Pedological Regional Variations in Well-drained Soils, Denmark

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Soil profile investigations were carried out within a national 7 km grid. The profiles were classified according to the 1974 FAO-Unesco Soil Classification System. This paper describes the regional variations in soil profile development and the related dominant soil formation processes.

Keywords: *Soil variation, FAO major soil groupings.*

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During the past twenty years, extensive soil investigations have been carried out in Denmark. In the late 1970s, a national soil mapping was carried out. By this mapping the agricultural land was grouped into 8 soil classes, according to the texture of the plough layer (Mathiesen, 1980). This mapping was followed up by soil profile investigations during the 1980s. A pilot project was carried out in 1980 in Himmerland, northern Jutland. In this project methods were tested in order to establish a national soil profile database (Madsen, 1983). From 1981 until 1983, soil profile investigations were carried out along the trench of the gas pipeline, that was constructed across the country from the North Sea and the German border to Copenhagen (Madsen & Jensen, 1986). The investigations provided information on the regional variations of soils related to landforms, parent material, topographical features etc. However, due to the geographical location of the gas pipeline system, studies were limited to the southern part of Denmark. The goal of achieving a national soil profile database could not be realized immediately.

In 1986, in order to predict the amount of nitrogen fertilization and manuring required by Danish agriculture with the aim of reducing waste and pollution, The Danish Agricultural Advisory Centre set up a national study, based on a 7 km grid. At each grid intersection, a soil sampling test site, measuring 50 m by 50 m, was established. In total, about 800 sites were established, of which approximately 650 were on farmland, 80 on forest land, while the remainder were located on i.e. heathland, in orchards, or within sand dune areas.

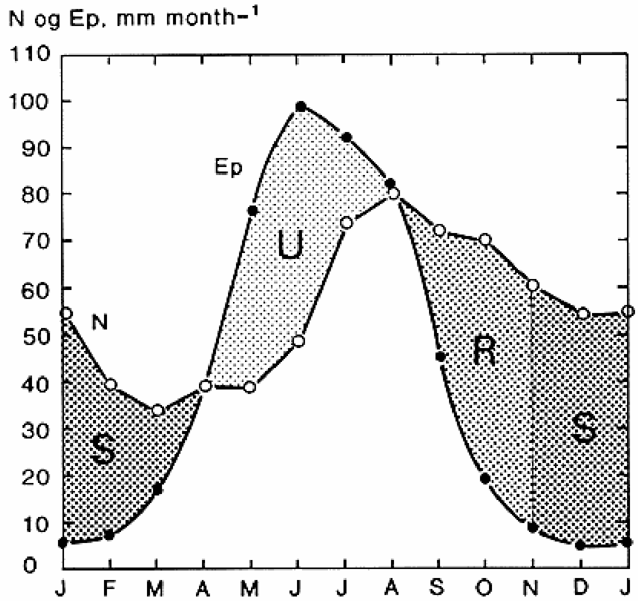


Fig. 1. Denmark - the mean monthly precipitation, potential evapotranspiration. Percolation (S), depletion (U), and replenishment (R) of water from the root zone.

At each site, composite soil samples from at least 16 augerings were collected several times a year. They were analyzed for their concentrations of nitrate and ammonia (Østergaard, 1990). During 1987-89, soil profiles were described at all sites and soil samples were collected from the profiles for chemical and physical analyses.

This paper shows the regional variations in the soils as classified according to the FAO-Unesco Soil Classification System. The main soil forming processes in Denmark are discussed based on a simple statistical treatment of the soil profile data from the 7 km grid.

SOIL FORMING FACTORS IN DENMARK

The pedological development of soils is a function of the soil forming factors; climate, vegetation, parent material, slope, human activity and time (Jenny, 1941). Before discussing the pedological development of Danish soils, a short presentation of the soil forming factors relevant to Denmark will be given here.

Denmark is geographically situated at about 56°N 11°E. It has a temperate, Atlantic climate with a winter mean of about 0°C and a summer mean of about 17°C. The mean annual precipitation ranges from about 800 mm in central Jutland to below 500 mm in the Great Belt region. The annual potential evapotranspiration is about 550 mm, the annual actual evapotranspiration being about 380 mm, see fig. 1.

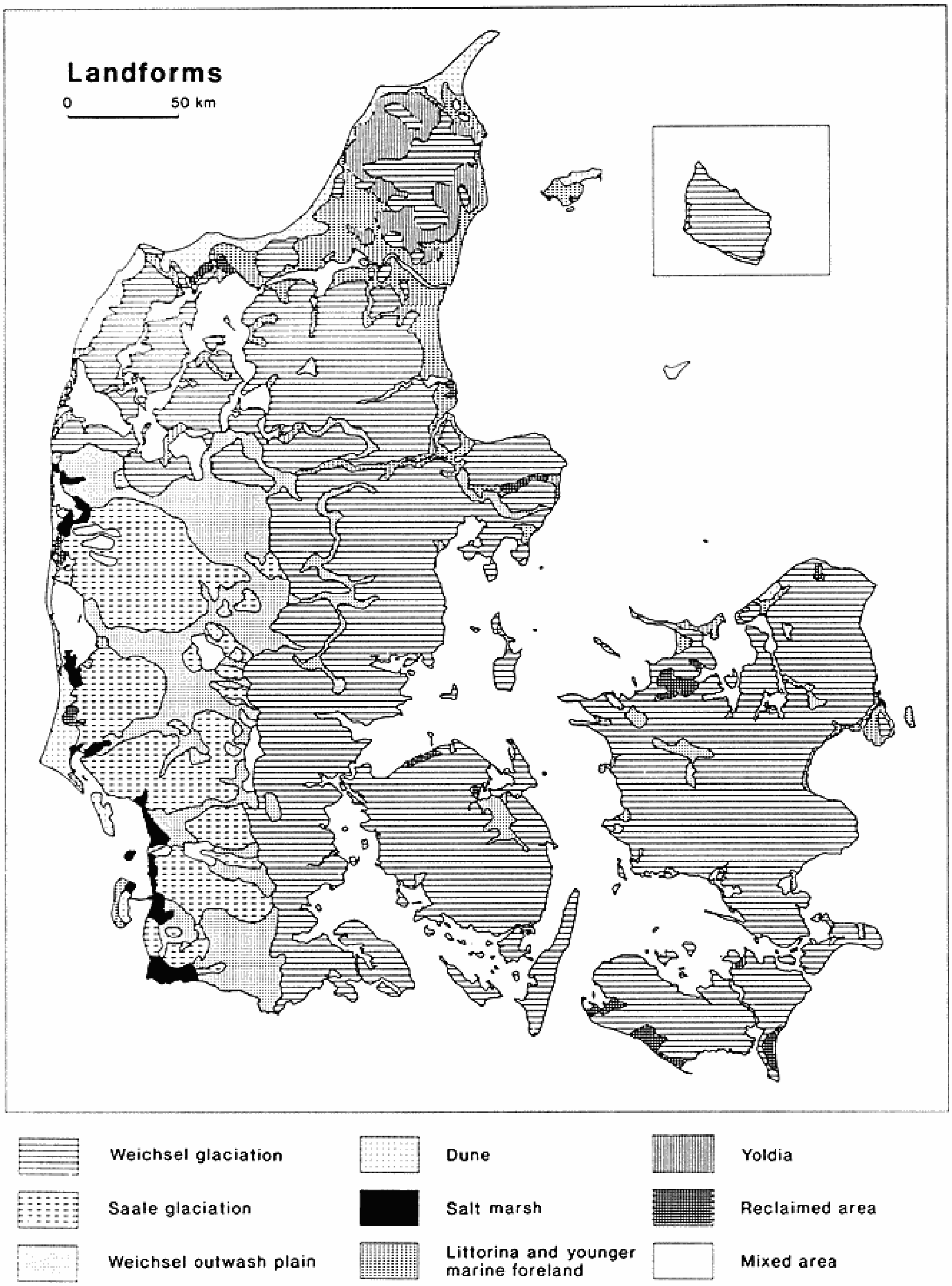


Fig. 2. Denmark - a simplified landscape map.

In spring and early summer, the potential evapotranspiration exceeds precipitation, and the vegetation utilizes water stored in the root zone, causing a depletion of soil water. In late summer and early autumn, the soil water reserves are replenished due to a precipitation surplus. In late autumn, winter and early spring, leaching takes place. In central Jutland, the annual percolation exceeds 400 mm. In the Great Belt region it is about 150 mm (Aslyng, 1978).

The natural vegetation is deciduous forest, the climax vegetation being beech wood. Today, about two-thirds of the country is agricultural land that is manured, limed and, to some extent, drained. Only about 10% is under forest, and a large part of this is spruce plantations.

Figure 2 shows the origin of the parent material of Danish soils. The major part of the country consists of Weichsel glacial deposits, mainly tills. In western Jutland, old relic Saale glacial deposits and the younger Weichsel outwash plain deposits dominate, while in northern Jutland marine deposits cover large areas. Along the west coast of Jutland, sand dune and saltmarsh deposits are dominant.

The Danish landscape is generally flat or slightly undulating. About only 1% of the country has slopes with gradients exceeding 12°. Today, half of this area is afforested. Therefore, severe soil erosion due to water is not a big problem, but colluvial deposits at the feet of slopes occur frequently due to sheet and rill erosion.

The overall soil forming processes on well-drained sites reflecting the soil forming factors are: acidification due to the leaching of calcium carbonate and exchangeable bases, weathering of the different minerals, migration of clay particles on loamy or clayey soils, and podzolization of sandy soils involving translocation of humus, iron and aluminium (hydr)oxides from the A to the B horizon. In wetlands, gleys and peats will form.

The pedological development occurring on sandy parent materials has been studied and described by, e.g. Muller (1879, 1884), Rix (1927), Weis (1929, 1932), Petersen (1976), Nørnberg (1977), Møberg (1976), and Madsen (1979, 1983). On very young deposits of well-drained sands like the coastal dunes, regosols predominate. On older, non-podzolized sands, cambic or luvic arenosols are frequently found, whilst on podzolized sands, humic and orthic podzols predominate.

The soils developed on well-drained loamy or clayey parent material have been described by Fobian (1966), Holstener-Jørgensen (1973), Madsen (1979, 1983), Madsen & Jakobsen (1980), Madsen & Jensen (1986), Dalsgaard et al. (1981), Nørnberg et al. (1985), and Møberg et al. (1988). On the youngest deposits, which are very rare and normally a result of human activity, regosols may predominate. Different types of cambisols and phaeozems, except luvic and some gleyey phaeozems, predominate in areas where clay illuviation is absent. The occurrence of phaeozems in Denmark is mainly due to the liming and fertilization of farmland. Luvisols, luvic and some gleyey phaeozems, acrisols and podzoluvisols are the soil types found in areas with clay illuviation. In the podzoluvisols, the pedological development has reached the stage where destruction of the Bt-horizon takes place, and they may develop into podzols, see fig. 3.

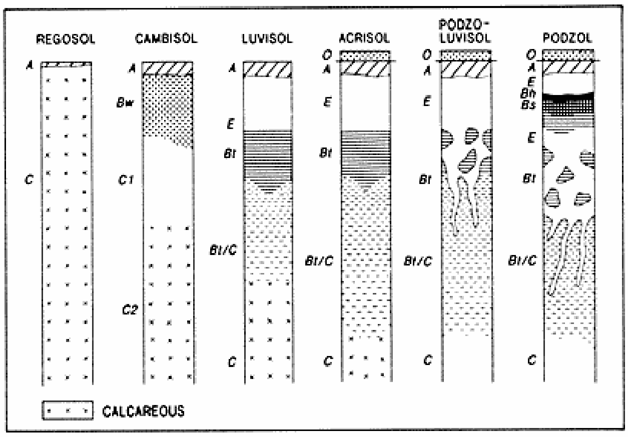
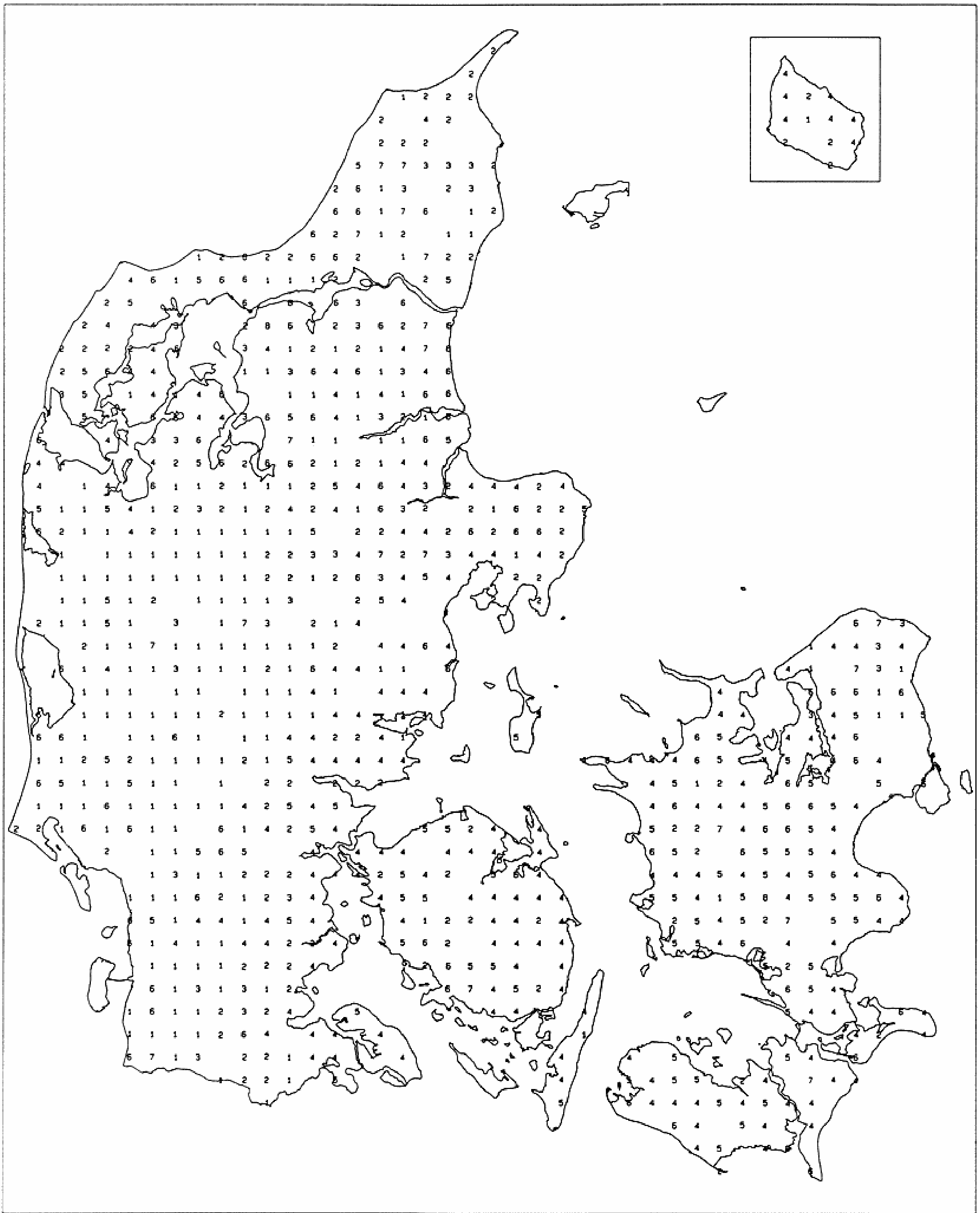


Fig. 3. Denmark - a schematic drawing showing the pedological development in a calcareous clayey till.

SOIL SAMPLING AND SOIL ANALYSIS

At the centre of each sampling site, a soil profile was excavated and described according to Madsen & Jensen (1988). From each horizon, soil samples were taken for physical and chemical analysis, and undisturbed samples were collected in tubes to determine soil water retention and bulk density. For each of the excavations, an augering was made to a depth of 2 metres, from which a soil sample was collected.

The fine earth samples from the different soil profile horizons and the augering were analyzed by the following methods: The particle size distribution was determined using sieves and hydrometers. The amount of organic carbon was determined by combustion in a LECO Apparatus. Calcium carbonate content was determined by the Scheibler Method. Soil pH was measured in water and 0.01 M $CaCl_2$ using a soil:liquid ratio of 1:2.5. The total nitrogen was determined by the Kjeldahl method. Exchangeable bases were extracted by 1 M NH_4OAc at pH 7.0, and determined by Atomic Absorption Spectrophotometry. Exchangeable acidity was determined at pH 8.1 by Pipers Method (Madsen & Jensen, 1986), and the CEC-value was calculated as the sum of the exchangeable bases and acidity. Soluble iron and aluminium were extracted by dithionite-citrate and pyrophosphate. The soil



water content was determined at the following pF-values: 1.0, 1.5, 2.0, 3.0 and 4.2. For pF-values up to 2.0, the sand box method was used. For higher pF-values, the pressure plate method was used.

All samples were analyzed for texture, pH, organic matter content and calcium carbonate content. All samples containing more than 0.5% organic carbon were analyzed for total nitrogen. Exchangeable bases, acidity, and cation exchange capacity were determined on half of the samples. Dithionite-citrate and pyrophosphate soluble iron and aluminium were determined on selected samples for classification purposes. Soil water retention was determined on all tube samples.

RESULTS AND DISCUSSIONS

All the soil profiles have been classified according to the FAO-Unesco Soil Classification system (1974). The sandy soils are mainly regosols, arenosols or podzols, while the more clayey soils are cambisols, phaeozems, luvisols, acrisols or podzoluvisols. The wetland soils are mainly gleysols, fluvisols or histosols.

The soils have been grouped into eight classes according to the FAO-Unesco soil classification. The classes reflect the dominant soil forming processes.

1) podzolized sandy soils FAO: *podzols*
2) non-podzolized sandy soils FAO: *arenosols*, regosols
3) acid loamy and clayey soils with clay illuviation FAO: *acrisols*, podzoluvisols
4) neutral or slighly acid loamy or clayey soils with clay illuviation FAO: *luvisols,* luvic and most gleyey phaeozems
5) loamy or clayey soils without clay illuviation FAO: *cambisols,* phaeozems except luvic and some gleyey ones
6) wetland soils showing gley formation FAO: *gleysols,* fluvisols
7) wetland soils showing deep peat formation FAO: *histosols*
8) soils on limestone FAO: *rendzinas.*

In the following passage, the italicized names above indicate the eight major soil groups.

Figure 4 shows the soils of the 7 km grid categorized into the eight groups defined above. Because the sampling was based on a fixed grid, it is statistically possible to make some simple estimations on the occurrence of different soils found within different geographical regions.

Fig. 4. Denmark - major soil groupings according to the 1974 FAO-Unesco Soil Classification System. 1: podzol; 2: arenosol, regosol; 3: acrisol, podzoluvisol; 4: luvisol, phaeozem with Bt; 5: cambisol, phaeozem without Bt; 6: gleysol, fluvisol; 7: histosol; 8: rendzina.

landscape	number	<--- percent					--->
		P	QR	AD	LH	CH	GJO
littorina	43	2	21	0	7	5	65
yoldia	24	17	46	8	4	8	17
dune	22	36	45	0	0	0	18
Saale moraine	87	60	11	8	7	5	9
outwash plain	100	66	17	1	1	5	10
Weichsel moraine	481	12	16	5	40	15	11
total	781	26	18	5	26	11	14
incl. salt marsh, reclaimed & mixed areas							

Table 1. Soil types in relation to landscapes. P: podzol. QR: arenosol and regosol. AD: acrisol and podzoluvisol. LH: luvisol and phaeozems with clay illuviation. CHE: cambisol, all phaeozems without clay illuviation, rendzina. GJO: gleysol, fluvisol, histosol.

Soils of different landscapes

Table 1 shows the number and percentage share of the different soils in relation to the landscapes shown in Figure 2. Rendzinas have been excluded from Table 1 because only three rendzinas were found. The landscapes of the reclaimed sea areas and salt marsh have also been excluded as the number of soils investigated in these areas was very small. However, most of the soils of these two landscapes are fluvisols or gleysols. Areas with mixed landscapes where the soils cannot be related to a definite landscape have been excluded.

In the littorina areas, wet soils dominate: 56% are gleysols or fluvisols, while 9% are histosols. On the more elevated parts, arenosols are most common while podzols are rare. On the Yoldia plain, well-drained, non-podzolized, sandy soils predominate, while loamy soils are rare. The wetlands are mainly situated in deep narrow valleys. In these valleys, histosols predominate. The dune landscapes have arenosols (regosols) and podzols on the well-drained parts, while the wetlands are characterized by gleysols, some of which have thin histic epipedons. In the Saale glacial landscape and on the Weichsel glacial outwash plains, podzols predominate, accounting for about two-thirds of the profiles investigated, while arenosols cover less than 20% of the area. Among the loamy soils, no specific soil type predominates. The wetland soils, mainly gleysols and fluvisols, cover about 10% of the area. Only 1% are histosols. In the Weichsel glacial landscape, luvisols are the predominant soil type, accounting for 40% of the investigated profiles. Cambisols cover 15% of the area, while acrisols cover only 5%. Among the sandy soils, arenosols seem to be a little more common than podzols. The wetland soils account for 11% of the inves-

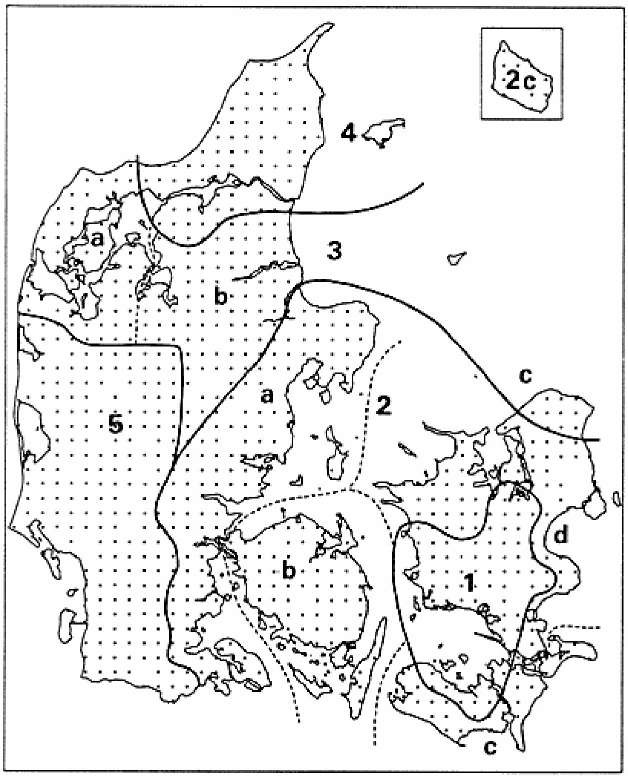


Fig. 5. Denmark - soil regions based on soils on loamy or clayey parent materials. 1: cambisol)luvisol; acrisol absent; 2: luvisol))cambisol; acrisol nearly absent; 3: luvisol)acrisol = cambisol; 4: acrisol))luvisol = cambisol; 5: acrisol = cambisol)luvisol. Ratio:))higher than 3,)1.5 to 3, = less than 1.5. For detailed definition of the major groups and sub-groups, see table 2.

	number			percentage share		
	AD	LH	CH	AD	LH	CH
I	0	12	36	0	25	75
II	3	146	31	2	81	17
IIa	2	53	12	4	79	18
IIb	0	35	11	0	76	24
IIc	0	25	2	0	93	7
IId	1	33	6	3	83	15
III	16	35	11	26	56	18
IIIa	4	18	7	14	62	24
IIIb	9	14	4	33	52	15
IIIc	3	3	0	50	50	0
IV	10	2	2	71	14	14
V	8	5	9	36	23	41
total	37	200	89	11	61	27

Table 2. The regional variations in the pedological development of loamy and clayey non-wetland soils. AD: acrisol and podzoluvisol. LH: luvisol and phaeozems with clay illuviation. CHE: cambisol, phaeozem without clay illuviation and rendzina.

tigated profiles, 9% were gleysols/fluvisols and 2% were histosols. The three rendzinas, mentioned earlier, were also found in these areas.

In the country as a whole, podzols and luvisols are the most common soils. Each covers 26% of the investigated area. Arenosols, cambisols and gleysols each cover 10% to 20% of the investigated area, while acrisols, histosols and rendzinas are rare, covering 5%, 2% and less than 1%, respectively. The rather well-drained soils cover 86% of the area, and the wetland soils 14%.

Soils on loamy and clayey parent materials

Figure 5 shows the predominant soils, and hence the dominant soil forming processes, for well-drained loamy and clayey soils in different parts of the country. Five major regions have been identified, and some of these have been subdivided. Two major geomorphological features can be recognized on the map; the Main Terminal Moraine and the East Jutland Terminal Moraine. Table 2 shows the number and percentage share of the different soil types within the various regions.

Region 1 (cambisol)luvisol) includes the southwestern part of Zealand and the northern part of Lolland. The parent material in this region is mainly loamy calcareous till. The dominant soil forming processes are weathering and structure formation. The soils are classified as cambisols. Clay illuviation leading to the formation of luvisols was only apparent in one-quarter of the profiles. Acid soils with clay illuviation are not found in the region.

Region 2 (luvisol))cambisol) covers almost the entire remaining area east of the East Jutland Terminal Moraine. In this region, which has been subdivided into a: East Jutland, b: Funen, c: Lolland-Falster and Bornholm, and d: Zealand, about 80% of the soil profiles are luvisols. These are neutral or slightly acid soils with clay illuviation. Only about 20% of the soils are cambisols, and acrisols are nearly absent. There is no great variations between the four sub-regions, proving that Region 2 is relatively homogeneous. On the other hand, Table 2 shows that there is a distinct difference between Regions 1 and 2 on Zealand.

Region 3 (luvisol)acrisol=cambisol) has a ratio of soils with and without clay illuviation similar to that found in Region 2, but acid soils with clay illuviation are more common, making up about one-quarter of the soils investigated. Luvisols are still predominant, covering more than half of the area. The sub-regions are less homogeneous than the subregions in Region 2. The soils in the western part of Jutland are less acid than in the eastern part. In western Jutland only 14% of the soil profiles have been classified as acrisols as compared with 33% of the soils in the eastern part. The northeastern part of Zealand has been referred to Region 3, but only very few profiles have been investigated in this sub-region.

Region 4 (acrisol))luvisol=cambisol) covers Vendsyssel and the northern part of Himmerland. The area is mainly sandy and only 14 soil profiles have developed on loamy or clayey parent material. Among these, acrisols predominate, making up about 70% of the profiles. The loamy and clayey soils in the northern part are more acid than in the south, but soils with a loamy and clayey texture are rare in this region.

Region 5 (acrisol=cambisol)luvisol) includes the loamy and clayey parts of the Saale glacial landscape. None of the three types predominate in this region. There is more or less the same areal extent of acrisols and cambisols (about 40% each), while luvisols cover about 20% of the area.

Overall, luvisols are predominant on well-drained loamy and clayey deposits, and they constitute about two-thirds of the profiles. Cambisols, which are predominant in Region 1, account for about one-quarter of the investigated soil profiles, while acrisols make up one-eighth. This means that clay illuviation is the dominant soil forming process in loamy and clayey soils, and the large majority of the soils are only slightly leached (acidified).

The regional variations in soil types is probably mainly due to differences in the physical and chemical properties of the parent material and the time factor. In Regions 1 and 2, the Baltic ice deposited a loamy till with a clay content of about 25%. East of the Great Belt and in eastern Funen, the till was often calcareous when deposited, and in many places it still contains calcium carbonate within a depth of two metres. The parent material has therefore been very resistant to acidification, and acid, clay-illuviated soils are rare in these regions. In Region 3a, the soils have a similar texture to those of Regions 1 and 2, but they are not so calcareous. Therefore, the frequency of acrisols is higher than in Region 2. The tills of Regions 3b and 4 are not so clayey, containing 10 to 15% clay, and in practically none of the soils was calcium carbonate detected within a depth of two metres. Resistance to acidification is low, and acid soils with clay illuviation are common. No soils in the regions mentioned above are older than about 15,000 years, the time when the Weichsel Glaciation terminated in Denmark. By contrast, the parent materials in Region 5 might be much older because the tills were deposited during the Saale Glaciation. This has caused a severe leaching of the soil bases and thereby the formation of acid soils. The frequency of acrisols is therefore high in this region.

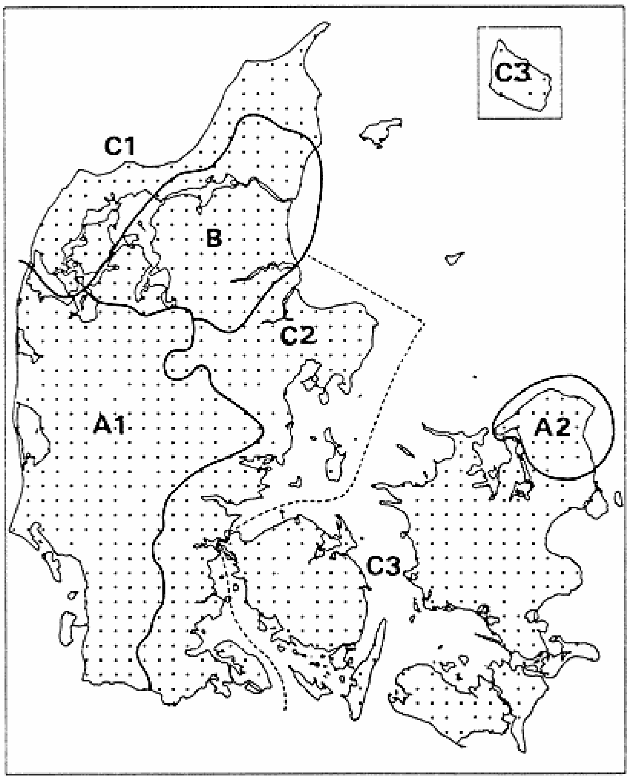


Fig. 6. Denmark - soil regions based on soils on sandy parent material. A: podzols))arenosols; B: podzols)arenosols; C: arenosols))podzols. Ratio:))higher than 3,)1.5 to 3, = less than 1.5. For detailed definition of the major groups and sub-groups, see table 3.

Soils on sandy parent materials

Figure 6 shows Denmark divided into three regions according to the frequency of podzolized sandy soils. Region A, (podzol)) arenosol), covers the area west of the Main Terminal Moraine of central Jutland and some parts of central eastern Jutland. Furthermore, northeastern Zealand belongs to this soil group. There is a clear predominance of podzols making up about 90% of the sandy profiles. In Region B, (podzol)arenosol), about two-thirds of the sandy soils are podzols, while in Region C, (arenosol))podzol), the non-podzolized soils dominate, making up more than 80% of the sandy soils. In total, 60% of the sandy soils are podzols (table 3).

Regional differences in the frequency of podzolization are probably mainly due to differences in parent material, land-use, natural vegetation and time. In the west, mainly in Regions A and B, heather vegetation (Calluna Vulgaris) has covered the land for centuries, generating a strong and deep podzolization of the soils. Podzolization is also common in soils in areas afforested with spruce, but not in

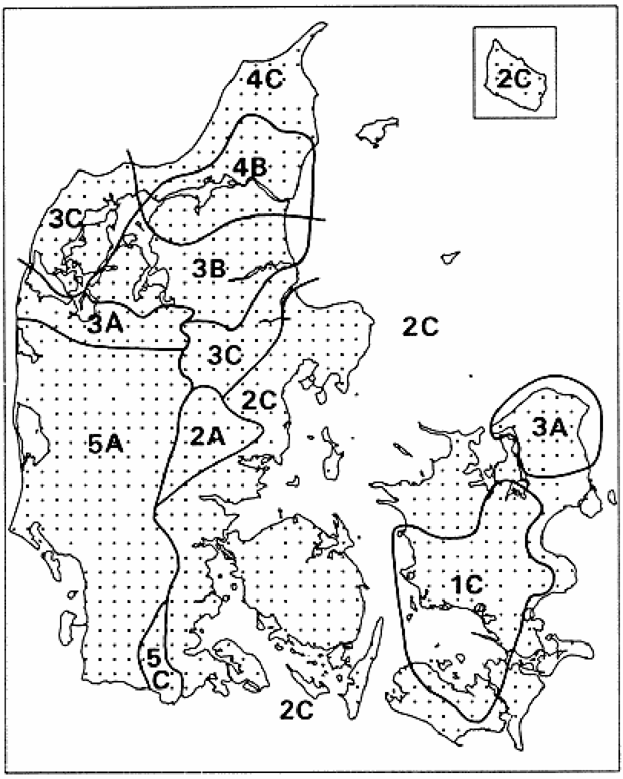
	number		percentage share	
	P	QR	P	QR
A	151	19	89	11
A1	145	19	88	12
A2	6	0	100	0
B	30	18	63	37
C	18	98	16	84
C1	4	25	14	86
C2	8	50	14	86
C3	6	23	21	79
total	199	135	60	40

Table 3. The regional variationss in the podzolization of sandy non-wetland soils. P: podzol. QR: arenosol and regosol.

soils under oak forest (Muller, 1884; Larsen, 1971). Oak may even destroy an existing podzol profile (Nielsen et al., 1987a, 1987b). Sandy materials, low in iron and aluminium hydroxides, are also more vulnerable to podzolization than more iron and aluminium-rich soils (Petersen. 1976 Madsen, 1983). A strongly developed podzol soil will not lose its characteristic subsurface horizons when subjected to ploughing, but this may occur in weakly developed podzols with shallow B-horizons. Therefore, in agricultural areas with weakly developed podzols, the podzol characteristics may disappear during cultivation and the soil becomes an arenosol. Furthermore, agricultural practices prevent podzolization because of liming, manuring, and the conversion of mor into mull. The time factor is especially important in the sand dune areas of Denmark. The deposits in these regions may be so young that the degree of podzolization will be very low. Regional variations in the effect of the Danish climate, especially its influence on the amount of percolation, do not seem to play an important role, as podzols can be found in all climatic zones even in the dry areas of the Great Belt, such as those found on the island of Langeland, at Røsnæs, and in the coastal cliff at Knudshoved Odde.

General soil regions

Figure 7 shows a map indicating the dominant pedological processes affecting well-drained, sandy, loamy and clayey parent materials. Apart from minor adjustments, the map is a combination of Figures 5 and 6. Figures 1 to 5 indicate the soils formed on loamy and clayey deposits. Letters A, B and C indicate the soils formed on sandy parent material. For example, 2C shows that the predominant soils on loamy materials are luvisols, while acrisols are nearly absent, and arenosols predominate on sandy parent material.



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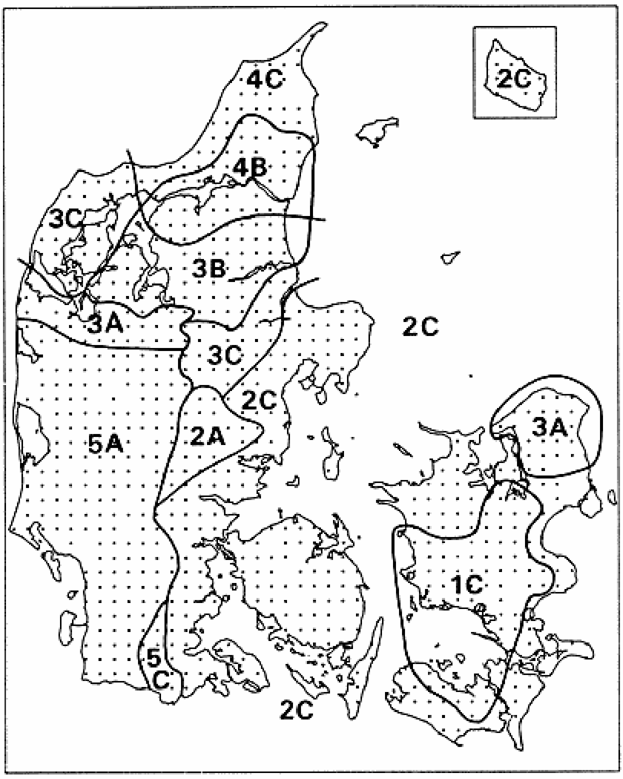

Fig. 7. Denmark - soil regions based on soils on well-drained parent materials. 1: cambisol)luvisol; acrisol absent; 2: luvisol))cambisol; acrisol nearly absent; 3: luvisol)acrisol = cambisol; 4: acrisol))luvisol = cambisol; 5: acrisol = cambisol)luvisol; A: podzol))arenosol; B: podzol)arenosol; C: arenosol))podzol. Ratio:))higher than 3,)1.5 to 3, = less than 1.5.For detailed definition of the different groups, see tables 2 and 3.

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