grass on clay soils and sandy soils without nitrogen fertilizers can amount to 7 to 8 ton of dry matter per ha, whereas the gross yield of dry matter on shallowly drained peat soils can amount to 9 to 10 ton per ha.

Not only the gross yield of dry matter is higher but also the protein yield. This indicates a higher nitrogen supply from the peat soils. In other words, an additional nitrogen supply is obtained from peat soils drained to greater depths (Neller, 1944; Stephens and Speir, 1969; Levin and Shoham, 1972; Scheffer and Bartels, 1974; Waydbrink, 1974).

Nitrogen deficiency due to an insufficient depth of drainage can be corrected by adding nitrogen fertilizers (Van Hoorn, 1958; Minderhoud, 1960; Sieben, 1974).

On the experimental fields an important nitrogen response was observed (see Fig. 8). At a drawdown of the ditchwater level of 0.5 m the gross yield

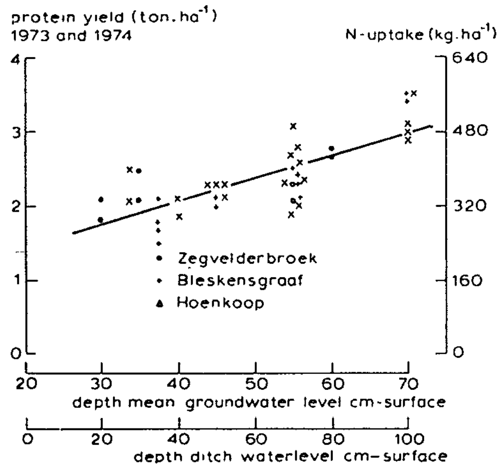

Fig. 8. Protein yield of grass without nitrogen fertilizer and nitrogen uptake from soil as a function of depth of ditchwater levels and groundwater levels.

TABLE XI

Mean gross yield of dry matter and mean protein yield of grass without nitrogen fertilizer at different depths of ditchwater level, total N-uptake, the additional N-uptake from peat and the calculated loss of organic matter

	Zegvelderbroek (1970—1974)				Bleskensgraaf (1973—1974)				Hoenkoop (1973—1974)		
Depth ditch-water level (m—surface)	0.20	0.30	0.70	0.80	0.35	0.35	0.70	1.00	0.40	0.70	1.00
Dry matter (ton ha^{-1})	10.1	11.3	11.4	12.8	8.8	10.3	11.1	13.9	10.8	11.5	13.4
Protein (ton ha^{-1})	2.0	2.2	2.5	2.9	1.6	2.0	2.3	3.4	2.1	2.5	3.1
Total N-uptake (kg ha^{-1})	320	352	400	464	256	320	368	544	336	400	496
Additional N-uptake (kg ha^{-1})	80	102	160	224	16	80	128	304	96	160	256
Loss of organic matter (dry weight in ton ha^{-1})	4.0	5.6	8.0	11.2	0.8	4.0	6.2	15.2	4.8	8.0	12.8

of dry matter without use of nitrogen fertilizer increased to roughly 12 to 13.5 ton per ha as an average over 5 years. The protein yields of grass calculated for the years 1973 and 1974 from the N-content of the dry matter are given in Table XI. At a protein content of 20% the protein yield was 2 ton per ha at shallow drainage and at a content of 22% it increased to 3 ton per ha at a 0.5 deeper drainage. This corresponds with a N-supply of 320 and 480 kg N per ha from the soil.

Increase in N-supply by the soil can be caused by additional decomposition of organic matter. This loss of organic matter causes a decrease in the total volume of peat and consequently greater subsidence of the surface.

The loss of organic matter due to oxidation can be calculated from the soil nitrogen-supply to plants. In mineral soils where no subsidence due to loss of organic matter is to be expected, a yield of 8 tons dry matter and 3% N takes up 240 kg N per ha from soil. On shallowly drained peat soils with a yield of 10 ton dry matter per ha and 3.20% N the N-supply is 320 kg N per ha. This agrees with an additional N-supply of 80 kg for organic soils. On peat soils drained 0.5 m deeper a mean yield of 13.5 ton dry matter per ha was reached with a N-content of 3.55%. This means an additional N-supply of 240 kg per ha.

According to soil analyses of the experimental fields the N-content of the organic matter is 4%. Only part of the soil nitrogen present will be taken up by the crops. According to De Boer (1966) the uptake of nitrogen from fertilizers is mostly about 60%, but in wet soils it may be only 45%. On the experimental fields the uptake at shallow drainage was 57% of the 150 kg nitrogen fertilizer applied and it decreased to 37% at deep drainage as a result of the increasing supply of soil nitrogen. Sieben (1974) found for arable crops a soil nitrogen uptake percentage of 69% on deeply drained loamy soils and 64% of the nitrogen fertilizers applied.

When calculating losses of organic matter from peats under grass, it seems reasonable to use a mean crop uptake percentage of soil nitrogen of 50%.

Then an additional N-supply of 240 kg corresponds with a loss of organic matter of $240/(0.5 \times 0.04) = 12{,}000$ kg ha^{-1} (dry weight). With a mean bulk density of organic matter of 0.2 g cm^{-3} in the topsoil (0 to 0.30 m — surface), according to Table IX the loss of organic matter can be expressed in cm thickness. Then a loss of 12 ton per ha corresponds with 0.12 g cm^{-2}/0.2 g cm^{-3} = 0.6 cm.

In this way the subsidence due to oxidation (S_0) was calculated for each trial plot (see Table XII).

A bulk density of organic matter of 0.2 g cm^{-3} corresponds with an earlier study (Schothorst, 1967) in the northeast peat area of The Netherlands where a bulk density of 0.18 g cm^{-3} was found. Moreover in a later study in Zegvelderbroek a bulk density of 0.2 g cm^{-3} was found for the organic matter lost due to ploughing for arable crops. The oxidation is therefore considered to amount to 1 cm per year.

According to Fig. 9 and Table XII the thickness decrease (ΔV) above

TABLE XII

Measured surface subsidence (S), thickness decrease above groundwater level (ΔV), compression (S_c) and calculated oxidation (S_o) in relation to the depth of ditchwater level (D) in cm, as the average for 1973 and 1974 *

Plot nr.	D	S	S_c	$\Delta V = S_{sh} + S_o$	S_o
Z—13	20	8	4	4	2.0
Z—8	30	—	—	—	2.8
Z—3	70	10	2	8	4.0
Z—16	80	11	5	6	5.6
B—V	35	2	0	2	2.0
B—III	70	5	1	4	3.2
B—I	100	10	3	7	7.6
H—E	40	7	3	4	2.4
H—D	70	2	0	2	4.0
H—B	100	7	2	5	6.4

* S, S_c and ΔV, all in mm, are derived from Table VII.

groundwater level after some years of deeper drainage can, for the largest part, be ascribed to oxidation of organic matter.

It is therefore concluded that the oxidation rate increases from about 0.2 cm per year with high ditchwater levels to about 0.6 cm per year with deep ditchwater levels.

Components of subsidence with six years of deep drainage

A schematic view of the amount of the identified components of subsidence over a period of six years (1969—1975) at different drain depths is given in

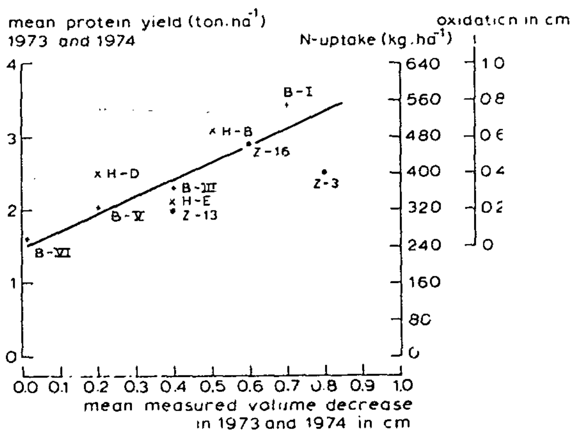

Fig. 9. Mean yield of protein and nitrogen uptake from unfertilized plots in comparison to volume decrease above groundwater level ($\Delta V = S_{sh} + S_o$).

TABLE XIII

Irreversible shrin[...] face subsidence, [...]

Experimental field

Zegvelderbroek

Bleskensgraaf

Hoenkoop

Table XIII. Ir[...] (S_c), as meas[...] tion (S_0) for [...] age $S_{sh} = S$ — [...]

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TABLE XIII

Irreversible shrinkage after 6 years of deeper drainage in comparison with the total surface subsidence, oxidation and compression

Experimental field	Depth of ditch-water level (cm—surface)	Surface subsidence (mm)	Compression (mm)	Oxydation (mm)	Irreversible shrinkage (mm)
Zegvelderbroek	25	45	15	14	16
	75	92	27	29	30
Bleskensgraaf	35	10	0	12	—2
	70	52	16	19	17
	100	101	38	46	17
Hoenkoop	40	20	7	14	—1
	70	40	14	24	2
	100	64	24	38	2

Table XIII. In this table the total surface subsidence (S) and the compression (S_c) as measured with the disk system, were taken from Table VI. The oxidation (S_0) for six years is from the rates in Table XII. The irreversible shrinkage $S_{sh} = S - S_c - S_0$ $(S_c = 0.35\ S)$.

After six years of deeper drainage the irreversible shrinkage ranges from practically zero in the Hoenkoop field to 1.7 cm in the Bleskensgraaf field to about 3.6 cm in the Zegvelderbroek field. These values are related to the organic matter content in the surface layers, given in Table III. Higher irreversible shrinkage goes with higher levels of organic matter. With a clayey cover of 0.40 m, the irreversible shrinkage is very low.

It is to be expected that compression and irreversible shrinkage will gradually decrease but that oxidation of organic matter will continue at a more or less constant rate per year till a new lowering of the ditchwater level will be necessary.

The surface subsidence of about 0.7 cm per year at high ditchwater levels in the Zegvelderbroek field cannot be explained entirely by oxidation (only 0.2 cm per year), as contrasted with the Bleskensgraaf experimental field. In the first field irreversible shrinkage and compression plays a role. This may be connected with deep groundwater flow. As already mentioned, in the polders Bleskensgraaf and in Hoenkoop a positive seepage from rivers is present as contrasted with the polder Zegvelderbroek. Here a negative subsurface inflow moves towards a lake reclaimed in the 19th century and situated 5 km northward (polder Wilnis).

The increase in surface subsidence during the past century, discussed in the History-section, is not a result of water control in winter but a consequence of negative subsurface inflow appearing after reclamation of lakes with sandy bottoms.

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