Soil evolution in the remnants of natural forest vegetation: An example from an old oak-lime coppice wood in Denmark

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Abstract

A mixed Quercus-Tilia forest was investigated to study the soil development in a forest that resembled the natural Danish forest composition before 4000 BC. This study of the impact of vegetation upon soils, provides morphological and chemical data to support the findings. Soil survey and laboratory data showed that the soils are podzolized in the western and southern borders of the forest. This podzolization process is mainly facilitated by a difference in parent material from loamy sand to sand. In contrast, brunifed soils with only minor traces of podzolization were found in the interior of the wood, even where an 80 cm thick layer of sand was found on top of sandy loam. These soils were expected to have developed Spodic horizons in their upper sequence. This indicates that the oak-lime type of forest prevents or retards podzolization under the present Danish edaphic and climatic conditions. pH data of surface soil showed a decrease of 0.7-0.9 units within the last 50 years, which suggests that the present soil development might change rapidly.

Keywords

Soil genesis, forest soils, podzolization, Quercus, Tilia, Spodosols, Ultisols. Introduction

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The interaction between soil and vegetation is important in understanding soil development in a highly man influenced landscape like the Danish. 4000 BC, the Stone Age farmers began to clear the forest for grazing. In the central and western Jutland, the forests were gradually replaced by Calluna heath, which at its maximum extension in the last part of the eighteenth century, continuously covered nearly all of western Jutland. Only 10% was ploughed agricultural land and forests were extremely rare.

The mixed oak-lime forest is, compared with a pure beech (*Fagus sylvatica*) forest, believed to maintain brunification, also on nutrient poor soils, because of the easier decomposition of the lime and oak leaves (Heath et al. 1965). Accordingly, oak and/or lime has been shown to retard or prevent podzolization in a few Danish studies in nutrient poor soils. Nielsen et al. (1987) investigated the oak invasion on nutrient poor soils of the Hjelm Hede heathland, Western Jutland. They found that the invading oak trees had a depodzolizing effect relative to the former heath vegetation. Aaby (1983) showed by pollen analysis in the Draved forest, southern Jutland, that podzolization first started after humans changed the forest composition from lime-oak-birch to beech-oak forest. The tendency for a given soil to podzolize depends not only on forest composition but also

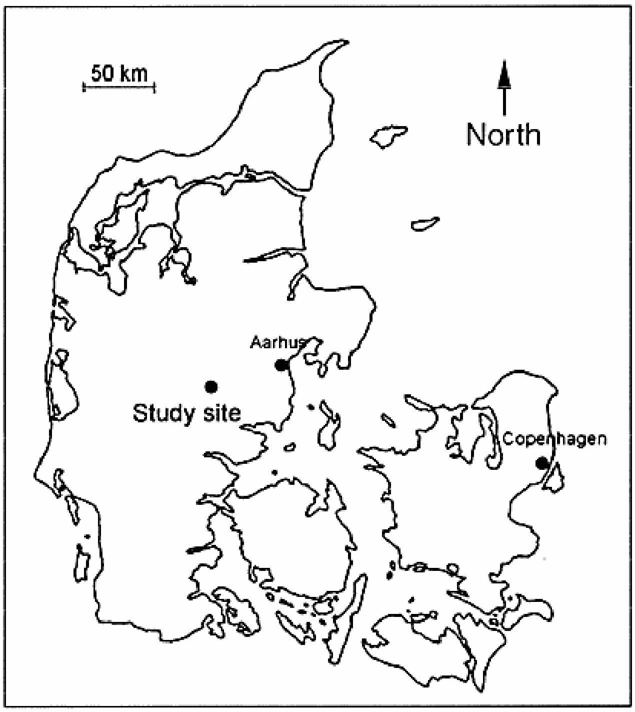

Figure 1: Location of the study site in Danmark

on the parent material. The most important factors are i) fine clay (< 0.2 μm) content, ii) free iron content, iii) weatherable mineral content, iv) low calcium content and v) a reasonable permeability of the upper part of the soil (Duchaufour 1982). Previous investigations show that under a temperate Atlantic climatic, tree species, forest composition and parent material is the most important factors in the development of Spodosols.

This pedological study was performed to investigate the impact of the original mixed oak-lime (*Quercus-Tilia*) forest upon soil development in a nutrient poor, semi-natural Danish forest.

Study area

The study area, Holtkrat, is a 10 ha wood that was formerly a coppice, but since the 1940's has been left to grow natural. Oak (*Quercus petraea and Q. robur*) is the dominant tree species together with approximately 150 lime trees (*Tilia cordata*) located in the centre. The western part has a substory of bucktorn alder (*Frangula alnus*), whereas the central part has a hazel substory (*Corylus avellana*). The site is situated 100 metres above sea level, in the middle of Jutland, near Silkeborg at 56° 05' N, 9° 28' E (figure 1). Yearly average temperature is 7.3 °C and the average precipitation is approximately 810 mm. The wood is situated on the border between the moraines and the outwash plains of Late Weichselian age and the eastern and southern sides of the forest fall abruptly 20 metres down to a subglacial outwash valley. The sediments are highly variable. Till, with a texture of sandy clay loam, dominates the northern part, changing towards the south and west into sandy till covered by a 10 cm to 80 cm thick layer of sand. Towards the south and west, the till changes to fluvio-glacial sand/gravel, at the forests boundary. Below the till, a 5 cm to 10 cm thick gravely layer is found, with many boulders above the fluvio-glacial deposited sand. The topography inside the forest is level, sloping slightly toward the west, with a weak microrelief covering approximately 5 % of the total forest surface. The microrelief is due to old anthills, badger pits and wind throws.

The history of the Holtkrat forest can be dated back to the first written documents in 1670 that described it as an underwood (or coppice), but already in 1494 the name Holt was used (Oksbjerg 1996). Compared to similar forests with a known history and land use, the wood has a very diverse ground flora. The diverse flora, in association with no visible archaeological structures, indicates forest continuity and absence of past soil management (Worsøe 1996). The tree composition, with lime, hazel, and oak, resembles what was found in the Atlantic period before the Stone Age farmers started to clear the forest, which at that time covered the whole country. According to Aaby (1993), forests on well-drained sites were then lime-hazel-(oak) forest on nutrient rich soils and on nutrient poor soils a more open birch-lime-hazel-(oak)-Calluna-herb forest. The presence of lime trees is remarkable, as this tree species is today very rare in Denmark, especially in the western part of the country, probably due to human interference. It disappeared gradually from the Danish forests, and was replaced by beech in the eastern part of the country from about 0 BC. It is probably the coppice management of the wood, which has preserved this wood as all other forests in the region, were converted to Calluna heath due to grazing. The coppice use dates back to before 1586. At that time, a part of the copyholders rent was paid as hop poles. The lime is the only tree species in the area which could produce this product (Worsøe 1996).

Methods

Field work

Before the profile sites were chosen, soil augering and sampling of the surface soil pH was done to find representative sites for soil profile digging. Surface soil pH sampling was done and compared with a 50 year old data set. The number of samples from the 1940's (Køie 1951) was multiplied by 5 to give comparable data sets. Sampling was then done in a grid at 35 places. The augering survey was done to a depth of no less than 1.5 metres. 61 observations were made inside and 52 were from outside the forest. Soil profiles were dug to 1.8 metres depth in four places, in areas that were homogenous. Two sites were chosen to represent the most developed Ultisols and Spodosols, respectively, and two sites in between to represent the transition. Profile descriptions were made according to Soil Taxonomy (Soil Survey Staff 1975), except that (g) was used to indicate pseudogley. Soil samples from each horizon were collected as bulk samples for chemical and textural analysis, as well as in steel tubes for bulk density determination. Profile descriptions and vegetation analyses are shown in Table 1.

Laboratory analyses

Soil samples were air dried at 50 °C for 14 days and subsamples were sieved (2 mm). Bulk density samples were weighed and 2 mm sieved. Volume and weight of material above 2 mm was subtracted from the final bulk density, which was calculated on basis of 110 °C dried, < 2 mm soil. pH was determined with a glass/calomel electrode in both 1:1 soil:water and 1:1 soil:1 M KCl suspensions. Texture analysis was made by wet separation using a 38 µm sieve; the fraction above 38 µm was dried and sieved; the fraction below 38 µm was determined in a starring pipette. Exchangeable cations were extracted with NH_4OAc (pH 7.0) on an automatic extractor according to Soil Survey Laboratory Staff (1992), and determined using a Perkin-Elmer® 5100 PC Atomic absorption spectrophotometer. CEC was also determined according to Soil Survey Laboratory Staff (1992) with NH_4OAc (pH 7.0). The following chemical methods were used to characterise the fine earth in the crushed subsamples. Iron and aluminium was extracted by dithionite-citrate-bicarbonate (Al_D and Fe_D) (Mehra & Jackson 1960), pyrophosphate (Al_P and Fe_P) (Soil Survey Staff 1972) and oxalate (Al_O and Fe_O) (Soil Survey Laboratory Staff 1992) and determined using a Perkin-Elmer® 5100 PC Atomic absorption spectrophotometer. Carbon was determined by dry combustion and weighing of the evolved CO_2 (Nørnberg & Dalsgaard 1994). Total phosphorus was determined, after ignition at 550 0C and extraction with 1 M HCl, using spectrophotometer as described by Svendsen et al. (1993). Nitrogen was determined by the total Kjeldahl method (Bremner 1965). Soil classification was done according to Soil Survey Staff (1996), supplemented with FAO (1998) names. Humus classification names were given according to Green et al. (1993).

Results

Soil distribution

The soil survey (figure 2) showed that brunification (as defined by Duchaufour (1982), as the process where iron freed by weathering coats the clay particles in situ), and clay transport was the dominant soil forming process inside the wood and in the surrounding arable land. Spodosols were found throughout the heathland areas outside the forest. In former agricultural land, only Ultisols were found. Ultisols are also the dominant soil type in the northern and central parts of the wood, whereas Spodosols are only found at the outermost 5 to 10 metres of the western and southern borders. With the exception of a small tongue in the central south of the wood, which is 100 metres long and extends 30 metres into the wood. The parent material here is fluvio-glacial deposited sand. The total data representing soil surface pH are not fully presented but the main findings are included in table 3. The average pH value is 4.17 with a standard deviation of only 0.233. pH minima and maxima are 3.61 and 4.65, respectively.

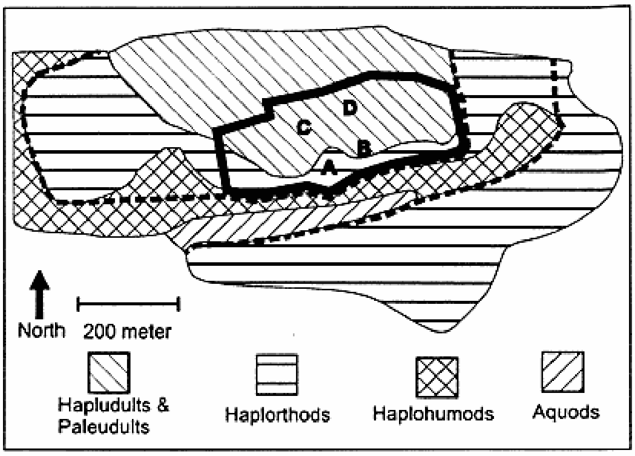

Figure 2: *Soil map of the wood and its surroundings with USDA (1996) classification. The contours of the wood are indicated with a bold black line, the limits of the glacial outwash vally south and east of the wood are by dotted lines, and the locations of the four soil profiles are shown with capital letters.*

Soil profiles

characteristics are shown in Tables 1, 2, and 3. Profile A is a Typic Haplorthod (Soil Survey Staff 1996) and Haplic Podzol (FAO 1998), with sandy texture throughout, very low base saturation in all horizons, $pH_{(H_2O)}$ surface values around 4, high C/N values and a humus decomposition of the mor humus type. It is located next to the forest border on parent material of fluvio-glacial sand. The plant community reflects a typical oak shrub forest, with mor decomposition. In the top 50 cm of the soil, there is on average only 1.9 % clay, while free Fe amounts 2.3 g Fe_D/kg soil.

Profile B, an Arenic Hapludult/Arenic Luvisol, was 15 metres from the podzolized forest border and was selected to represent the bisequal sandy and sandy loam parent material with A-E-Bw-Bt(g) or A-E-B(s)-Bt(g) horizon sequences (table 1). Ground flora is restricted to Anemona sp. and has a coverage of less than 5%. The profile has a strong textural contrast at 89 cm depth, where the clay content increases by 15 % (table 3). A diffuse pseudogley with Fe and Mn nodules covers 5-10 % of the profile just below this discontinuity. Base saturation data in table 2 shows low values

Table 1: Morphological data and site information for the four selected soil profiles.

Pedon/ Horizon	Depth cm	Munsell Colour (moist)	Structure	Consistency	Boundary	Distance to border[a] m	Vegetation
Profile A	**Typic Haplorthod**					10	**Oak forest**
Oi-Oe-Oa	3-0						*Quercus petraea/robur*
A	0-3	7.5YR 3/2	w f cr	lo	ai		*Frangula alnus*
E	3-20	7.5YR 7/2	s g	lo	ai		*Deschamsia flexuosa*
Bhs	20-25	5YR 3/3	s M	fi	ab		*Maiantherum bifolium*
Bs	25-55	7.5YR 5/6	w f sb	fr	di		*Pteridum aquilinum*
BC	55-99	10YR 5/6	s g	fr	gi		
2Cd	99-250	10YR 7/6	s g	fi			
Profile B	**Arenic Hapludult**					15	**Oak-lime forest**
Oi-Oe	4-1						*Quercus petraea/robur*
A	0-5	10YR 3/1	w g	lo	ci		*Tilia cordata.*
E/B	5-28	10YR 5/2	w g	lo	cw		*Anemone ssp*
Bw	28-89	10YR 5/2	w sb	fi	ab		
Bt(g)	89-120	10YR 4/6	s sb	v fi	cw		
2C	120-125	10YR 4/4	st	fi	cw		
3Cd	125-250	10YR 6/8	st	v fi			
Profile C	**Aquic Paleudult**					100	**Oak-lime forest**
Oe	2-0						*Quercus petraea/robur*
A1	0-7	10YR 3/2	s cr	fr	cw		*Tilia cordata*
A2	7-18	10YR 4/2	mo cr	fr	cw		*Anemona ssp*
Bw1	18-51	10YR 5/5	mo g	fr	cw		*Holcus mollis*
Bw2	51-61	10YR 6/5	mo M	fi	cw		*Oxalis acetosella*
Ed(g)	61-79	10YR 7/2	s M	v fi	cb		*Stellaria holostea*
Bt(g)	79-106	10YR 5/8	mo vc pr	fi	ds		*Konvellaria majaris*
BC	106-161	10YR 5/8	mo vc pr	fi	as		*Maiantherum bifolium*
2C	161-250	10YR7/8	s g	lo			
Profile D	**Aquic Paleudult**					150	**Oak-lime-hazel forest**
Oi-Oe	4-2						*Quercus petraea/robur*
A1	0-7	10YR 3/2	s vf cr	fr	gw		*Tilia cordata*
A2	7-31	10YR 4/2	mo f cr	fr	gw		*Corylus avellana*
B(g)1	31-38	10YR 6/4	M	fi	cb		*Anemone sp*
B(g)2	38-55	10YR 6/4	M	v fi	cb		*Oxalis acetosella*
Bt(g)	55-120	10YR 4/5	mo vc pr	v fi	ds		*Melica uniflora*
BC	120-150	10YR 4/4	mo vc pr	v fi	cw		*Milium effusum*
2C	150-250	10YR 4/6	M	fi			*Stellaria holostea*
							Dactylis glomerata

Structure: w-weak; mo-moderate; s-strong; vf-very fine; f-fine; me-medium; vc-very coarse; pr-prismatic; sb-subangular blocky; g - granular; cr - crumby; st -structureless; M-massive.

Consistence: lo-loose; v fr-very friable; fr-friable; fi-firm; v fi-very firm.

Boundary: a-abrupt; c-clear; g-gradual; d-diffuse; s-smooth; w-wavy; i-irregular; b-broken.

[a] Relative to the woods southern border, as this is the nearest border where podzolization has started (figure 2).

Table 2: Cation exchange characteristic, pH, phosphorus, C7N ratio, abd carbon content in the four selected profiles.

Pedon/ Horizon	Depth cm	pH 1:1 (H_2O)	pH 1:1 (KCl)	Total Carbon g kg^{-1}	C/N Ratio	Total P mg kg^{-1}	Exchangeable cations cmol$_c$ kg^{-1}				CEC$_{POT}$ pH 7 cmol$_c$ kg^{-1}	Base saturation %
							K	Na	Mg	Ca		
Profile A	**Typic Haplorthod**											
A	0-3	4.14	2.85	34	24	88	0.17	0.08	0.20	0.13	7.49	7.7
E	3-20	4.17	3.42	2	24	13	0.02	0.01	0.00	0.01	0.58	6.5
Bhs	20-25	4.19	3.45	7	20	44	0.05	0.02	0.03	0.03	4.11	3.1
Bs	25-55	4.69	4.32	5	26	60	0.03	0.02	0.01	0.00	2.52	2.4
BC	55-99	4.74	4.52	3	16	51	0.03	0.01	0.01	0.02	2.29	2.9
2Cd	99-250	4.54	4.41	0		35						
Profile B	**Arenic Hapludult**											
A	0-5	4.00	2.84	33	19	99	0.22	0.08	0.19	0.38	7.11	12.3
E/B	5-28	4.29	3.71	6	19	39	0.02	0.03	0.03	0.04	1.62	7.7
Bw	28-89	4.75	4.19	4	19	62	0.02	0.04	0.02	0.04	2.24	5.3
Bt(g)	89-120	4.74	3.62	3	12	88	0.23	0.14	0.71	0.18	13.81	9.0
2C	120-125	4.77	3.68	1		62						
3Cd	125-250	5.07	3.96	4								
Profile C	**Aquic Paleudult**											
A1	0-7	4.54	3.72	21	15	139	ND	ND	ND	ND	ND	ND
A2	7-18	4.61	3.86	10	17	224	0.05	0.03	0.02	0.05	2.66	5.4
Bw1	18-51	4.80	4.22	5	17	134	0.02	0.02	0.01	0.04	1.33	6.5
Bw2	51-61	4.85	4.40	4	20	117	0.01	0.02	0.01	0.02	1.20	5.2
Ed(g)	61-79	4.90	4.40	2	31	135	0.02	0.02	0.02	0.05	1.42	7.0
Bt(g)	79-106	5.04	3.78	2	12	97	0.23	0.11	1.36	0.53	10.02	22.3
BC	106-161	4.59	3.66	2	11	163	0.20	0.07	0.16	0.68	8.78	12.6
2C	161-250	5.08	4.11	1								
Profile D	**Aquic Paleudult**											
A1	0-7	4.13	3.62	19	13	252	0.33	0.03	0.04	0.33	6.27	7.7
A2	7-31	4.37	3.93	9	13	159	0.09	0.03	0.03	0.09	5.46	4.1
B(g)1	31-38	4.46	4.13	3	12	206	ND	ND	ND	ND	ND	ND
B(g)2	38-55	4.33	4.17	3	12	101	0.08	0.03	0.03	0.08	4.43	4.4
Bt(g)	55-120	5.07	3.76	2	6	190	0.23	0.10	1.55	0.23	11.19	25.8
BC	120-150	5.33	3.71	2		275	0.20	0.10	1.61	0.20	11.02	25.7
2C	150-250	5.56	4.11	1		253						

ND, not determined.

Table 3: Physical data for the selected soil profiles

Pedon/ Horizon	Depth cm	Stones > 2 mm	Sand 2000-50 µm	Silt 50-2 µm	Clay < 2 µm	Bulk density g cm^{-3}
Profile A	**Typic Haplorthod**					
A	0-3	0	89	9	2	1.1
E	3-20	5	92	7	1	1.68
Bhs	20-25	6	91	6	3	1.44
Bs	25-55	12	88	10	2	1.35
BC	55-99	11	87	11	2	1.58
2Cd	99-250	0	98	1	1	1.82
Profile B	**Arenic Hapludult**					
A	0-5	2	83	13	3	1.1
E/B	5-28	4	87	11	2	1.32
Bw	28-89	3	78	16	6	1.47
Bt(g)	89-120	4	57	22	21	1.54
2C	120-125	46	67	21	12	ND
3Cd	125-250	7	87	7	6	1.95
Profile C	**Aquic Paleudult**					
A1	0-7	2	71	21	8	1.0
A2	7-18	2	87	10	3	1.40
Bw1	18-51	12	90	8	2	1.41
Bw2	51-61	13	89	9	2	1.49
Ed(g)	61-79	10	83	15	2	1.83
Bt(g)	79-106	8	63	18	19	1.67
BC	106-161	3	60	22	18	1.68
2C	161-250	3	75	14	11	1.72
Profile D	**Aquic Paleudult**					
A1	0-7	9	86	9	5	1.0
A2	7-31	29	74	18	8	1.12
B(g)1	31-38	5	68	21	11	1.48
B(g)2	38-55	4	65	20	15	1.26
Bt(g)	55-120	4	56	22	21	1.62
BC	120-150	7	61	21	18	1.72
2C	150-250	1	69	19	12	1.60

ND, Not determined.

of 5-9 % in the subsoil but somewhat higher values, 12 %, in the A horizon. A C/N ratio of 19 is in agreement with the occurrence of a moder humus form. Profile B has on average, in the upper 50 cm, a clay content on 4.3 % and 2.3 g Fe_D/kg soil. The pH(H_2O) values of this soil resembles those of profile A, even through there are less morphological signs of podzolization, as no spodic horizon are recognised. Profile C is an Aquic Paleudult/Glossalbic Luvisol, with an A-Bw-Bt(g) sequence (table 1) in the same parent material as profile B. The profile has a strong textural contrast at 79 cm depth, where the clay content increases by 17 % (table 3) and the diffuse pseudogley covers 5-10 % of the profile in Bt(g). In contrast to profile B, an Ed(g) horizon was found just above the textural discontinuity. The texture is comparable with profile B, with an average clay content of 3.0 % in the upper 50 cm, only slightly less than in profile B. C/N ratios are 15 in the topsoil reflecting a moder type of decomposition. Base saturation is 5 to 7 % in the upper sequum, increasing in Bt(g) and BC to 22 and 13 %, respectively. The average total Fe_D content is 2.3 g/kg soil in the upper 50 cm, as in profile A and B. This site is comparable with profile B except for higher pH (both H_2O and KCl), lower C/N and slightly more Stagnic properties in Bt(g)/Ed(g).

Profile D has the most fertile parent material, but still classifies as an Aquic Paleudult/Stagnic Luvisol. It has sandy loam above sandy clay loam, base saturation of 25% from 50 cm depth, surface C/N ratio in the range of mull development with evidence of abundant soil fauna as e.g. earthworms and moles. Profile D has an average clay content in the upper 50 cm, of 9.9 %. The highest Fe_D content is found here, with 4.5 g/kg soil in average, again in the upper 50 cm. The humus form is mull and the ground flora is a herb community typical for nutrient rich and fertile soils.

The data on soil morphology, physical a nd chemistry properties reveal the trend that the soil and site conditions become more fertile from profile A to profile D. There is a clear difference in parent material and soil development from profile A to D. Profile B and C have comparable parent materials and major soil formation but differences in ground vegetation, phosphorus content, Stagnic properties at depth, and chemical and morphological indications of weak podzolization.

Discussion

Podzolization evidences: Distribution of Fe and Al

In this study, podzolization is an important process and its absence or presence can be seen in different ways. The forms of extractable Fe are chosen to illustrate the differences, as they are crucial when deciding which soil forming process dominate, and how pronounced it is (Duchaufour 1982). Fe_P is considered to represent organic bound amorphous forms of iron (Barrett 1997, McKeague et al. 1971), with some reservations as found by Parfitts and Childs (1988). Fe represents all pedologically freed iron, both amorphous and crystalline. The degree of podzolization is

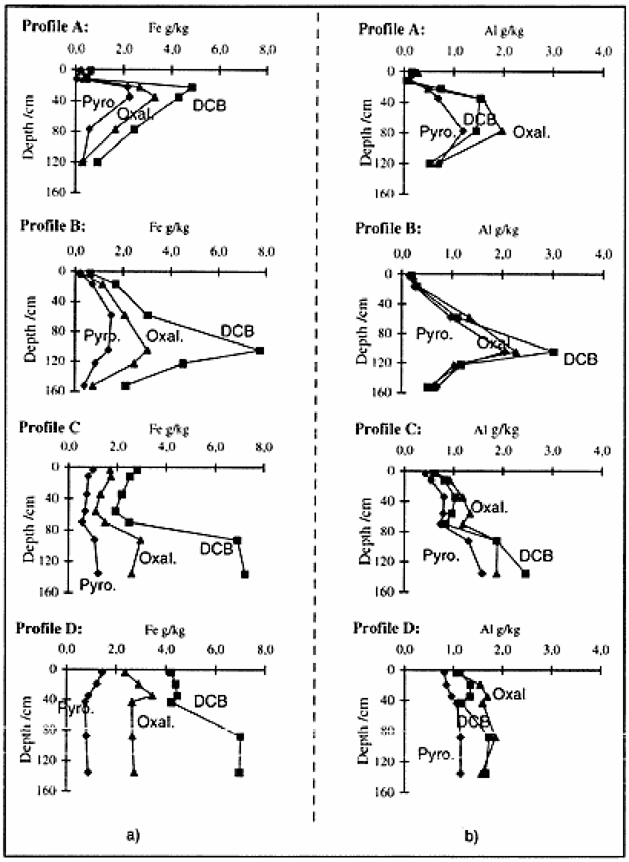

Figure 3: DCB, oxalat, and pyrophosphate extracted Fe a) and Al b) from bulk samples from the four selected soil profiles.

reflected in the ratio FeP/FeD. A high FeP/FeD ratio is indicative of the podzolization in B-horizons and the ratio is thus expected to be low under non-podzolizing conditions (Blume 1988). In brunified, soils evidence of Fe redistribution is absent or restricted to horizons with illuvial clay or redox accumulations. The Al extractable forms are presented in figure 3b, but the value of especially AlP and AlD in connection with podzolisation is poor (Barrett 1997, Kaiser & Zech 1996), so emphasis is on the Fe forms.

The content of extractable Fe is shown in figure 3a. Profile A, B and C has the same average Fe_D content until 50 cm but different vertical Fe distributions. The peaks in Fep, FeO and Fe_D (figure 3) are clearly coincident in profile A. This is evidence of strong podzolization with depleted topsoil and an enriched Spodic horizon. Profile D has no signs of podzolization. Fe_P is accumulated at the surface. Accordingly, the peak of Fe_D in the Bt(g)-horizon reflects the clay illuviation, and the Fe_P/Fe_D ratio has no subsurface maximum. Profile B has a high Fe_D content in the Bt(g) layer due to a higher clay content but the Fe_P has a maximum at about 50 cm, indicating a weak illuviation. The Fe_P/Fe_D distribution in figure 4 shows enriched FeP contents in the Bw horizon, so here organic bound Fe has been translocated. Profile C also has a high Fe_D content in the Bt(g) horizons (figure 3) but no peak in Fe_P. Furthermore, Fe_D reaches a maximum in the A horizon where Fe_P is immediately immobilised. Profile C has an A horizon Fe_P/Fe_D ratio (figure 4) as high as profile D but also has a minor peak in the Bw horizons, maybe indicating a weak podzolization. The content of Fe_P, Fe_O and Fe_D is high in the whole profile and there are no signs of a depleted A-horizon, so profile C has no morphological, and only very weak chemical signs of podzolization.

The different degree of Stagnic properties in profile B and C as reflected in the weak pseudogley at 80-100 cm, and is not believed to influence the podzolization and Fe distribution in the upper sequum. The soils in the transition zone between the sand and loamy sand parent material have thus, developed Ultisols, with few or no signs of starting podzolization. Profile B and C were expected to have developed bisequa (A-E-Bs-'E-Bt-C), as sandy soils under heath or oak forest in this region have all developed Spodosols. This is in accordance with studies by Schaetzl (1996), from similar bisequal parent materials in Michigan, USA. Here the podzolization was believed to be triggered by increasing sandiness and acidity due to the relative clay-impoverishment of surficial layers and/or a change in vegetation from mixed broad-leaved to coniferous.

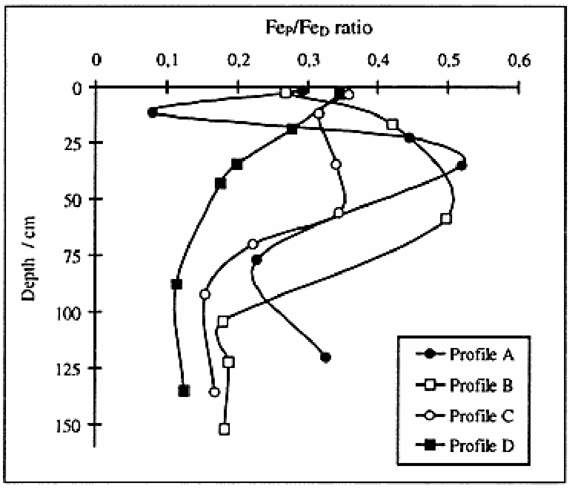

Figure 4: Fe/Fe_D ration from the four profils showing the relative distribution of organic bound Fe.

Preservation of the brunification process

The interesting question is whether or not the areas (profile B and C) classifying as Ultisols would have been Spodosols if i) the forest was absent, ii) they had a different tree species combination or iii) they had another wood management.

Parent materials, clay content, particle size, CEC, base saturation, FeD content, root depth, tree vegetation and cultural history are comparable in the two profiles. The features that separate profile B and C are i) microclimate, ii) ground vegetation, iii) surface pH and iv) phosphorous content to a depth of 1 metre. The explanation for podzolization/non-podzolization must then be found in one of these factors, or be related to an unknown historical or environmental event. Of the things listed immediately above i), ii) and iii) strongly interact and both ground vegetation and microclimate and was found to change from forests borders to forests interior (Andersen & Nielsen 1994). The phosphorus content interferes with ii), but has not been reported directly to influence the podzolization processes. This suggests that the forest's interior is less exposed to podzolization because of differences in soil ecosystem, forest floor plant community or micro-climatic conditions. The forest also influences soil development in this study, as profile B closest to the forest border has weak podzolization, whereas profile C further inside the forest show no indication of podzolization (figure 2). Despite that parent materials are comparable. That the agricultural land north of the wood has all developed Ultisols and no Spodosols is not a surprise, as it all has been cultivated for more than 1000 years.

Duchaufour (1982) gives threshold values for both clay percentage and free iron content, above which podzolization is inhibited. But these minimum contents are not reached in any of the profiles, so podzolization could then be expected from this alone. It should, however, be kept in mind that these results are from a natural, unmanaged beech forest in France, so the usefulness regarding this Danish managed oak-lime forest is questionable. Rackham (1980) supplied soil surface pH threshold values for podzolization/non-podzolization in eastern England. These are apparently more informative about the processes regarding this forest. Profile B has surface pH of 4.0 and is thus, below pH 4.1, which he states is the lower limit, where mull can form below lime trees. Profile C has a surface pH of 4.5 which is above the pH range (pH 4.4 - 4.1) where mulls can form with both oak and lime trees. If only the threshold values from Rackham (1980) are used, is it evident that podzolization is started in profile B, whereas the profile C still maintains a mull and probably brunification under the present day conditions. This hypothesis regarding pH, organic matter decomposition, is supported by the iron data so it seems that the interior of this lime-oak forest is capable of maintaining brunification due to sufficient active organic matter decomposition. When other authors find podzolized soil under primary Danish forests on sandy soils as here in Holtkrat (Aaby 1983, Andersen 1984), the question could be asked if not the coppice style and/or tree species combination has maintained an active soil biology that could support brunification and thus, suppress podzolization. The former coppice management might have inhibited podzolization, as a relatively large amount of light is allowed to reach the forest floor when the trees are coppiced with intervals of 5 to 10 years. As a result, a species rich ground flora will develop with a concomitant mull formation with active soil biota and the brunification process. If the observed distribution of podzolized/non-podzolized soils persists in the future is uncertain, as soil morphology and chemistry has been studied, but not the active soil processes e.g. by means of soil water chemistry. English investigations have suggested that a semi-natural ecosystem like this is not stable with today's nitrogen and sulphur deposition rates (Blake 1999). This point of view is supported by an observed pH decrease of 0.9 units in this forest within the last 50 years (table 4), when present day surface pH is compared with that of the 50 years old observations (Køie 1951). Only one in seven of Køie's (1951) samples had a pH value comparable to that found in the forest today. The average pH decrease for all samples is 0.9 pH units. This should be compared with the reliability of the measurements in the 1940's

Table 4: *Topsoil pH values from 1995 and 1940's. Data from the 1940's is from Kæie (1951), as are the names of the humus forms. The 1995 study was named according to Green eet al. (1993), but here grouped as in 1951.*

	Mor	Transition mor to mull	Mull
1940's investigation			
Average pH (H_2O)	3.9	5.2	5.2
Minimum-maximum	-	-	5.0-5.6
Number of samples	1	1	5
1995 investigation			
Average pH (H_2O)	3.96	4.23	4.30
Minimum-maximum	3.6-4.2	3.9-4.4	4.1-4.7
Number of samples	11	8	17

and now. Hallbäcken & Tamm (1986) found the electrode reliability to be 0.2 pH units or better. The soil:water ratio is poorly described by Køie (1951). The ratio used at that time was just sufficient to measure in free water e.g., around 1:1 or less, which gives similar or even lower pH than the method applied in the present study. Andersen et al. (1992) found a similar pH decrease, around 0.8-0.9 pH units in southern Jutland and also Hallbäcken & Tamm (1986) found it in southern Sweden.

These observations suggest that present day soil distribution might be changing fast due to soil acidification. This possibility still needs to be validated in Danish forest soils.

Conclusion

The soil map of the interior of the wood shows Ultisols in some places, where Spodosols were expected, due to the distribution of the parent material. The absence of podzolization inside the wood is attributed to the continuous forest cover since 6-7000 BC with lime-oak trees, which is capable of maintaining a mull or moder humus form. There are, however, small differences in texture, Stagnic properties at depth, and phosphorus content that might interfere. This is, however, unlikely as base saturation, Fe, upper sequum permeability, and clay percentage data contradicts or does not support a difference in soil forming factors which have all been reported to be the major factors influencing podzolization. Therefore, it seems that this managed oak-lime forest ecosystem is capable of recycling nutrients relatively quickly and hence of maintaining brunification. Thus, preventing podzolization all over the interior of the wood, where the surface pH values and the Fe and clay contents of the parent material are above certain threshold values. If the observed soil development pattern is stable, with our present day nitrogen and sulphur deposition rates, has not been investigated, but surface pH data shows a decrease of 0.7-0.9 units within the last 50 years, suggesting rapid changes in the soil genesis.

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