The Danish Pesticide Leaching Assessment Programme

Site Characterization and Monitoring Design for the Lund Test Field

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Preface

This report was prepared jointly by the following authors from the Geological Survey of Denmark and Greenland (GEUS), and the Department of Agroecology at Aarhus University (AGRO): Eline B. Haarder (GEUS), Preben Olsen (AGRO), Peter Roll Jakobsen (GEUS), Christian Nyrop Albers (GEUS), Bo Vangsø Iversen (AGRO), Mogens H. Greve (AGRO), Finn Plauborg (AGRO), Kirsten Kørup (AGRO), Morten Skov (AGRO), Lasse Gudmundsson (GEUS), and Annette E. Rosenbom (GEUS). While all authors contributed to the whole report, authors were responsible for separate aspects as follows:

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Table of Contents

1 Introduction

The detection of pesticides in groundwater over the past three to four decades has fueled the need for enhancing the scientific foundation for the existing approval procedure for pesticides and to improve the present risk assessment tools. A main issue in this respect is that the EU assessment, and hence also the Danish assessment, of the risk of pesticide leaching to groundwater, is largely based on data from modelling, laboratory or more seldom lysimeter studies. However, these types of data may not adequately describe the leaching that may occur under actual field conditions. Moreover, laboratory and lysimeter studies do not include the spatial variability of the soil parameters (hydraulic, chemical, physical, and microbiological soil properties) affecting pesticide transformation and leaching. This is of particular importance for silty and clayey till soils, in which preferential transport may have a major impact on pesticide leaching. In fact, field studies suggest that considerable preferential transport of several pesticides and their degradation products occurs (e.g. Jacobsen and Kjær, 2007; Rosenbom et al., 2015).

In Denmark most of the rural land is intensely cultivated and the drinking water supply is based almost entirely on untreated groundwater. To be able to evaluate the quality of the Danish groundwater, the Danish National Groundwater Monitoring Programme (GRUMO; Thorling et al., 2018) was initiated in 1989. During the 1990s this monitoring revealed increasing detections of pesticides and their degradation products in the groundwater. The growing public concern about the contamination of ground and surface waters by pesticides and their degradation products and GRUMO-results, paved the road for the dedicated monitoring of young, shallow groundwater formed underneath conventionally farmed arable fields. In 1998 the Danish Parliament adopted a resolution, which provided funding for the establishment of the Danish Pesticide Leaching Assessment Programme (PLAP), and the funding for PLAP has since then been renewed so that the programme has generated 20 years of monitoring data.

The overall purpose of PLAP is to investigate whether regular use of a number of pesticides approved for application on arable fields in rotation at maximum permitted dosages under Danish field conditions, can result in leaching of the pesticides and/or their degradation products to the groundwater in concentrations above the applicable requirement values for groundwater and drinking water. The survey results are reported annually in an English-language PLAP report with an independent Danish summary. The PLAP report contains results from the entire monitoring period (since 1999) with a focus on the two recent monitoring years. PLAP assesses leaching related to the use of pesticides on arable farmland solely, excluding forestry, fruit orchards and horticulture.

Initially, the PLAP was established with six conventionally cultivated arable fields, at which the monitoring of pesticides and degradation products in soil water and shallow groundwater was possible both upstream and downstream the field. On four of the fields, the shallow subsurface consisted of clayey till soils, and on two fields it consisted of sandy soils. On all PLAP fields the distance from the surface to the groundwater is approximately 1-4 m. This enables a short response time for authorities to take the appropriate precautionary measures, in case the application of a pesticide causes unacceptable leaching to the groundwater downstream the treated area of the field, documented by analysis results on water collected from both upstream and downstream well screens installed adjacent to the treated area of the field. The monitoring design as well as descriptions of each field site was published in Lindhardt et al. (2001). Due to economic constraints, monitoring at one of the clayey till field sites (Slaeggerup) had to be terminated 1 July 2003.

Since its initiation in 1999 the PLAP has published 18 reports that present the results of the pesticide monitoring at the field sites. Based on 20+ years of monitoring it has become evident that clayey till soils can in fact be considered vulnerable. Data from PLAP has repeatedly shown that the number of detections of pesticides and/or their degradation products in water from drainage/suction cups (1 m depth) and groundwater is higher for clayey till soils than for sandy soils (Rosenbom et al., 2015; Rosenbom et al., 2021). Long-term leaching of pesticide degradation products in high concentrations takes place at the sandy fields, whereas both pesticides and their degradation products are found to leach dynamically/momentarily through the clay till fields. The presence of biopores and fractures in the clayey till soils is responsible for this increased vulnerability to leaching of pesticides and their degradation products.

In 2015, provisional funding for a period of four years made it possible to include an extra field located on a soil type not covered by the existing five field sites: a fractured clayey till overlaying chalk. The search for a suitable field site was initiated in 2015. Based on the geological knowledge of the area, geological profiles including depth to groundwater obtained from a drilling survey and maps on tile drain systems, it was decided to establish the field site near the village of Lund on the southern coastline of the Stevns peninsula in Southeastern Zealand (Figure 2.1). With the inclusion of a clayey till soil overlying chalk in the PLAP, it is expected that the understanding of the vulnerability of this type of soil regarding pesticide leaching will be improved.

Field work at the Lund field site took place in the autumn of 2016 and spring of 2017; and monitoring was initiated on 1 July 2017. As with the existing PLAP fields, extensive investigations of the geological, pedological and hydrological properties and conditions were undertaken. In addition to the drilling of piezometer and monitoring wells and excavations for installation of soil sensors, a large excavation to a depth of 6 m was made in the neighboring field (Figure 3.1). Here, among other investigations, mapping of biopores and fractures was done. Data from the field work was used in a project termed "Transporer", also funded by the Danish EPA, investigating the mobilization, retardation, and transport of sorbing pesticides in macropores (Johnsen et al., 2020). Additionally, the presence and motility of bacteria in the different soil domains being exposed via the 6 m deep excavation were investigated (Bak et al., 2019; Krüger et al., 2019).

Based on the above-mentioned extensive field investigations the present report presents and characterizes the new PLAP field site at Lund.

2 Site selection

In general, the risk of groundwater contamination by pesticides is dependent on both natural factors such as soil type, hydrogeology, and climate, as well as the agricultural practices used on the specific fields. Selection of appropriate field sites for the PLAP is critical because the results must be generally applicable if they are to be utilized in the pesticide approval procedures. Further, it is important that the landowner provides general permission to use the field and install the equipment needed, and there must be all-year accessibility by road as well as electricity for the many installations needed. The agricultural practices such as crop types and previous pesticide applications should be known approximately five years back, such that the baseline conditions at the field can be evaluated. For Lund, such permissions as well as information for the period 2012-2016 have been obtained. It is also important that the field has not previously been subjected to e.g. excess drilling or excavations. Within the PLAP it is made sure that all installations and soil sampling deeper than 25 cm depth are restricted to a buffer zone surrounding the treated area.

Knowledge of the very shallow subsurface (i.e. to 1.m depth) stems from the systematic and detailed mapping of Quaternary deposits in Denmark carried out by GEUS since 1888. The geologic composition of sediments to a depth of 5-10 m depth is known from geological maps, profiles, outcrops, excavations, well data and geophysical data. The uppermost geological layers in general have a complex glacial origin and have been subjected to glaciotectonic activity, and therefore vary considerably in grain size distribution, internal structure, and mineralogical and geochemical composition both in the vertical and horizontal direction.

When choosing a suitable field site, it is also important that the groundwater level is close to the soil surface, and thus has a rapid response downstream of the field. It is also important that the amount of surface runoff is minimal, which is acquired by choosing a field that has a low topographic slope, less than 2%. In Denmark, most agricultural areas comprising structured soils are drained. The drain system must be well known, isolated from the surrounding fields and have a single outlet. Moreover, it is important that the tile drain system is old, such that the soil can be expected to have had time to consolidate. Base flow (contribution from groundwater) in the tile drain system should be avoided to avoid any possible dilution.

The most important climatic parameter controlling pesticide leaching is the precipitation, which, unlike temperature and evaporation, varies across Denmark even though the country is relatively small. The annual mean precipitation in Denmark during the period 1961–90 was 712 mm yr^{-1}, varying from 550 mm yr^{-1} in the Great Belt region to 900 mm yr^{-1} in the southern part of Jutland (Frich et al., 1997). Furthermore, the inter-annual variation in precipitation is generally higher in southern Jutland than on Zealand. Differences in pesticide leaching potential at different field sites cannot be ascribed to the variation in annual mean precipitation alone. The transport of pesticides through variably saturated soil is controlled by a complex interaction between the initial moisture content in the soil, the intensity of the precipitation as well as the timing between spraying and precipitation.

When PLAP was initiated it was required that the pesticide testing was carried out under worst-case conditions, and thus the field sites needed to be placed on so-called *vulnerable* soil types having an alleged high risk of groundwater contamination. Previously, vulnerable soils were mainly considered to be coarse-textured sandy soils with a low organic matter content. However, findings from the Danish National Groundwater Monitoring Programme (GRUMO) indicated that pesticide leaching was possible in areas dominated by structured soils as well. Consequently, it was decided to include field sites in PLAP that represent the main cultivated soil types. The field at Lund supplements the initial selection of fields with a highly fractured till on top of limestone and chalk deposits.

2.1 Overview of PLAP field sites

With the addition of the Lund field site, the PLAP at present encompasses five field sites being monitored (Jyndevad, Silstrup, Estrup, Faardrup and now Lund) and one field site on "stand-by" (Tylstrup). Two of the sites are located on sandy soil and four on clayey till soil. Key data for each site is presented in Table 2.1 and the location of each site is shown in Figure 2.1. The cultivated area of the fields varies between 1.2 and 2.4 ha. Three field sites (one sandy soil and two clayey tills) are found in regions with relatively high precipitation, while the other three are in relatively drier regions. All clayey till field sites have tile drain systems installed at approximately 1.1 m depth. For a more in-depth description of the original site selection criteria and the methods used, please refer to the publication "Site characterization and monitoring design", which was published in 2001 following the establishment of PLAP (Lindhardt et al., 2001).

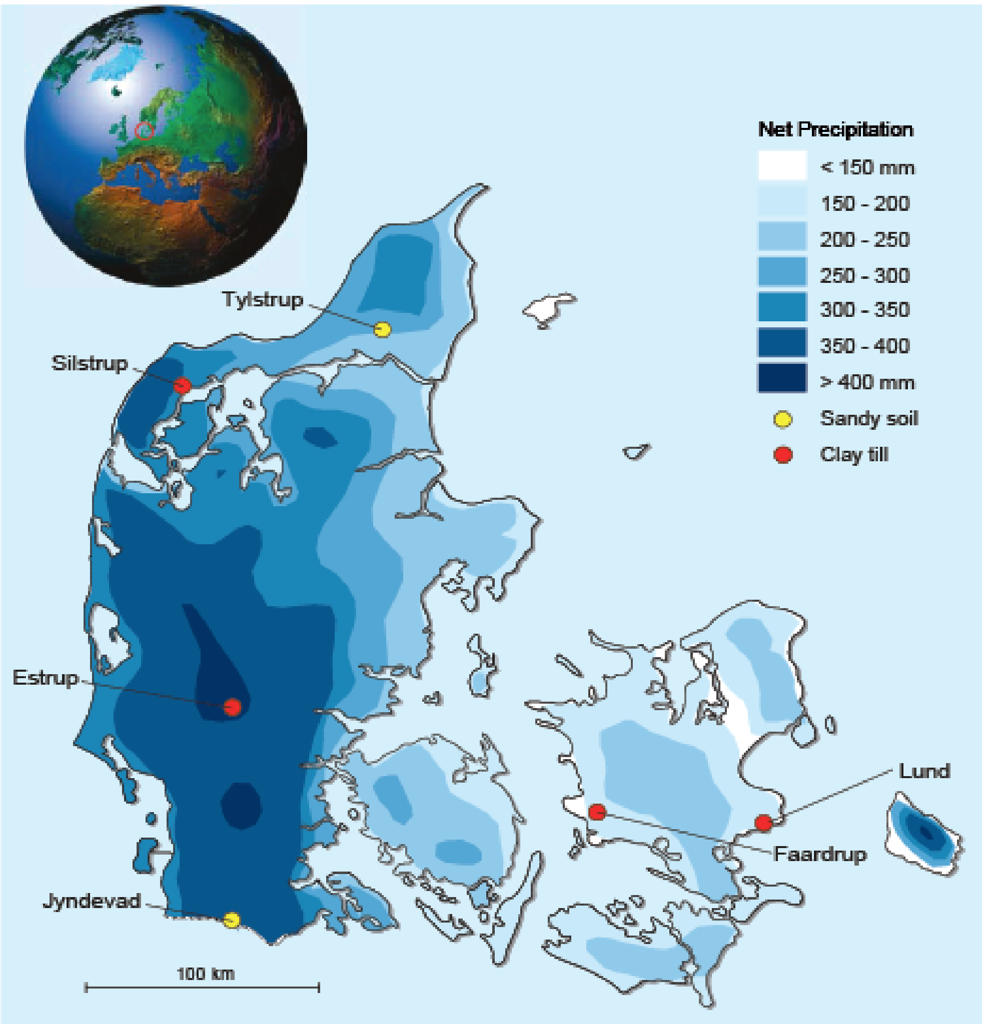

Figure 2.1. *Location of PLAP fields and annual net precipitation across Denmark* *https://www2.mst.dk/Udgiv/publikationer/1992/87-503-9581-5/pdf/87-503-9581-5.pdf, in Danish.*

Table 2.1. Key data for the six PLAP fields						
	Tylstrup	**Jyndevad**	**Silstrup**	**Estrup**	**Faardrup**	**Lund**
Location	Broenderslev	Tinglev	Thisted	Askov	Slagelse	Lund
Precipitation[1)] (mm y^{-1})	668	858	866	862	558	577[4)]
Pot. evapotransp.[1)] (mm y^{-1})	552	555	564	543	585	568[4)]
Width (m) x Length (m)	70 x 166	135 x 180	91 x 185	105 x 120	150 x 160	80 x 230
Area (ha)	1.2	2.4	1.7	1.3	2.3	2.1
Tile drain	No	No	Yes	Yes	Yes	Yes
Depths to tile drain (m)			1.1	1.1	1.2	1.1
Monitoring initiated	May 1999	Sep 1999	Apr 2000	Apr 2000	Sep 1999	July 2017
Geological characteristics						
– Deposited by	Saltwater	Meltwater	Glacier	Glacier /meltwater	Glacier	Glacier
– Sediment type	Fine sand	Coarse sand	Clayey till	Clayey till	Clayey till	Clayey till
– DGU symbol	YS	TS	ML	ML	ML	ML
– Depth to calcareous matrix (m)	6	5–9	1.3	1–4[2)]	1.5	1.5
– Depth to reduced matrix (m)	>12	10–12	5	>52)	4.2	3.8
– Max. fracture depth3) (m)	–	–	4	>6.5	8	>6
– Fracture intensity 3–4 m depth (fractures m^{-1})	–	–	<1	11	4	<1
– Ks in C horizon (m s^{-1})	$2.0 \cdot 10^{-5}$	$1.3 \cdot 10^{-4}$	$3.4 \cdot 10^{-6}$	$8.0 \cdot 10^{-8}$	$7.2 \cdot 10^{-6}$	$5.13 \cdot 10^{-5}$
Topsoil characteristics						
– DK classification	JB2	JB1	JB7	JB5/6	JB5/6	JB5/6
– Classification	Loamy sand	Sand	Sandy clay loam / sandy loam	Sandy loam	Sandy loam	Sandy loam
– Clay content (%)	6	5	18–26	10–20	14–15	13.7-16.7
– Silt content (%)	13	4	27	20–27	25	30.9-33.4
– Sand content (%)	78	88	8	50–65	57	49-53.7
– pH	4–4.5	5.6–6.2	6.7–7	6.5–7.8	6.4–6.6	6.9-7
– TOC (%)	2.0	1.8	2.2	1.7–7.3	1.4	0.9-1.7

[1)] Yearly normal based on a time series for the period 1961–90. The data refer to precipitation measured 1.5 m above ground surface. [2)] Large variation within the field. [3)] Maximum fracture depth refers to the maximum fracture depth found in excavations and wells. [4)] Scharling, 2000.

Table 2.2. Site location and ownership, Lund	
Region	Zealand
Municipality	Stevns
Land registry no.	5i, Lyderslev, Lund
Ownership	Private, leased by Dep. of Agroecology, AU

Table 2.3. Cultivation history for Lund	
Year	Crop
2012/13	Winter wheat
2013/14	Winter rape
2014/15	Winter wheat
2015/16	Winter wheat

2.2 Location, ownership, earlier cultivation, and use

The field site at Lund is situated in the southern part of the Stevns peninsula in the eastern part of Zealand 500 m west of the village Lund (Figure 2.2). The area is located south of the road Lundeledsvej, approximately 500 m north of the shoreline at an elevation of 7-10 m above sea level. It covers an area of 2.76 ha, of which the cultivated area makes up 2.06 ha. The field is privately owned and leased by the Department of Agroecology at Aarhus University. The field has previously been conventionally farmed using standard cultivation practice.

Plans were made to install tile drains beneath the field as early as in 1907, which means the field has been used for agricultural purposes for more than 100 years. Maps from the first half of the 1800s show that the main road to the village Lund used to be approximately 50 m south of the current location of Lundeledsvej, which means this road passed through the northern part of the field site. The road is no longer visible at the surface, and we did not encounter any traces of the road during field work at the field site. The tile drain system at Lund was installed in 1943 based on the tile drain plan designed by Hedeselskabet in 1907. The tile drain system beneath the cultivated area consists of five parallel N-S trending tile drains, with the main collector drain in the southeastern corner of the field. All tile drains were clayware tile with a diameter of 55 mm in the laterals and 110 mm in diameter for the mains. Table 2.3 shows the cultivation history of the Lund field from 2012-2016, i.e. in the years prior to the field being included in PLAP. A list of pesticides used during 2012-2016 can be found in Appendix A.

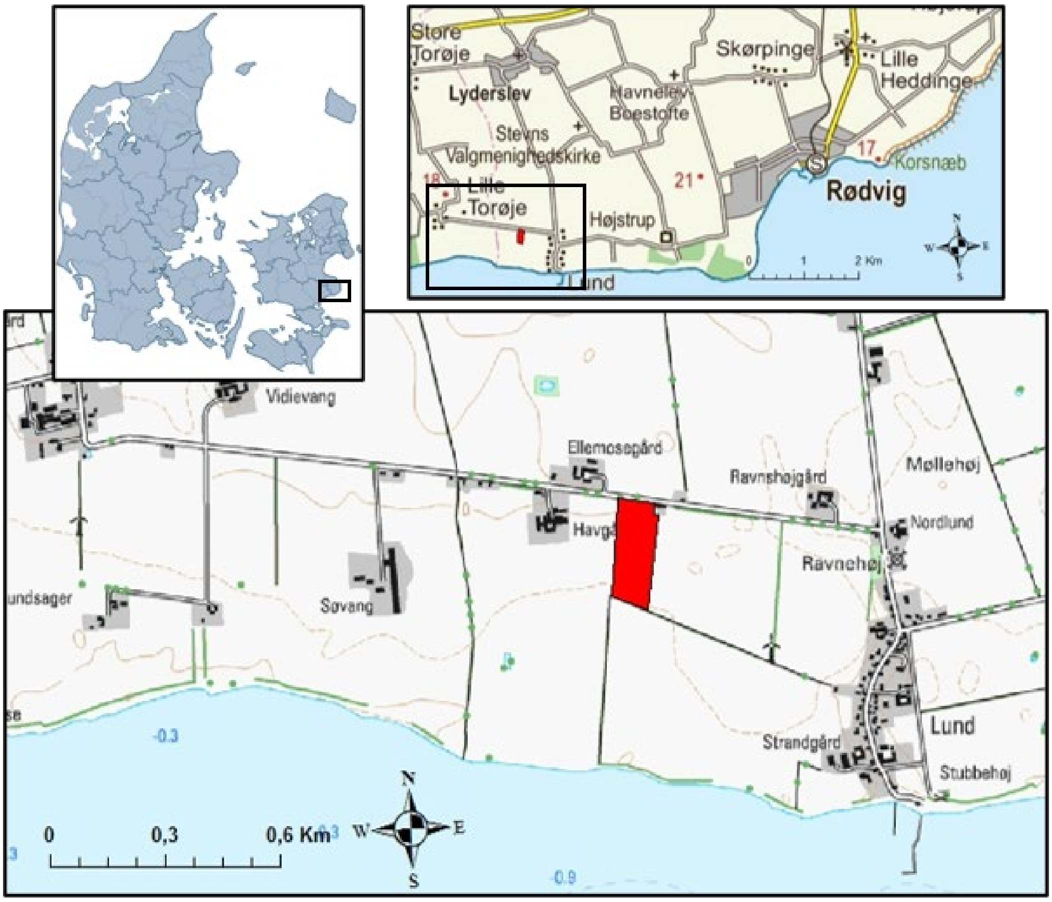

__Figure 2.2__ Location of the PLAP field Lund.

3 Installations and modifications of the field

Before monitoring could be initiated at the Lund field site, it was necessary to make the same type of installations and modification as had been done on the other tile drained PLAP fields. Whereas horizontal wells are installed beneath the cultivated area of the original five fields this has not yet been done at Lund. For more information about these types of installations the reader is referred to the report published in 2001 (Lindhardt et al., 2001), where a more in-depth description of the PLAP monitoring design can be found, and Rosenbom et al. (2021) in which Appendix 8 describes the design of the new horizontal wells installed at the five PLAP-fields in 2011.

Field work and installation of technical instrumentation at the field site was carried out during September 2016 - April 2017. The instrumentation at the new field site in Lund is similar to the older PLAP field sites. Further, the Lund site is equipped with an automatic climate station and rain gauge for precipitation measurement. The locations of all installations are shown in Figure 3.1.

The buffer zone around the cultivated area is 12 m wide towards the north and 8 m to the south. Along the western side of the cultivated area, the buffer zone is between 5 and 8 m wide, and along the eastern side it is 10 to 16 m wide. In the southeastern corner of the area, within the buffer zone, a 2.5-by-3.5 m shed was built for housing the drainage well and other permanent sampling and monitoring equipment. The climate station and rain gauge are located in the buffer zone north of the shed.

3.1 Tile drain system and drainage collection

To isolate the tile drain system of the "treated area" (white area in Figure 3.1), additional drainpipes (110 mm diameter) were installed in the buffer zone west, north, and east of the cultivated area. These additional drainpipes ensure that only drainage from within the "treated area" is collected in the drainage monitoring well, which was installed in the shed. As previously mentioned, the five parallel tile drain lines (laterals) were installed in 1943 and have not been affected by the addition of the surrounding tile drains. Figure 3.1 shows the location of both the original tile drains as well as newly installed drains and collector pipes. The drainage monitoring well is located inside (underneath) a shed to protect the equipment from the weather. An electrical heater in the shed keeps the temperature above 5°C.

The glass fiber monitoring drainage well is 1.25 m in diameter and 2.2 m deep and is constructed with a sharp-crested V-notch weir (Thomson weir) made of 5 mm stainless steel plate. The Thomson weir is the most exact profile for measuring runoff with a large variation in flow rate (Bos, 1976). The same system is used for measuring drainage at the other PLAP fields having tile drain systems. A 30° V-notch angle was chosen as a compromise between high precision at relatively low flow rates and low sensitivity to blockage of the notch. The height of the notches is not less than 30 cm.

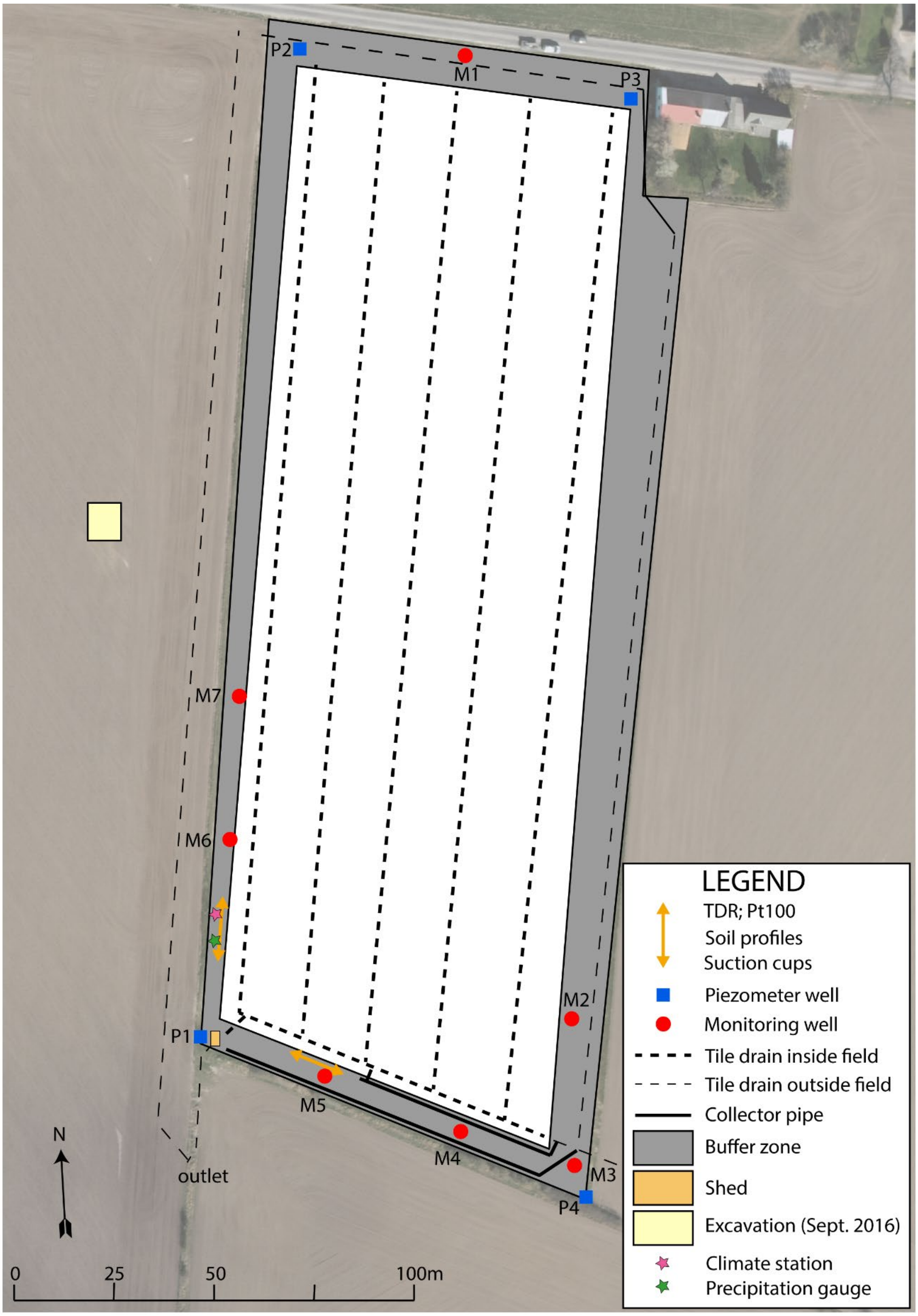

Figure 3.1*. Overview of the Lund field. The innermost white area indicates the cultivated area ("treated area"), while the grey area indicates the surrounding buffer zone. The positions of the two well types in the buffer zone are given – the vertical monitoring wells M1 (upstream) and M2-M7 (downstream) together with the piezometer wells in each corner of the field. Additionally, the location of the tile drain system of the field is visualized including inside and outside field tile drains plus collector pipes bringing the drainage from the cultivated area only to the drainage monitoring well installed in the shed.*

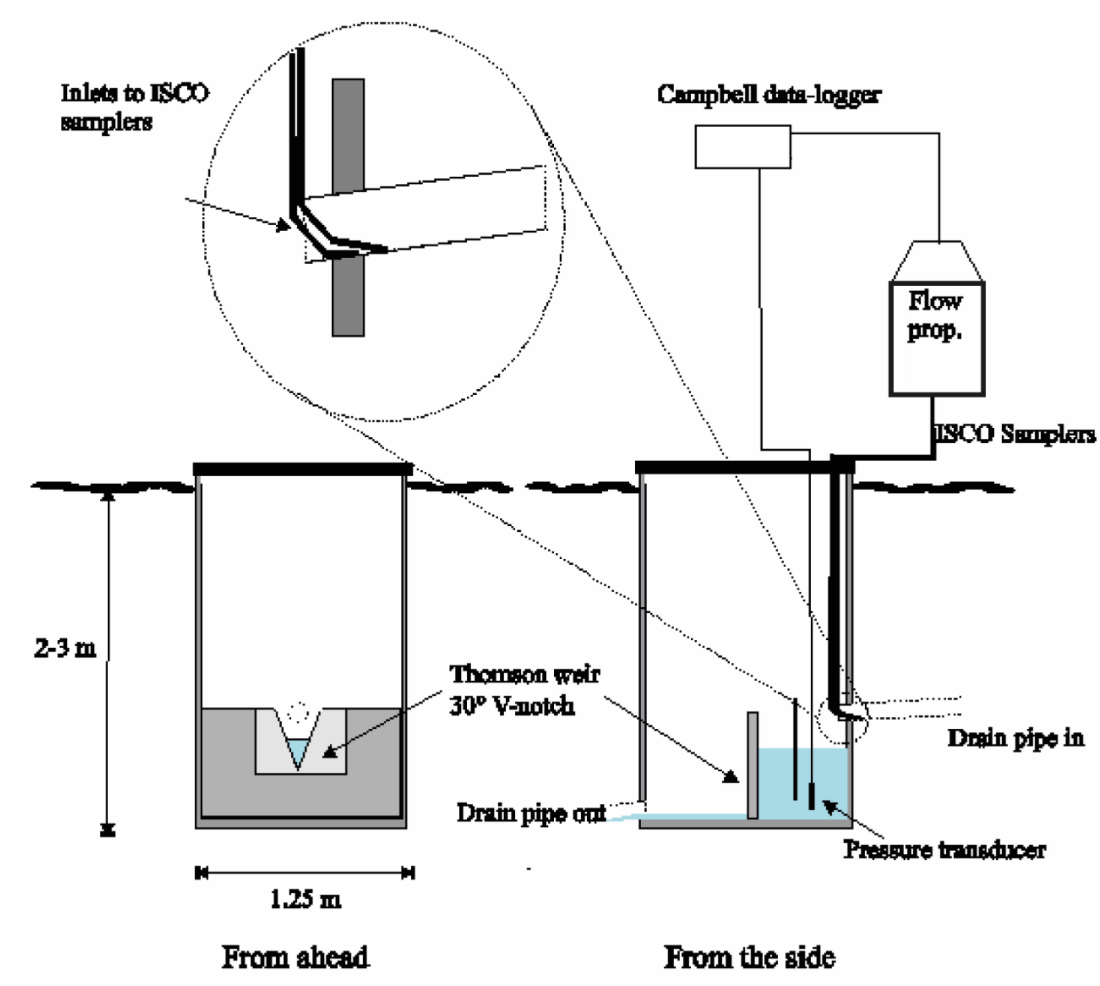

Figure 3.2. *Drainage monitoring well with Thomson weir and water sampler (Lindhardt et al., 2001).*

Table 3.1. Infiltration per ha vs. flow in the tile drain system.

Height above the Thomson weir, h (cm)	Flow in tile drain system, Q (L s^{-1})	Infiltration, q (mm ha^{-1} day^{-1})
5	0.23	2
10	1.2	10
20	6.8	59
30	19	164

A Thomson weir requires a free fall from the weir notch of at least 25 cm. The water level above the V-notch is monitored using a pressure transducer (Ott PLS sensor, OTT HydroMet GmbH, DE). The transducer is mounted in a stainless-steel tube (length 1100 mm, diameter 21.5 mm) fixed to the wall of the well by means of a stainless-steel clamp (Figure 3.2). To protect the transducer from turbulent water at high flow rates, it is placed in a special chamber behind the weir and as far away from the drain inlet as possible (Figure 3.2). The pressure transducer is connected to the central Campbell datalogger. Manual measurements of the water height at the V-notch are collected weekly and used for calibration and validation of the transducer measurements. An additional logger, IN-SITU Aqua TROLL 200, is also installed upstream of the weir for measurement of water level, temperature, and conductivity. At Lund there was a build-up of water downstream of the weir because the drainage flow exceeded the capacity of the collector pipe at the outlet of the well. To maintain the proper free fall height from the weir it was necessary to install a pump downstream of the weir.

The drainage samples are collected using ISCO 6700 (ISCO, Inc. US) samplers equipped with eight 1,800 ml glass bottles (boron silicate), teflon suction tubes and intakes of stainless steel. The intakes are placed a few centimeters into the inlet of the drainpipe to ensure sampling of "flowing" drainage and particulate matter. Sampling is carried out as flow-proportional, i.e. a sample of 200 mL is taken by the ISCO sampler for every 3000 L of drainage. During periods of continuous drainage one weekly sample of the drainage is collected for pesticide monitoring.

3.2 Wells

3.2.1 Piezometer wells

Four piezometer well pairs used for monitoring of the groundwater table were installed in each corner of the field in the buffer zone surrounding the cultivated area. Each pair consisted of a deep and a shallow 1-m long screen. The piezometer wells were drilled from the surface using a 6" (152 mm) solid stem auger, and PEH pipes with a 63 mm diameter were used for casing and screen. Type 2 filter sand with grain sizes from 0.7-1.2 mm was used as filter pack material, and the wells were sealed from 0.2 m above the screen to the surface using bentonite (CEBOGEL, CEBO International, Netherlands). Table 3.2 shows details for each piezometer well in terms of total depth and screen depth. Not all piezometer wells have a specific DGU-number in the Jupiter database, since they are too close (less than 1 m) to one another. At P2 and P3 it was necessary to establish a third well with filter screen depth at 5-7 m depth due to problems during installation of the first wells.

Table 3.2. Piezometer wells at the Lund field site.

DGU-no.	PLAP-name	Depth (m)	Screen depth (m)
223.154	P1-1	7.0	6.0 - 7.0
223.155	P1-2	10.7	10.0 - 10.7
-	P2-1	7.0	6.0 - 7.0
223.156	P2-2	9.1	7.0 - 8.0
223.149	P2-3	7.0	5.0 - 7.0
-	P3-1	7.0	6.0 - 7.0
223.157	P3-2	10.0	9.3 - 10.0
223.150	P3-3	7.0	5.0 - 7.0
-	P4-1	5.8	4.8 - 5.8
223.158	P4-2	9.0	7.9 - 8.9

3.2.3 Monitoring wells

Monitoring wells were installed as one monitoring well cluster upstream (M1) and six well clusters downstream of the field site (M2-M7). Each well cluster contains three separate 1 m screens covering the depth interval 3-5 m, and one screen covering the depth between 5-7 m, see Table 3.3. Similar to the piezometer wells, the monitoring wells were drilled from the surface using a 6" (152 mm) solid stem auger, and PEH pipes with a 63 mm diameter were used for casing and screen. Type 2 filter sand with grain sizes from 0.7-1.2 mm was used as filter pack material, and the wells were sealed from 0.2 m above the screen to the surface using bentonite (CEBOGEL, CEBO International, Netherlands).

Table 3.3. Monitoring well clusters at the Lund field site.

DGU-no.	PLAP-name	Depth (m)	Screen depth
223.142	M1	7.0	2.0-3.0 m, 3.0-4.0 m, 4.0-5.0 m, 5.0-7.0 m
223.143	M2	7.0	2.0-3.0 m, 3.0-4.0 m, 4.0-5.0 m, 5.0-7.0 m
223.144	M3	7.0	2.0-3.0 m, 3.0-4.0 m, 4.0-5.0 m, 5.0-7.0 m
223.145	M4	7.0	2.0-3.0 m, 3.0-4.0 m, 4.0-5.0 m, 5.0-7.0 m
223.146	M5	7.0	2.0-3.0 m, 3.0-4.0 m, 4.0-5.0 m, 5.0-7.0 m
223.147	M6	7.0	2.0-3.0 m, 3.0-4.0 m, 4.0-5.0 m, 5.0-7.0 m
223.148	M7	7.0	2.0-3.0 m, 3.0-4.0 m, 4.0-5.0 m, 5.0-7.0 m

3.2.4 Temporary wells

Prior to making the 6 m deep excavation in the neighboring field West of the PLAP field, three boreholes were drilled at this location. The purpose of installing these boreholes was to acquire borehole Ground Penetrating Radar (GPR) data (see chapter 7.4). These boreholes were also included in the JUPITER database, see Table 3.4, however they do not exist anymore, since the entire area was excavated.

Table 3.4. Temporary wells at the Lund field site.

DGU-no.	PLAP-name	Depth (m)	Screen depth (m)
223.151	GPR-NV	7.1	-
223.152	GPR-NOE	7.0	-
223.153	GPR-S	7.0	-

3.2.5 Groundwater level

Groundwater level measurements in the piezometers from September 2016 indicated that the direction of groundwater flow was towards the south, as expected based on the field site's proximity to the coast. Figure 3.3 shows measurements of depth to the groundwater table in six screens (M1.3, M3.2, M3.3, M4.3 and M6.2 and P1.1) at the Lund field site from late 2016 to the summer of 2020. The data until July 2018 were also presented in the PLAP report Rosenbom et al. (2020). Many of the screens did not initially respond well to seasonal fluctuations in the groundwater table and was pumped clean. The wells are now responding as expected and data from 2018-2020 show a more balanced and natural response. The other wells at the field site are also pumped and cleaned to improve their hydraulic response, and for future monitoring it needs to be defined, which wells are in contact with the hydraulic active system in the clayey till.

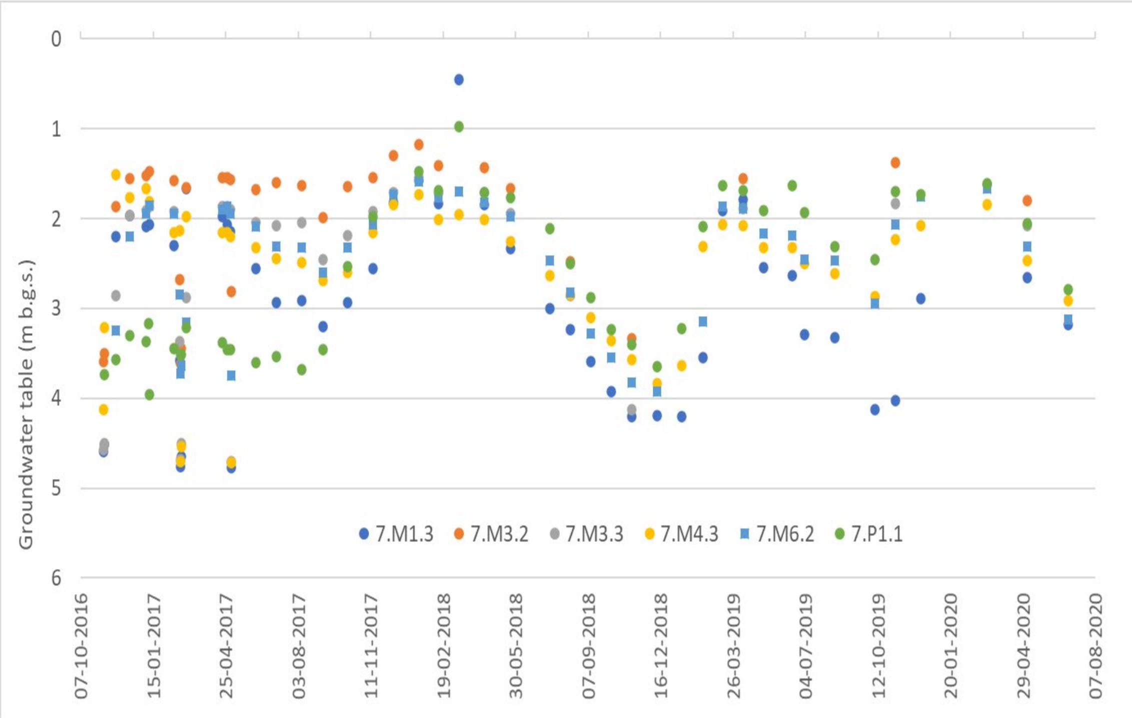

Figure 3.3. *Depth to groundwater table (m) measured in selected well screens 2016-2020.*

3.2.6 Water sampling

At Lund, a different sampling procedure is applied compared to the other PLAP fields. Water samples for pesticide monitoring are collected using a Whale High Flow Sub pump (model GP 1652) equipped with teflon tubes. Each monitoring well intake has its own designated pump and tubes (28 in total = 7 well clusters with 4 intakes each), which are removed from the well between samplings. This is done to ensure that there is no contamination of water samples from the equipment. As is the case for the other PLAP sites, not all wells have automatic data acquisition equipment installed. At Lund, the wells M5-4 and P4-2 are currently equipped with In-Situ Aqua TROLL 200 loggers (In-Situ Inc., CO, USA), which measure water level, temperature, and conductivity.

3.3 Soil sensors, suction cups, TDR and Pt-100 sensors

Two 15-meter long and 2.5 m deep trenches were excavated in the western and southern buffer zone surrounding the cultivated area of the field. The trenches were excavated by the Department of Agroecology, Aarhus University, using a backhoe, and were used for installation of soil sensors as well as for pedological sampling and profile description. Time Domain Reflectometry (TDR)sensors and Pt-100 temperature sensors were installed in the northern-most and eastern-most ends of the trenches, while suction cups were installed in the southern-most and western-most ends of the trenches. Location of the soil sensors can be seen on the overview of the field site in Figure 3.1. The suction cups, TDR and Pt-100 sensors at Lund were installed as depicted in Figure 3.4 as it was made sure that there was no digging or disturbance of the soil within the cultivated area.

- The suction cups installed in 1 m depth were placed at a horizonal distance of 1 m from the edge of the field.
- The suction cups installed in 2 m depth were placed at a horizontal distance of 1.5 m from the edge of field.
- The installation holes were drilled manually with a hand auger.
- Suction cups were installed with four replicate probes at 2 depths, 1 m and 2 m.

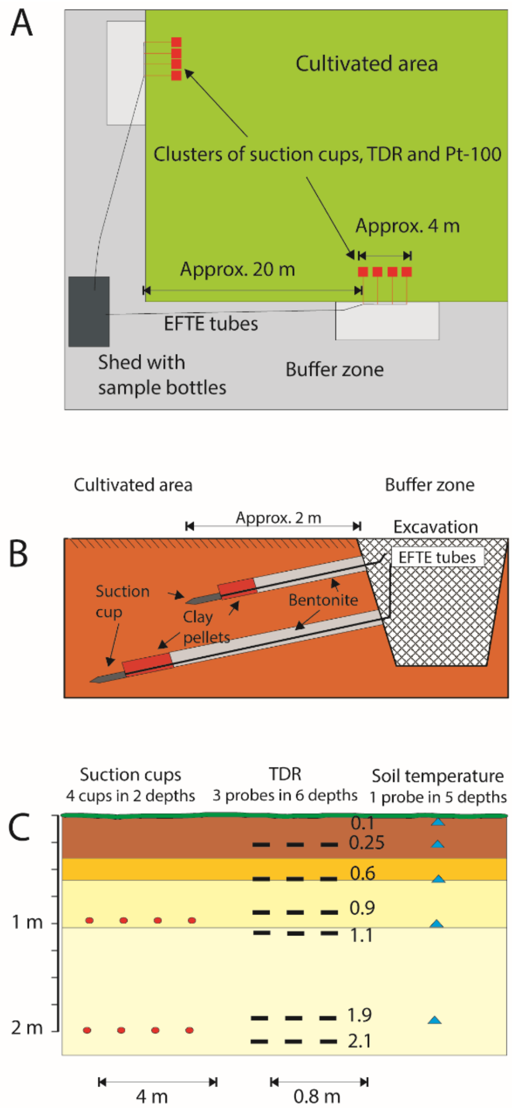

Figure 3.4. *A) Location of suction cups, TDR and soil temperature probes, B) a cross section showing the installation of the suction cups, and C) a plan view of an excavation wall indicating the location of the suction cups, TDR and soil temperature probes. (Lindhardt et al., 2001)*

3.3.1 Soil moisture

Soil moisture is measured using a CR10X-controlled Time Domain Reflectometry (TDR)-system. The central unit in the TDR-system is the cable tester from Tektronix 1502C (Tektronix Inc., Beaverton, OR, USA). The soil moisture probes are developed at Department of Agroecology, Aarhus University and consist of a 40 m coaxial cable RG214C/U (Mikkelsen Electronic A/S, DK) connected through a solid plastic box to three 30 cm steel rods spaced 2.5 cm apart. The accuracy of the soil water measurements is around 1 vol. %. Soil moisture is measured in two profiles at each site at the depths of 0.25, 0.6, 0.9, 1.1, 1.9 and 2.1 m (Figure 3.4C), with three replicate probes at each depth. A CR10x datalogger (Campbell Sci., UK) records hourly values of soil moisture. Communication is established via a modem using GSM phone transmission every night for daily remote data collection.

3.3.2 Soil temperature

Soil temperature is measured with platinum resistance thermometers (Pt-100, length: 10 mm, diameter: 5 mm). The accuracy of the measurements is ±0.1°C (Class B ± (0.3 + 0.005 x T_{actual}) °C). Soil temperature is measured in two profiles at each site with one sensor at each of the following depths: 0.1, 0.25, 0.6, 1.0 and 2.0 m (Figure 3.4C). A CR10x datalogger (Campbell Sci., UK) records hourly values of soil temperature. Communication is established via a modem using GSM phone transmission every night for daily remote data collection.

3.4 Climate station

The locations for the original PLAP fields were chosen such that they also represent the variability of precipitation across Denmark. Moreover, all the “old” PLAP fields were situated close to an automatic climate station, which is not the case for the Lund field site. Therefore, an automatic climate station from Campbell Scientific (UK) was installed for local measurements of climate parameters. The barometric pressure is measured with a pressure sensor (PTB101B, Vaisala, SF) with an accuracy of 2 mbar. The precipitation gauge is a Pluvio2 rain gauge (OTT Hydromet, Germany). The rain gauge is of high quality with an accuracy and resolution of ± 0.05 mm and 0.1 mm, respectively. The climate station includes a CR1000 datalogger, which measures and stores 10-min values of global radiation, air temperature, relative humidity, wind speed and direction, precipitation and barometric pressure. Communication is established via a modem using GSM phone transmission four times a day for remote data collection. Figure 3.5 shows the climate station at the Lund field site.

Figure 3.5. *The climate station at the Lund PLAP field site. View direction is toward the South. The shed in the background is situated in the southwestern corner of the field. Photograph: Kirsten Kørup*

4 Geology

4.1 Regional geology

The peninsula of Stevns is situated in eastern Denmark, approximately 40 km south of Copenhagen and it is delimited toward the east by the river Tryggevælde Å, which runs S-N and enters the ocean just south of the city of Køge. Figure 4.1 shows the topographical, geomorphological, soil type and geological map of Stevns with the location of the Lund field site marked by a black star. The highest points in the area are found at the coastal cliff, Stevns Klint toward the east, at which the elevation is approx. 40 m above sea level, whereas the field is situated approx. 10 m above sea level along the southern coast of Stevns, about 500 m from the sea. The entire area is a glacially formed till plain formed during the Weichselian glaciation, and the topographic map shows that there are mega-lineations trending SE-NW across the landscape. These are formed subglacially and indicate the ice movement direction (Houmark, 2011). The soil types in the area are classified as clayey till, with only minor areas with organic soil in the river valleys. The Prequarternary surface at Stevns consists of the Stevns Klint Formation, which is bryozoan limestone of Danien age. The bryozoan limestone overlies Cretaceous chalk, and both formations are visible as outcrops along most of the coastal cliff sections and quarries.

4.2 Local geology

The field site is situated between 7 and 10 m above sea level approximately 500 m north of the coastline. The surface has a 1-1.5 % slope and at the coastline, there is a 5 m drop to sea level. The topsoil is approximately 0.3-0.5 m thick, and the total thickness of till is 8-10 m at the field site.

4.2.1 Monitoring wells and piezometer wells

Figure 4.2 shows a cross-section through all the installed wells at the field site. It is evident that P3 differs from the other profiles, since it shows two distinct layers of sand within the top 5 m. The first layer is from 2.8 to 3.4 m depth, and it is dominated by relatively coarse sand and gravel (0.2-2.5 mm). The second layer is found from 3.8-4.5 m depth and is dominated by finer sand (0.06-0.5 mm). The remaining well profiles show only clayey till, which is also what is found in the 6 m deep excavation at the neighboring field west of the PLAP field site (see section 5.3). It cannot be estimated from the well samples, how far into the field the sand layers reach. However, since M1 did not contain sand, the extent is probably limited, at least in the E-W direction. To fully delineate the extent of the sand layers, it would be necessary to obtain more well samples e.g. from wells south of P3 (within the buffer zone).

Samples of the underlying limestone were only obtained from well P3 (at 9.0- and 9.8-meters depth). At P4, the depth to the underlying chalk is unknown, while at P1 and P2, it seems to start at a depth of approximately 11 and 9 m, respectively, although no samples from those depths were obtained. Based on the soil color, the redox boundary was estimated at 3.0, 4.5, 4.7 and 3.2-meters depth at P1, P2, P3 and P4, respectively (Figure 4.2).

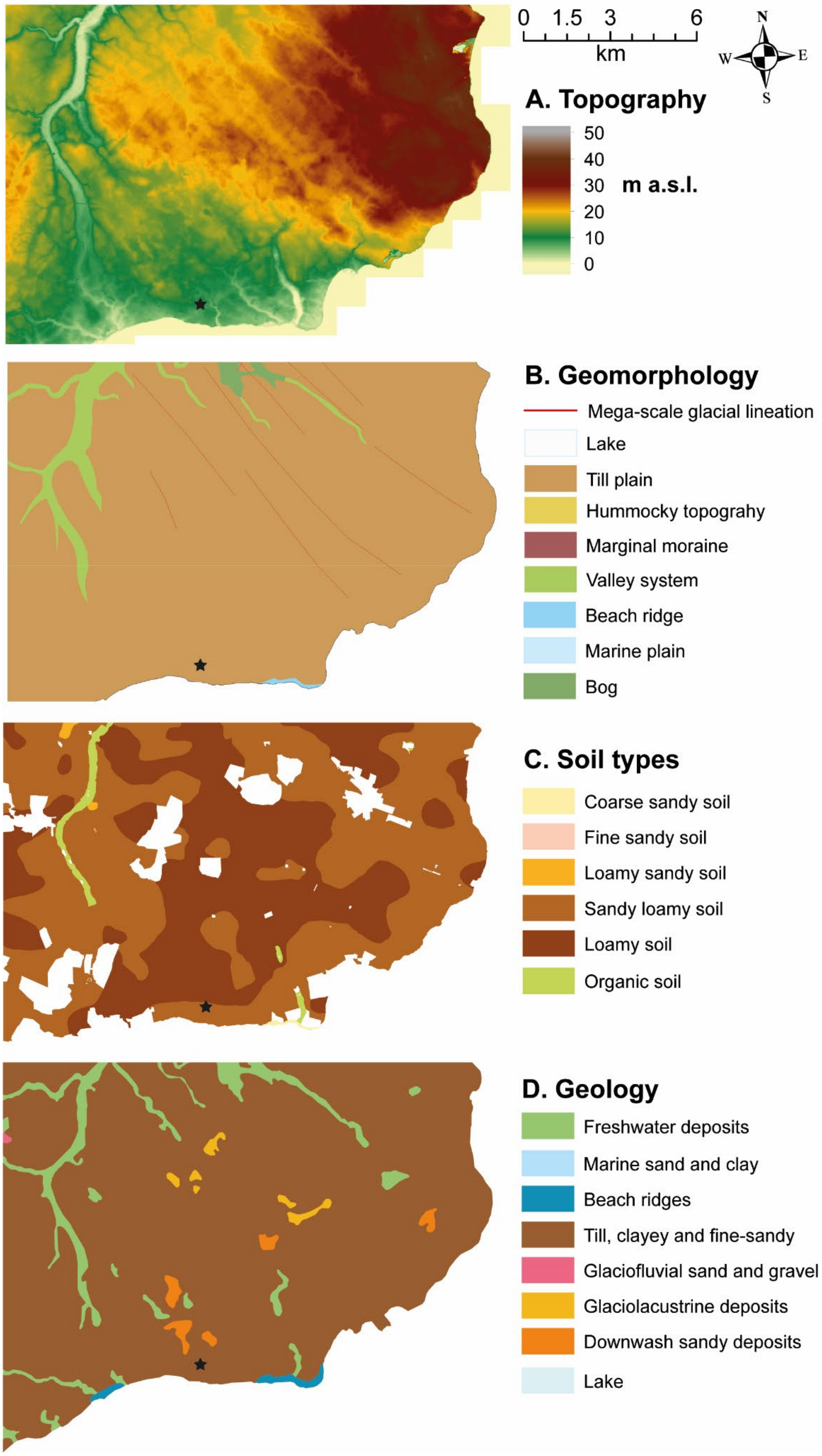

Figure 4.1. *Location of the PLAP field site at Lund (black star) superimposed on: A: Topographical map of Stevns. B: Geomorphological map of Stevns. C: Soil type map of Stevns, and D: Geological map of Stevns.*

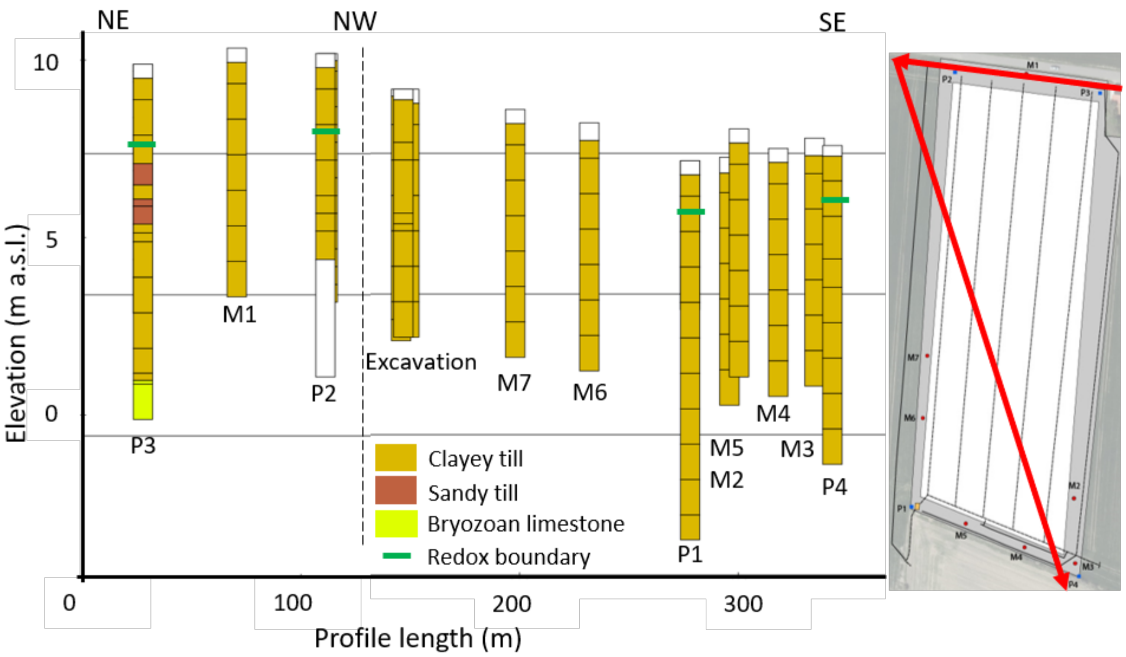

Figure 4.2. *Lithological cross-sections based on information from both monitoring (M) wells and piezometers (P) installed at the field site. The green horizontal lines on well P1, P2, P3 and P4 indicate the estimated redox boundary based on soil color.*

4.2.2 Excavation

In September 2016 an excavation to a depth of 6 m was carried out approximately 50 m west of the field site (Figure 3.1 and Figure 4.3). The purpose of the excavation was to obtain lithological descriptions, fabric analyses and fracture description and characterization. Samples were obtained for grain size distribution, fine gravel analysis and chemical analysis.

In the excavation, a topsoil layer as well as two tills were identified (Figure 4.4 and Figure 4.5). The two tills could be separated based on their lithology, the fine gravel composition and clast fabric. Both tills have a Baltic provenance (see fine gravel analysis below). Furthermore, the fracture characteristics are different in the two tills (see later sections). The lower till can be classified as a basal till type B (Klint et al., 2001). It is strongly mixed with clay and contains abundant limestone clasts and few sand lenses. The upper till is also classified as a type B till. However, this unit contains more sand and does not contain limestone clasts. The transition from calcareous to non-calcareous matrix was found at a depth of approximately 1.5 m. The redox boundary is at approximately 3.8 m; however, it is very irregular as it follows the larger fractures to varying depths.

Figure 4.3. *Aerial view of the 6 m deep excavation at the neighbouring field of the PLAP Lund field. Photograph: Underground Channel, Sept. 2016.*

Figure 4.4. *Excavation west of the field site, view direction towards north. Bottom of the excavation is approximately 6 m below the soil surface. The red line outlines the boundary between the two tills. The dominant fractures have been marked with white lines, and the boundary between oxidized and reduced tills by a dotted white line. Photograph: Peter Roll Jakobsen, 2016.*

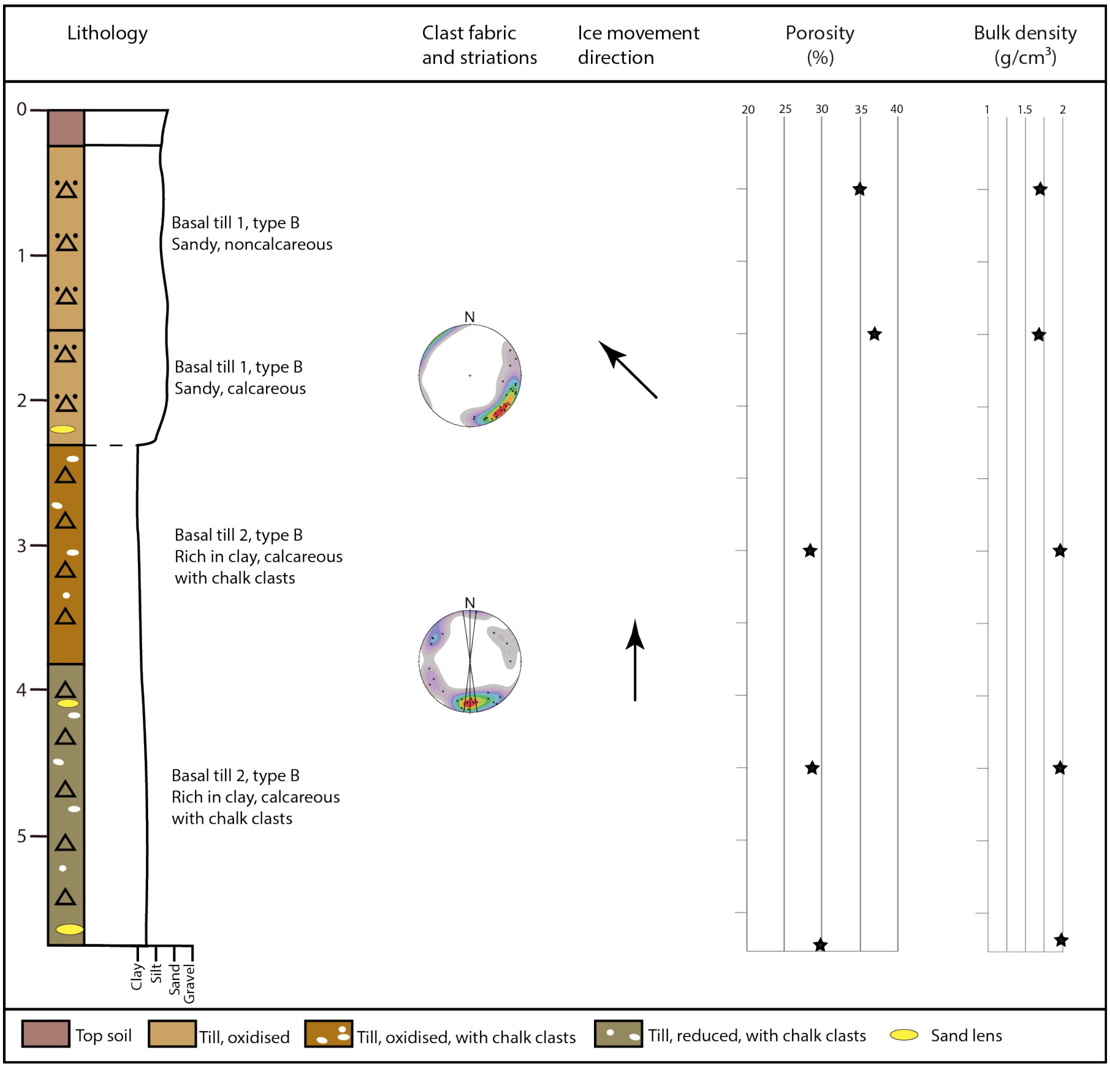

Figure 4.5. *Lithological log and profile showing the geology as observed in the 6 m deep excavation at the neighboring field of the PLAP Lund field site. The ice movement direction is indicated by the clast fabric and striations.*

Figure 4.6. *Outcrop of two till units in the coastal cliff west of the Lund Harbour, southeast of the field. The boundary between the two units is just above the 2 m high ruler. Photograph: Peter Roll Jacobsen, September 2016.*

4.2.2.1 *Coastal cliff section*

At the coastal cliff 900 m southeast of the 6 m deep excavation two till units are exposed (Figure 4.6). In the section there is a distinct boundary between the two tills. The lower unit is about two meters thick and rests on bryozoan limestone. It is brown (oxidised) and it contains many white limestone clasts. The upper till unit is about 1.5 m thick, brown (oxidised) and has no visible limestone clasts.

4.2.2.2 *Lithological description*

A lithological description of the sediments found in the 6 m deep excavation is given in Table 4.1 and the depths are average depths corresponding to the log in Figure 4.5. The description follows Larsen et al. (1995).

Table 4.1: Lithological descriptions from the excavation at Lund.

Depth (m)	Description
0-0.4	Topsoil, dark brown, noncalcareous
0.4-1.5	Clay till, strongly mixed with sand, silty, and gravely, yellow-brown. Non-calcareous. Numerous burrows and root channels that decrease in number with depth. Heavily fractured with vertical and horizontal fractures, the latter decreasing with depth. Vertical fractures contain root traces.
1.5-2.3	Clay till, strongly mixed with sand, silty, and gravely with few sand lenses, yellow-brown. Calcareous. Contains root channels that decrease in number with depth. Vertical and horizontal fractures, the latter decreasing with depth. Vertical fractures contain root traces.
2.3-3.8	Clay till, rich in clay, silty, slightly sandy and gravely with few sand lenses. Calcareous and contains limestone clasts. Vertical and horizontal fractures, the latter decreasing with depth. Olive-brown.
3.8-6	Clay till, mixed with silt, sand and gravel with few sand lenses. Calcareous and contains limestone clasts. Few horizontal fractures and few but very prominent vertical fractures. Matrix is generally olive grey but is olive brown around the vertical fractures.

4.2.2.3 *Fine gravel analysis*

Fine gravel analysis was carried out on five samples from the 6-meter-deep excavation at 1, 2, 3, 4.5 and 5.5 m b.g.s. and the results can be seen in Figure 4.7. The stable grains show that the two upper samples and the three lower samples are mutually alike. Especially the contents of quarts and flint differ between the upper samples and the lower samples. This suggests that there are two tills in the excavation. The uppermost sample does not contain limestone gravel, as it is from the leached non-calcareous part of the excavation. Both the upper till and the lower contain fairly large amounts of Palaeozoic limestone, which suggests a Baltic provenance of the glaciers that deposited the two tills. The difference in Mesozoic and Cenozoic limestone content between the sample from 2 m depth and the lower ones is consistent with the visible chalk content seen in the excavation and the coastal section (Figure 4.4 and Figure 4.6).

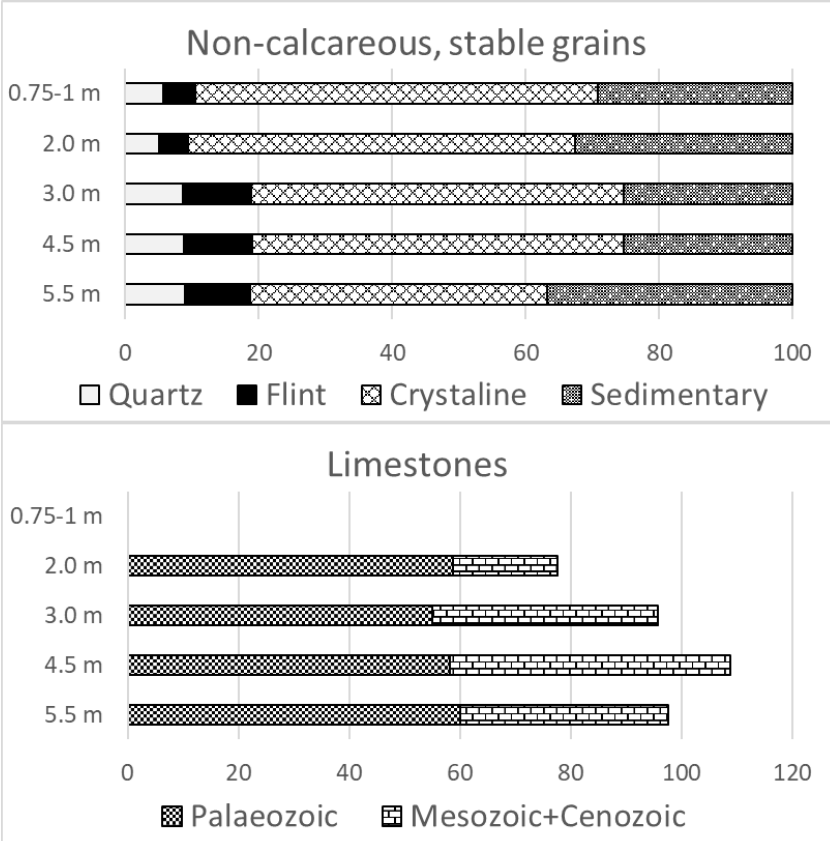

Figure 4.7. *Fine gravel analysis (3-5 mm) in five levels of the excavation.*

4.2.2.4 Clast fabric analysis

Clast fabric analyses was performed at 2 and 4 m depth (Figure 4.5). The fabric at 2 m depth is a strong fabric indicating ice-flow from southeast to northwest, which is the same orientation as the mega-scale glacial lineation in the area (Figure 4.1). The fabric from 4 m depth is not as strong as the upper one, but striations on boulders corroborate an ice-flow direction from south to north. An east-west direction would be expected, but it might reflect a local different ice-flow direction as it is otherwise known from this region. Nevertheless, the different directions corroborate the presence of two individual tills.

4.2.2.5 Fracture description

To develop a conceptual model of the fracture systems for the field site, fracture system parameters were measured in the excavation: orientation at various depth, positions, and frequencies. Furthermore, biopores were measured and described (Figure 4.8). From the topsoil and to about 1 m depth the upper till is heavily fractured and bioturbated. The vertical fractures have a random orientation, and there are 18 fractures per meter at 0.5 m depth. From the topsoil and to 1 m depth there are 27 fractures per meter of horizontal fractures, possibly connected to freeze/thaw processes. In this zone there are also many wormholes and root channels. At 0.5 and 0.75 m depth there are more than 200 wormholes per m^2 decreasing to 76 wormholes per m^2 at 1.25 m depth and some of them continue to the calcareous-noncalcareous transition depth. Roots follow primarily the fractures and wormholes and are seen to about 2 m depth. At 1.75 m depth there are eight root channels per meter and at 2 m depth there are 3 root channels per meter.

Horizontal fractures were measured along a vertical scan-line. Both tills have a higher frequency of horizontal fractures at the top (Figure 4.8). Vertical fractures are measured along horizontal scan-lines at 2 and 3 m depth representing measurements from both tills.

In the upper till, there are two dominating vertical fracture sets trending *c*. 175° and *c*. 30° with an average spacing of 0.85 m and 0.7 m, respectively (Figure 4.8). Fractures with a more random orientation occur as well. The fractures are surrounded by a grey halo, and the matrix is oxidized. Root channels are frequent within the fractures. In the lower till two very distinct vertical fracture sets are recognized trending *c*. 10° and 90°. The 10° fracture set has an average spacing of 0.5 m and the 90° fracture set has a spacing of 1 m. Vertically some of the fractures can be followed from 2.3 m depth to the bottom of the excavation and thus they are more than 4 m long. Laterally some of them could be followed for 5 m across the excavation, and seem to continue beyond that. The fractures are coated with Fe oxides and manganese, where they are surrounded by oxidised matrix. Some of the fractures continue deeper into the reduced clay till, having no oxidised zone.

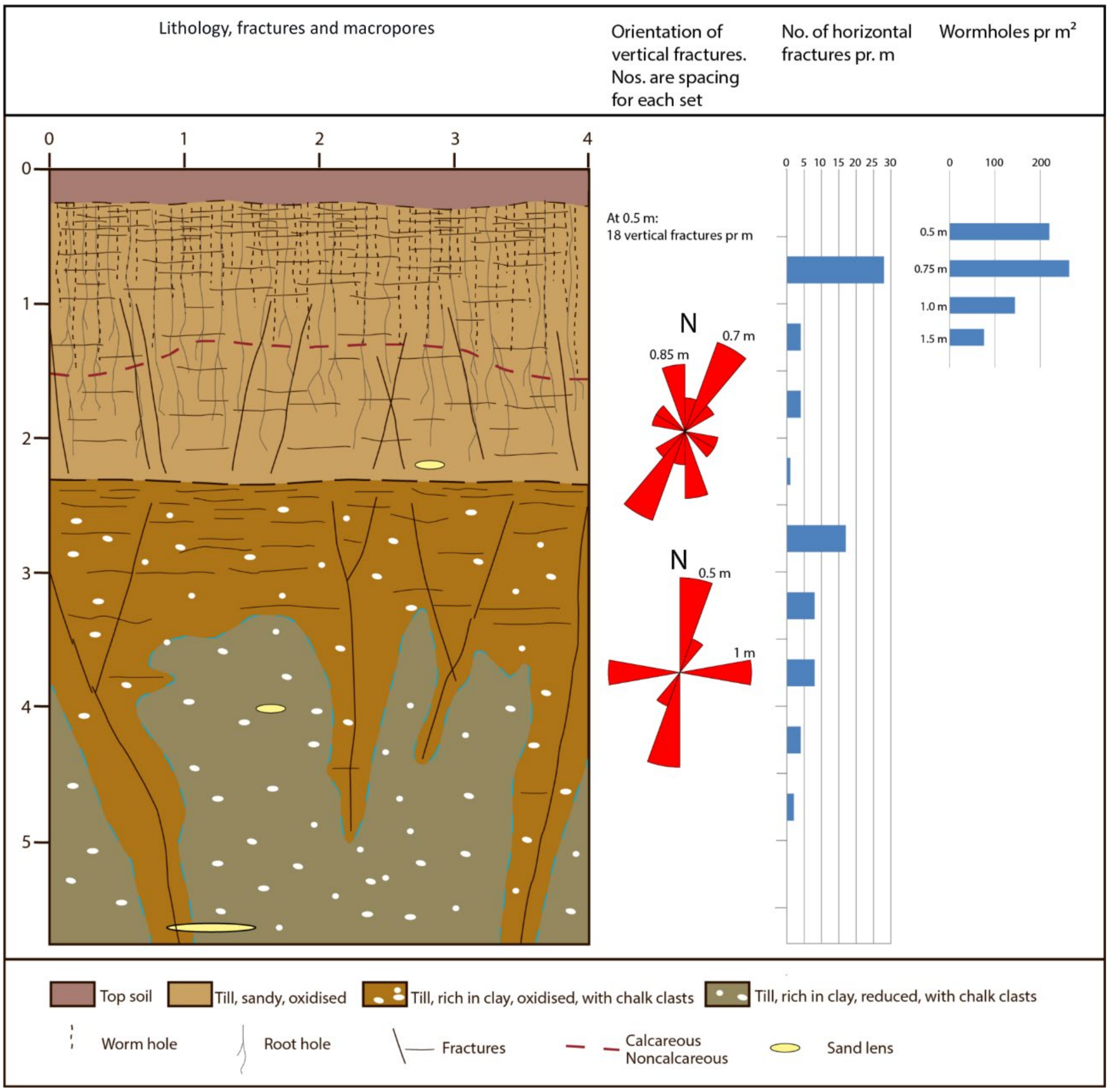

Figure 4.8. *Macropore data from the 6 m deep excavation. The profile to the left is measured on the W-E trending wall on the northern wall of the excavation.*

4.2.3 Laboratory analyses of soil samples

Three types of soil samples were obtained during drilling of piezometer wells or in the excavation:

- From piezometer wells P1, P3 and P4, bulk samples for grain size analysis as well as measurements of pH, inorganic and organic carbon content and water content were collected when the boreholes were drilled. At P3, soil was taken with a window sampler (core type sample). At P4 and P1, soil was recovered from an auger drill. In both cases, care was taken to remove the outer soil layer that was polluted with soil from more shallow layers. Soil was in general sampled where new horizons/layers were visually observed. Soil was not sampled from P2.
- From the 6 m deep excavation, 100 cm^3 soil cores for porosity determination were collected by hammering steel pipes (5x5 cm) vertically into the soil. The cores were then dug out and shaped with a knife to fit the bottom of the steel pipe. Four samples were taken at each depth (0.5 m, 1,5 m, 3.0 m, 4.5 m, and 5.9 m).
- From the 6 m deep excavation, soil from macropores and matrices were sampled. These types of samples were analyzed as part of the other studies mentioned in the Introduction. Three types of macropores were sampled: Brown biopores, located from below the plough layer to ~1.2 m depth, were scraped with a tiny spoon to get the outer 1-2 mm of the pore wall. Grey biopores, located from approximately 1.1-2.5 m depth, were cut out and a thin outer iron oxide layer was scraped off with a knife, to sample only the 5-10 mm wide inner greyish part of the pores. Reddish and black geologic fractures, located from approximately 2.5 m depth and downwards, were opened with a knife. The outer 1-2 mm cemented, and colored fracture wall was sampled with a spoon or by cutting with a knife.

The soil samples were analyzed at GEUS.

Porosity was determined by saturating 100 cm^3 soil cores with water and then drying at 105°C. Soil texture (0.063-32 mm) was determined by wet sieving 125 g of soil that had previously been dried at 105°C. Soil texture (< 0.063 mm) was determined using the traditional hydrometer method using 30 g homogenized subsamples shaken overnight with water and sieved. The fraction <0.063 mm was dried at 65°C, carefully homogenized and a subsample was then used for the analysis.

The following parameters were all determined on soil samples sieved through a 2 mm sieve at natural water content: Water content was determined by drying at 105°C. pH was determined with a pH electrode in a 1:2.5 soil:liquid slurry using either water or 10 mM $CaCl_2$ solutions. Total carbon (TC) was determined by combustion of dried (50°C) and crushed samples in a CS analyzer. Total organic carbon (TOC) was determined by combustion of TC-samples after acid treatment. Total inorganic carbon (TIC - carbonates) was calculated as difference between TC and TOC.

4.2.3.1 Grain size, carbon content, and pH

In general, the samples obtained from drilling piezometer wells were similar across the field site (Figure 3.1 and Figure 4.9). The samples are dominated by silty material (30-35 %), but also with a significant fraction of clay (10-25 %) and fine to medium sand fractions (30-50 % in total). The clay content is rather stable around 20 % throughout the profiles, with the Ap-horizon (upper-most sample) as exceptions with lower values. Samples from P1 and P4 overall show the same trends and do not exhibit large variations with depth. However, in P3 we found two sections containing sandy material at ~3 and ~4.2 m depth, and these are identified in the texture analysis as samples containing less than 20 % silt, less than 10% clay, and up to 76 % sand (sum of all sand fractions). Figure 4.9 shows grain size distribution for the samples from P1, P3 and P4, with the sand fraction divided into three subgroups.

Pieces of limestone were visible in the samples from ~2 m and below. This is also reflected in the chemical analyses, which show that there is a gradual increase in total inorganic carbon (TIC) from almost 0 % to more than 3 % from 2-4 m depth (Figure 4.10). Since 1% TIC corresponds roughly to 8 % $CaCO_3$, the samples from 4 m and below contain between 25 % (P3) and 50 % (P1 and P4) carbonate. The TIC analysis also confirmed that material from the two limestone layers found in P3 were almost pure carbonates (11 % TIC, corresponding to 92 % $CaCO_3$).

The pH determined in water varied from 7.4-7.8 in the Ap-horizon to between 8.5 and 9.2 at depths below 2 m. pH determined in 10 mM $CaCl_2$ varied from 6.1 in the plough layer to ~7.8 at depths below 2 m.

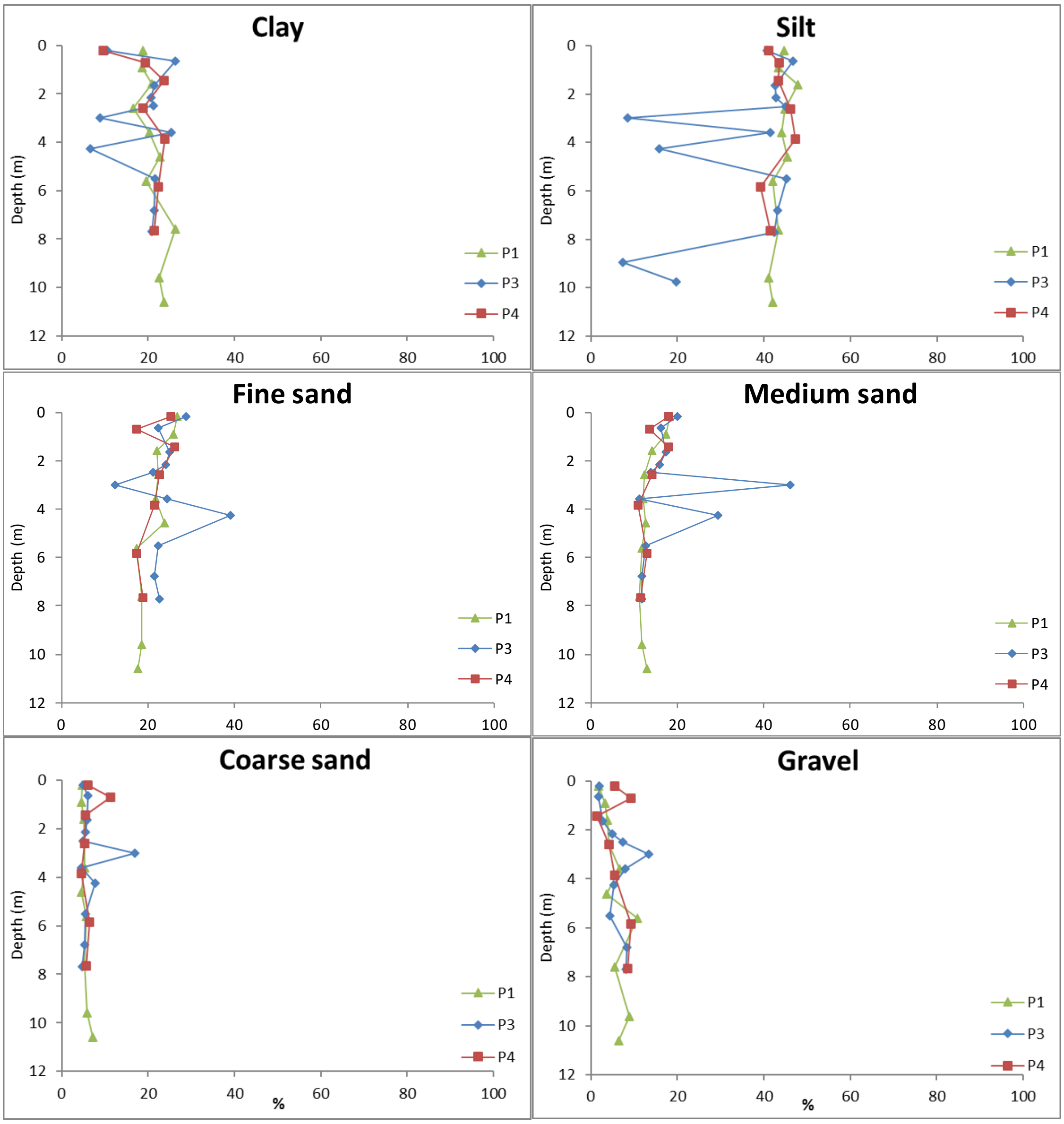

Figure 4.9. *Grain size distribution of soil collected when drilling piezometer P1, P3 and P4.*

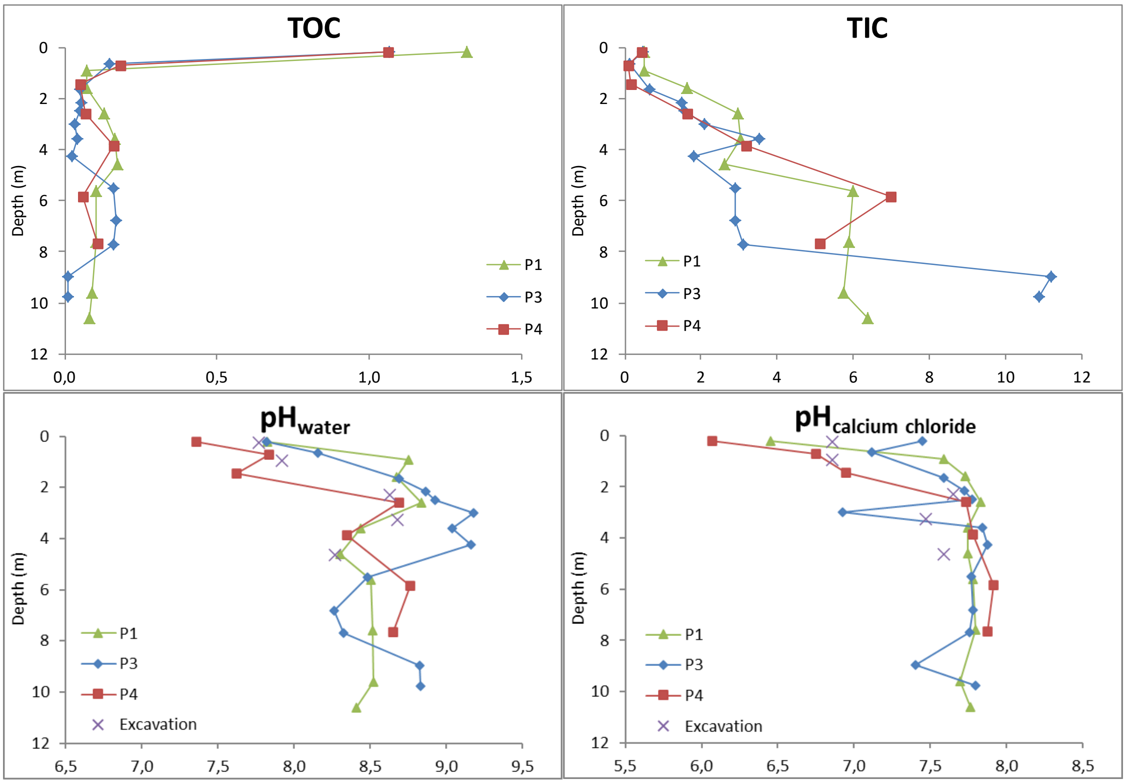

Figure 4.10. *Soil chemical parameters for samples from P1, P3 and P4. Top left: Total organic carbon (TOC). Top right: Total inorganic carbon (TIC) or $CaCO_3$-content. 1% TIC corresponds to approximately 8% $CaCO_3$ content. Bottom left: Soil pH measured in water. Bottom right: Soil pH measured in 10 mM $CaCl_2$. Note that samples from the excavation are included in both pH data plots.*

4.2.3.2 Porosity, bulk density, and water content

Table 5.2 shows the porosity, water content, water saturation and bulk density for soil samples collected from five depths either by drilling of piezometer wells or from the six-meter-deep excavation. The samples can be divided into two groups; an upper group consisting of samples from 0.5 and 1.5 m depth and the bottom group, which contains samples from 3, 4.5 and 5.9 m depth. Porosity and water content are slightly higher in the upper group, and thus the water saturation and bulk density are lower. These results agree with the results of the texture analysis, in which the clay content in the lower samples is higher, making the till denser below three meters depth (Figure 4.9).

Table 4.2. Porosity, water content, water saturation and bulk density of samples from the Lund field site. Values are mean of eight samples ± one standard deviation.

Depth (m)	Porosity (%)	Water content (Weight %)	Water saturation (%)	Bulk density (g cm^{-3})
0.5	34.7±0.6	13.1±0.2	74.8±2.5	1.72±0.02
1.5	36.7±1.7	13.9±0.9	74.7±2.7	1.70±0.05
3	28.4±0.7	11.5±0.5	90.1±0.8	1.96±0.03
4.5	28.5±1.0	11.9±0.4	92.0±2.2	1.94±0.04
5.9	29.6±1.1	12.5±0.6	95.1±0.6	1.97±0.04

5 Pedology

5.1 Pedological methods

Pedological description of all identified soil horizons was carried out in accordance with Madsen and Jensen (1988). Soil samples from every identified horizon were collected for laboratory analysis. The soil samples were analyzed at the Department of Agroecology, Aarhus University. A detailed description of the laboratory analysis methods used can be found in Hansen and Sørensen (1996). The most important methods and procedures are briefly summarized in Table 5.1.

Table 5.1. Summary of methods and procedures used in the laboratory pedological analyses of soil samples.

Parameter	Description
Soil texture	Particle size analysis subdivided the soil samples into the following classes: clay <2 μm, silt 2–20 μm, coarse silt 20–63 μm, fine sand 63–125 μm and 125–200 μm, medium sand 200–500 μm, and coarse sand 500–2,000 μm.
TOC	The total organic carbon (TOC) content was determined using dry combustion. Soil samples containing significant amounts of calcium carbonate (exceeding 1%) were also analyzed for $CaCO_3$ content.
pH	pH was measured following suspension of the soil in 0.01 M $CaCl_2$.
Fe and Al	Fe and Al were extracted using an ammonium oxalate solution and determined by atomic absorption spectrophotometry.
Total-P	Phosphorous content was determined spectrophotometrically following destruction of the soil by perchloric acid-sulphuric acid.
Total-N	The soil sample was combusted in an atmosphere of pure oxygen at 900°C. Water and CO_2 were removed and the nitrogen oxides were reduced to free nitrogen, which was then measured in a chemical conductivity cell.
Exchangeable cations	Exchangeable cations were extracted using ammonium acetate buffered at a pH of 7.0. Ca and Mg were determined using atomic absorption spectrophotometry. Na and K were determined by flame emission. Exchangeable hydrogen ions were determined by titration to equilibrium in a 0.06 M-nitrophenol solution.
CEC	CEC was calculated as the sum of cations.

The soil profiles were classified according to the World Reference Base (WRB 2014) for soil classification (IUSS Working Group WRB, 2015). Nomenclature for textural classes in this investigation follows the Danish system. The description and the analysis results from all the profiles have been stored in the Danish soil profile database.

5.2 Pedological profiles

The pedological field work at the Lund site was carried out in the autumn of 2016. Two profiles in the before-mentioned trenches in the western and southern buffer zone were used for pedological assessment. Both profiles were situated halfway between the groups of suction cups, and TDR- and temperature sensors just outside the field along the western and eastern border of the southwestern corner of the field (Figure 3.1).

Table 6.2. Description of soil Profile 1, Lund, Stevns (*Lund West*)

Soil classification, WRB	Anthric Luvisol		
UTM (zone 33U)	E: 709166	Profile depth	230 cm
	N: 6126998	Drainage class	Well drained
Parent material	Basal till	Groundwater level	>230 cm
Landform	Moraine	Vegetation	Wheat stubble
Elevation	7 m above sea level	Maximum rooting	90 cm
Topography	Flat	Authors	Mogens H Greve
Slope	0-2^{o}	Date of description	14 Nov. 2016
Precipitation	577 mm yr^{-1}		
Temperature (avg.yr.)	9^{o}C		

Profile 1, Lund	**Profile description**
	Ap (0-29 cm)
	Dark yellowish brown (10YR 3/4 f) clay, containing humus, a few small stones of varying shape and type, some fine roots, 1-10 pores per dm^2, moderately coarse granular structure, weak sticky consistency, clear smooth boundary.
	E (29 – 50 cm)
	Yellowish brown (10YR 5/4) clayey sand, humus poor, a few small stones of varying shape and type, frequent fine roots, 1-10 pores per dm^2, strong coarse angular structure, weak sticky consistency, moderately thick mottled coatings of clay minerals and humus in root channels and wormholes, diffuse wavy boundary.
	Bt (50 - 73 cm)
	Brown (10YR 5/3) clay, humus poor, some small and medium size stones of mixed form and type, a few small soft Fe and Mn oxide and hydroxide nodules of mixed form, a few fine roots, 1-10 pores per dm^2, strong coarse columnar structure, very sticky consistency when moist, continuous thick coatings of clay minerals and humus in root channels and on aggregate peds, diffuse wavy boundary.
	Btg (73 – 120 cm)
	Brown (10YR 5/3) clay; vertical stripes of clear light olive brown (2.5Y 5/4 f) spots with diffuse boundary, secondary spots of pinkish grey (7.5YR 6/2 f), humus poor, some small and medium size stones of mixed form and type, a few small soft Fe and Mn oxide and hydroxide nodules of mixed form, a few fine roots, 1-10 pores per dm^2, strong coarse columnar structure, very sticky consistency when moist, continuous thick coatings of clay minerals and humus in root channels and on aggregate peds, diffuse wavy boundary.
	BC (120 –230 cm)
	Yellowish brown (10YR 5/7) with some vertical stripes, large conspicuous yellowish brown (10YR 5/8 f) spots with clear boundary, humus poor, some small and medium size stones of mixed form and type + lumps of chalk, a few small soft Fe oxide and hydroxide nodules of mixed form, a few fine roots, 1-10 pores per dm^2 , moderately coarse columnar structure, sticky consistency when wet, continuous thick coatings of clay minerals and humus in root channels and on aggregate peds.

Table 6.3. Description of soil Profile 2, Lund, Stevns (*Lund South*)

Soil classification, WRB	Anthric Stagnic Luvisol		
UTM (zone 33U)	E: 709186	Profile depth	230 cm
	N: 6126853	Drainage class	Well drained
Parent material	Basal till	Groundwater level	>230 cm
Landform	Moraine	Vegetation	Wheat stubble
Elevation	7 m above sea level	Maximum rooting	90 cm
Topography	Flat	Authors	Mogens H Greve
Slope	0-2^{o}	Date of description	14 Nov. 2016
Precipitation	577 mm yr^{-1}		
Temperature (avg.yr.)	9^{o}C		

Profile 2, Lund	Profile description
	Ap (0 – 30 cm)
	Dark brown (10YR 3/3) Fine clayey sand, containing humus, a few small and medium size stones of mixed type, some fine roots; 1-10 wormholes and root channels per dm^2, very weak thin granular structure, slight sticky when wet, clear smooth boundary.
	Bw/E (30 – 55 cm)
	Yellowish brown (10YR 5/4) Fine clayey sand, humus poor, lots of small and medium size stones of mixed form and type, a few small soft Fe and Mn oxide and hydroxide nodules of mixed form, some fine roots; 1-10 wormholes and root channels per dm^2, moderately coarse columnar structure, sticky consistency when wet, mottled thick coatings of clay minerals and humus in root channels and on aggregate peds, gradual wavy boundary.
	Btg (55 - 85 cm)
	Light brownish gray (2;5YR 6/2) Fine clayey sand, vertical stripes of clear light olive brown (2.5Y 5/4 f) spots with diffuse boundary, secondary spots of pinkish grey (7.5YR 6/2 f), humus poor, some small and medium size stones of mixed form and type, a few small soft Fe and Mn oxide and hydroxide nodules of mixed form, a few fine roots, 1-10 pores per dm^2, strong coarse columnar structure, very sticky consistency when moist, continuous thick coatings of clay minerals and humus in root channels and on aggregate peds, diffuse wavy boundary.
	Cc (85 –230 cm)
	Brown (10YR 5/3) Clayey sand, humus poor, lots of small and medium size stones of mixed form and type lumps of lime, a few small soft Fe oxide and hydroxide nodules of mixed form, very calcareous mainly as lumps, moderately medium strong angular structure, sticky consistency when moist; mottled, moderately thick coatings of clay minerals on aggregate peds.

Table 6.4. Soil texture analysis from the pedological profiles

Pro/Hor.	Hor. type	Depth (cm)	Soil texture (mm) %[1)]							OM (%)
			Clay	Silt	Coarse silt	Fine sand	Fine sand	Medium sand[1)]	Coarse sand[1)]	
1/1	Ap	0 – 39	16.7	15.3	18.1	13.2	10.2	19.1	6.5	0.9
1/2	Bt	50- 73	6.7	5.8	11.0	14.9	20.2	34.4	6.8	0.2
1/3	Btg	73 –120	21.7	14.3	19.3	12.4	11.0	14.1	6.9	0.2
1/4	BC	120 –230	17.6	16.4	16.9	14.5	11.3	16.3	6.9	0.2
2/1	Ap	0 – 39	13.7	14.3	16.6	14.5	14.5	19.0	5.7	1.7
2/2	Bw/E	29 – 50	18.6	15.4	20.2	17.9	12.5	10.5	4.2	0.7
2/3	Btg	50- 73	20.7	14.3	16.2	13.5	11.5	16.8	6.6	0.3
2/4	Cc	102 –230	16.7	17.3	18.8	13.6	11.3	15.3	6.7	0.2

[1)] Soil texture intervals: Clay: <0.002 mm; silt: 0.002-0.02 mm; coarse silt: 0.02-0.63 mm; fine sand: 0.63-0.2 mm; coarse sand: 0.2-0.5 mm, coarse sand: 0.5-2 mm.

Table 6.5. Soil chemistry of samples from the pedological profiles

Pro./ Hor.	N_{tot}	C_{tot}	C/N	P_{tot}	P_{oxalat}	pH[1)]	K	Na	Ca	Mg	Tot. bases	H^+	CEC (tot.)	Base sat.	Fe (Oxalat)	Al
	(%)		(-)	(mg kg^{-1})		(-)			(cmol kg^{-1})					(%)	(mg kg^{-1})	
1/1	0.06	0.54	9	297.4	112.5	7,00	0.26	0.06	9.52	0.71	10.55	0.58	11.13	95	1889	669
1/2	[2)]	0.11	–	263.7	71.8	7.0	0.1	0.03	3.36	0.22	3.71	0.29	4,00	93	1334	292
1/3	0.01	0.14	14	271.3	70.9	7.1	0.21	0.09	10.97	1.13	12.4	–	11.64	100	1094	670
1/4	0.01	0.09	9	359.7	120.3	7.2	0.18	0.09	9.34	0.82	10.43	–	9.02	100	820	469
2/1	0.1	0.99	10	419.8	217.5	6.9	0.39	0.05	8.64	0.85	9.93	0.58	10.51	94	1492	793
2/2	0.04	0.42	11	297.0	99.1	7.0	0.18	0.07	10.27	0.71	11.23	–	10.86	100	785	691
2/3	0.02	0.2	10	233.2	49.6	7.1	0.22	0.08	10.31	0.76	11.37	–	11.09	100	1102	646
2/4	0.01	0.13	13	450.2	168.5	7.7	0.16	0.09	13.29	0.72	14.26	–	8.45	100	496	473

[1)] pH determined in $CaCl_2$ solution.
[2)] Not detectable

5.3 Pedological development

Two soil profiles (Profile 1 and Profile 2) were excavated and described at the Lund field site and the locations can be seen in Figure 3.1. Both profiles display soil that is developed on a calcareous basal till of Weichselian age. Clay and $CaCO_3$ are leached to a depth below 100 cm and 85 cm, respectively. The soil is well drained with pseudogley starting at a depth of 90 cm and 50 cm, respectively. The topsoil is a 30 cm thick humus rich A-horizon with a gradual transition to the underlying E-horizon. The E-horizon has abundant coatings in pores and on ped surfaces of material leached from the overlying horizon.

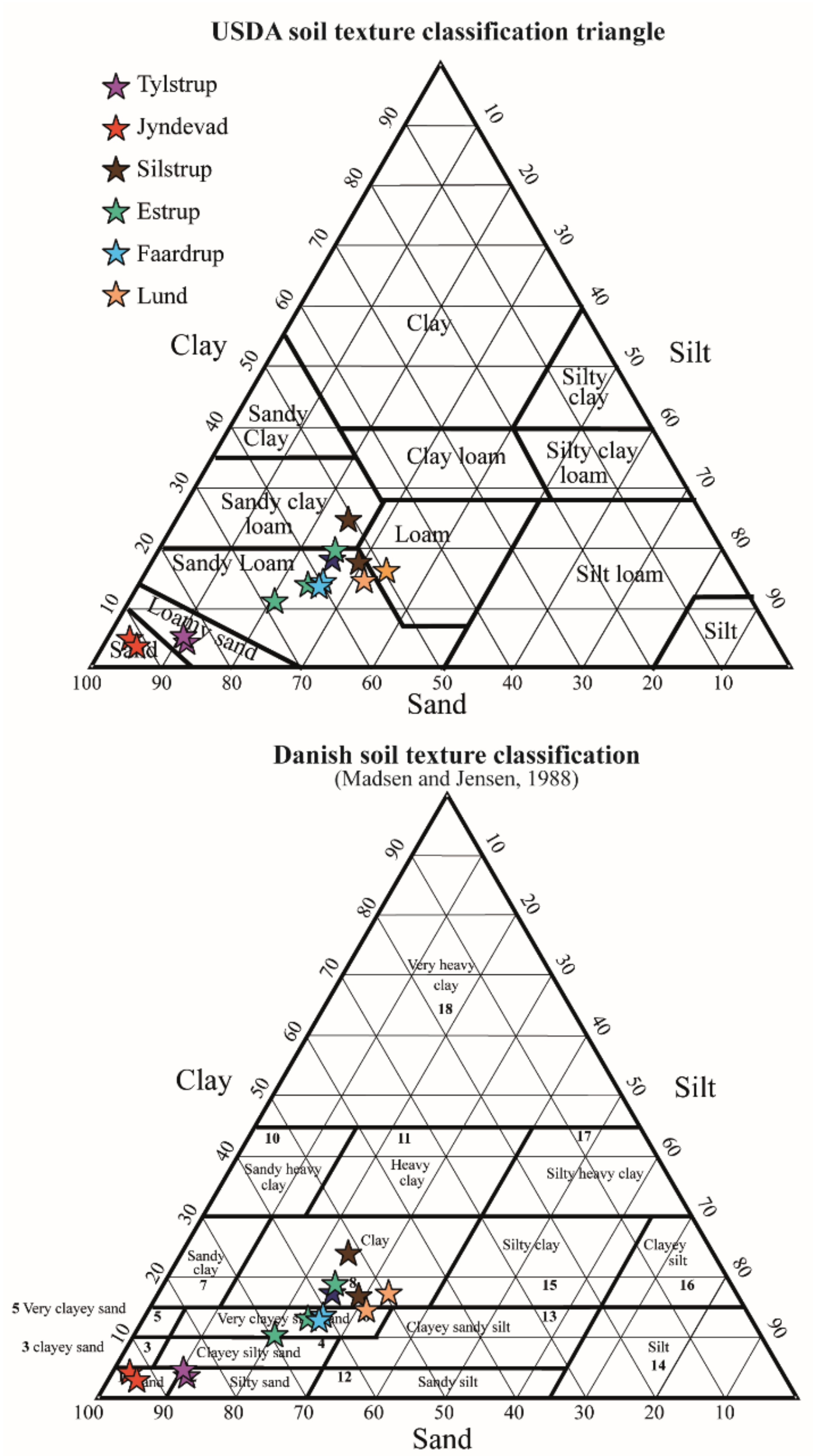

Figure 5.1. *Texture of the A-horizon of each PLAP-field plotted in the USDA soil classification triangle (Soil Survey Staff, 1999; top plot) and the Danish soil classification triangle (Madsen and Jensen, 1988; bottom plot).*

6 Soil hydrology

Large and small soil cores (100 and 6280 cm^3) for measuring soil hydraulic properties (soil water characteristic and hydraulic conductivity) where sampled at five depths in the two excavated profiles in the trenches. Sampling depths varied between 0 and 125 cm. The depths where chosen according to the different pedological horizons. In each horizon, nine small and five large soil cores were sampled. Soil water characteristics were determined on the small soil cores and the hydraulic conductivity on the large cores. To collect the large cores in the field, the cylinder was forced into the soil by means of a hydraulic press mounted on a tractor. To collect the small cores the cylinder was forced into the soil with a hammer using a special flange. All samples were protected from evaporation and stored at 2-5°C until further analysis, which was carried out at the Department of Agroecology, Aarhus University.

6.1 Saturated and unsaturated hydraulic conductivity

The large cores were placed on a ceramic plate in a box and slowly saturated during a period of three days. The cores were then drained to a soil water potential (h) of −20 cm and removed to a drip infiltrometer. The drip infiltrometer measured the hydraulic conductivity (k[h]) in the soil column under steady-state water flow conditions at different soil water potentials. The soil column was placed on a ceramic plate and five ceramic cups connected to transducers were placed in the soil column. When steady-state water flow was reached, a measurement was conducted during a period of 30 minutes and then continued at a lower soil water potential due to a lowering of the applied flow at the top of the column. Upon completion of the drip infiltrometer measurements, the soil samples were re-saturated and the saturated hydraulic conductivity (K_s) was measured using the constant-head method (Reynolds et al. 2002). k[h] was measured on three out of five samples, whereas K_s was measured on all five samples.

Mean values (geometric mean) of the saturated hydraulic conductivity (K_s, i.e. k[h=0]) lie between 50 and 3500 cm d^{-1} (Figure 6.1). Low values are seen in the clay enriched Btg horizon in Profile 2. High mean values above 1000 cm d^{-1} is found for the E and Bt horizons in Profile 1 and the Ap and Bw/EG horizons in Profile 2. In general, the variability between measurements in the individual horizons is high.

k[h] close to a soil water potential of zero is in general lower than 10 cm d^{-1} (log(K)=1) for most horizons in both profiles (Figure 6.1). Compared to the relative high values of K_s for most horizons, this indicates a possible high degree of preferential transport through the larger macropores at water contents close to saturation.

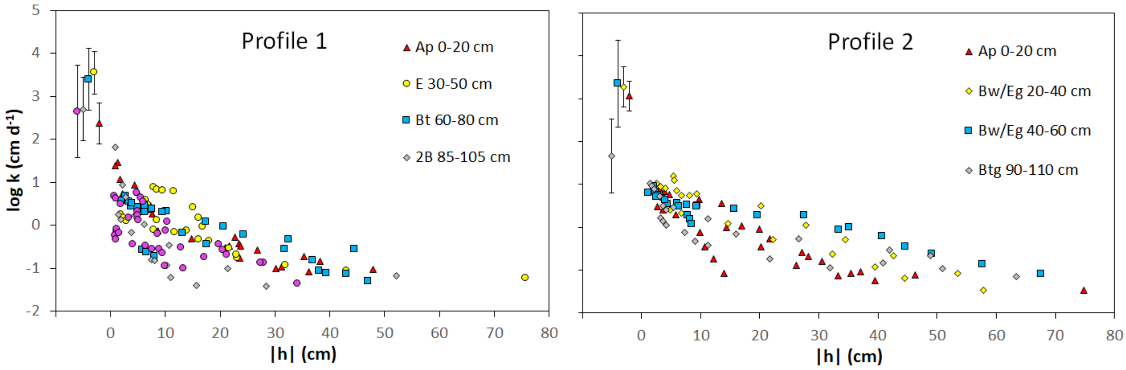

Figure 6.1. *Saturated hydraulic conductivity (K_s, h = 0 cm, n = 5) and unsaturated hydraulic conductivity k[h] for the different horizons in Profile 1 and Profile 2. Error bars correspond to ±1 standard deviation. K_s is plotted to the left of h = 0 for a better overview of the individual values for the different horizons.*

6.2 Soil water retention characteristics

For the wet region, small soil cores were placed on top of a sandbox and saturated with water from below. Soil water characteristic were determined by draining the soil samples successively to values of h at −10, −16, −50, −100, −160, and −1000 cm H_2O (pF 1, pF 1.2, pF 1.7, pF 2, pF 2.2, and pF 3.0) using a sandbox for values of h from -10 to -100 cm H_2O and a ceramic plate for values of h from −160 to −1000 cm H_2O (Dane & Hopmans, 2002). Finally, the soil cores were oven-dried at 105°C for 24 hours and weighed to determine the dry weight. For the dry region (values of h between −1000 and −50000 cm H_2O (pF 3.0 to 4.7)), the relation between water content and soil water potential was obtained using a temperature compensated WP4-T dewpoint potentiometer (METER Group Inc., Pullman, WA, USA). Here, measurements were performed on air dry bulk samples. First, the bulk samples were oven dried to determine the prevailing water content. Based on this, increasing amounts of water were added to each air-dry subsample to roughly obtain three different soil water potentials. To avoid evaporation losses, the moistened soil samples were sealed in storage bags and stored at 2-5°C for four weeks to allow equilibration. After the equilibration period, two consecutive soil water potential measurements were measured with the WP4-T. The samples were hereafter oven dried at a temperature of 105°C for 24 h to determine the gravimetric water content.

In Figure 6.2, the volumetric water contents ($cm^3 cm^{-3}$) are plotted against pF values (pF = log10[-h]). In the Figure, pF = 0 corresponds to the porosity of the soil calculated from the bulk density assuming a particle density of 2.65 g cm^{-3}. For Profile 1 porosity varies between 0.41 and 0.35 $cm^3 cm^{-3}$, and in Profile 2 it varies between 0.43 and 0.32 $cm^3 cm^{-3}$. In both profiles the largest porosity is found in the plough layer (Ap horizon) and the porosity generally decreases with depth. In Profile 2 there is further a noticeable difference between the three upper (0-60 cm depth) and the two lower horizons (60-125 cm).

In general, both profiles show a relatively high water-holding capacity until pF 3 (h = −1000 cm) after which the water content drops markedly with decreasing soil matric potential. A clear difference around the wilting point (pF 4.2) is seen for the E horizon in Profile 1 where the water content is significantly lower compared to the other horizons.

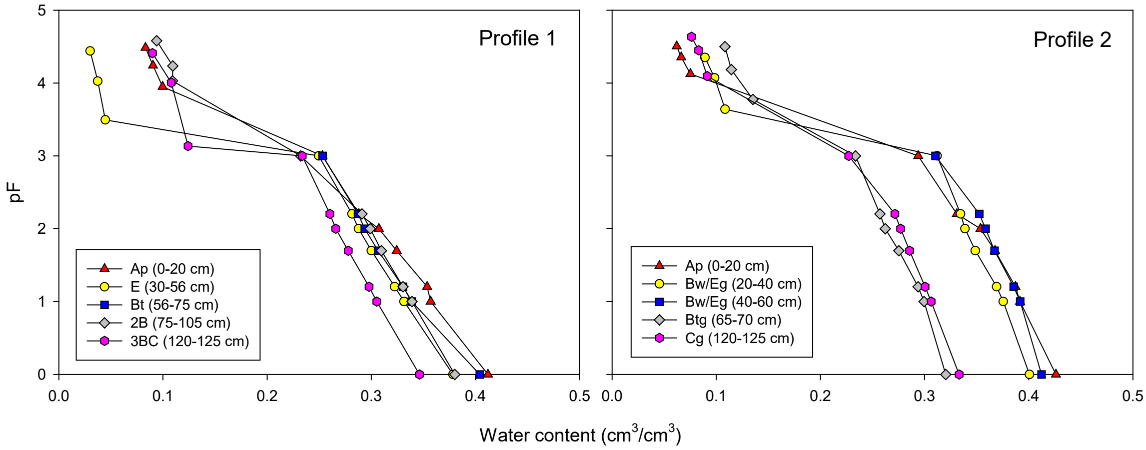

Figure 6.2. *Soil water retention characteristics for the different horizons in Profile 1 and 2. Values of water contents (n = 9) in relation to the soil matric potential, h, are expressed as pF (pF = log10[-h])*

Table 6.6. Mean values of volumetric water content, θ, in relation to soil water potentials, *h*, determined on small soil cores, pF = $\log_{10}(-h)$ (n=9). Geometric mean value of saturated hydraulic conductivity (n=5) measured on large soil cores.

Pro.	Hor.	Depth[1]	θ (cm^{-3} cm^{-3}) at pF values						K_s	Bulk density	Porosity[2]
		(cm)	1.0	1.2	1.7	2.0	2.2	3.0	(cm d^{-1})	(g cm^{-3})	(cm^{-3} cm^{-3})
1	Ap	0-20	0.36	0.35	0.32	0.31	0.29	0.25	236	1.56	0.41
	E	30-56	0.33	0.32	0.30	0.29	0.28	0.25	3513	1.65	0.38
	Bt	56-75	0.34	0.33	0.31	0.29	0.29	0.25	2479	1.58	0.40
	2B	75-105	0.34	0.33	0.31	0.30	0.29	0.23	502	1.65	0.38
	3BC	120-125	0.31	0.30	0.28	0.27	0.26	0.23	443	1.73	0.35
2	Ap	0-20	0.39	0.39	0.37	0.35	0.33	0.29	1150	1.52	0.43
	Bw/Eg	20-40	0.32	0.31	0.29	0.28	0.27	0.22	1862	1.71	0.36
	Bw/Eg	40-60	0.38	0.37	0.35	0.34	0.33	0.31	2247	1.59	0.40
	Btg	65-70	0.30	0.29	0.28	0.26	0.26	0.23	46	1.80	0.32
	Cg	120-125	0.31	0.30	0.29	0.28	0.27	0.23	-	1.77	0.33

1) Sampling interval.
2) Assuming a particle density of 2.65 g cm^{-3}.

7 Geochemical and geophysical mapping

7.1 Total carbon mapping

The topsoil (0–25 cm) at the field site was sampled in a 20 m grid. Nine soil samples were collected at each grid point – one point exactly at the grid point and the other eight points arranged symmetrically around the grid point at a distance of 1 m. The nine samples were then pooled, and the total organic carbon content determined at the Department of Agroecology, Aarhus University (Tabatabai and Bremner, 1970).

The samples from the topsoil inside the field were analyzed for total organic carbon (TOC), which varied between 1.2 % and 1.8 % (dry weight). The TOC distribution was quite uniform with the lowest values in the northern and southern parts of the field and only slightly higher in the middle section of the field.

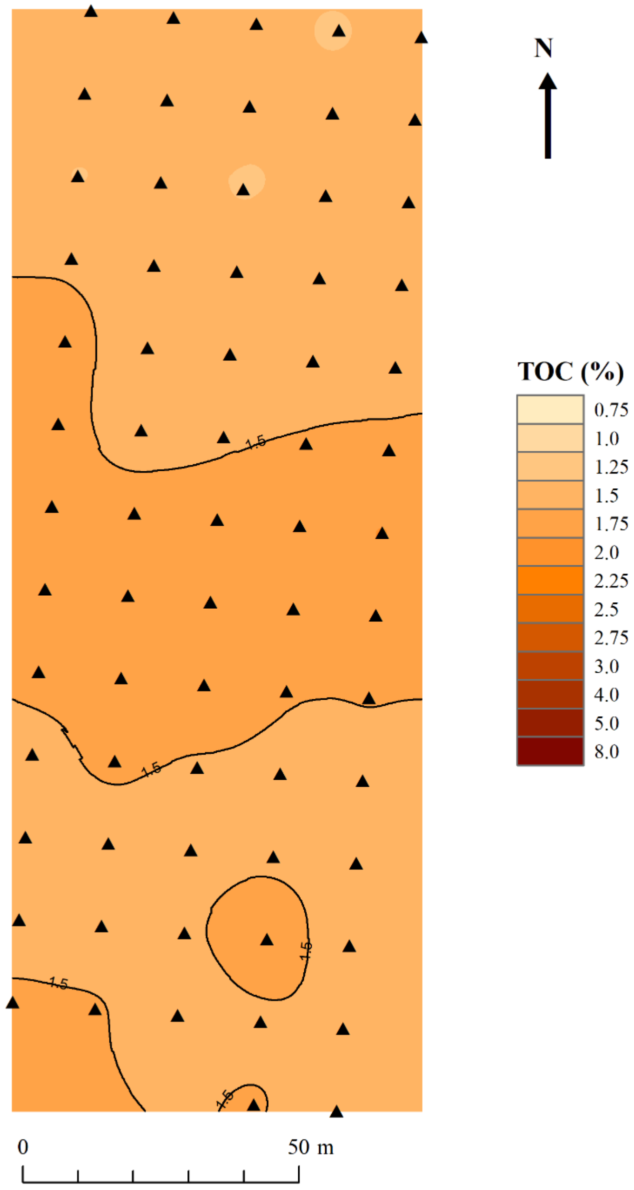

***Figure** 7.1. Map of the total organic carbon content (TOC) in the topsoil (0-25 cm depth) of the field site. Sampling points are indicated by triangles.*

7.2 Geoelectrical mapping

Geoelectrical mapping of the field site was performed using the DUALEM21s sensor for estimating clay content in the soil, as well as the DC resistivity (Multi-Electrode Profiling, MEP) method for determination of the depth to the limestone across the field. The DUALEM21s sensor measures the apparent specific conductivity of the soil by electromagnetic induction, and the DC resistivity method measures the electrical resistivity of the soil directly. These soil properties are a function of the contents of clay, salts and water (Rhoades and Corwin, 1981).

7.2.1 DUALEM

At the Lund field, the electromagnetic induction (EMI) data from the DUALEM21s are interpreted to represent the clay content in the upper 0.3-1.8 m of soil. Results from four depths are depicted in Figure 7.2, which shows that in general the apparent electrical conductivity increases with depth, which can be attributed to the increased amount of organic material and less clay in the plough layer compared to the more clayey till deposits at depth. This is corroborated by the observations in the pedological profiles. There is more variation in electrical conductivity at the two intermediate depths, i.e. at 0.6 and 0.9 m depth. At these depths, the electrical conductivity is generally higher in the southeastern half of the field, which is a tendency that can also be seen at 1.8 m depth. The higher electrical conductivity in this part of the field can be due to a higher moisture content, which is in accordance with historical aerial photos from the area, which show that the surface is naturally wetter southeast of the field site. In general, however, the limited variation in electrical conductivity across the area indicates that the top two meters of soil is quite homogeneous.

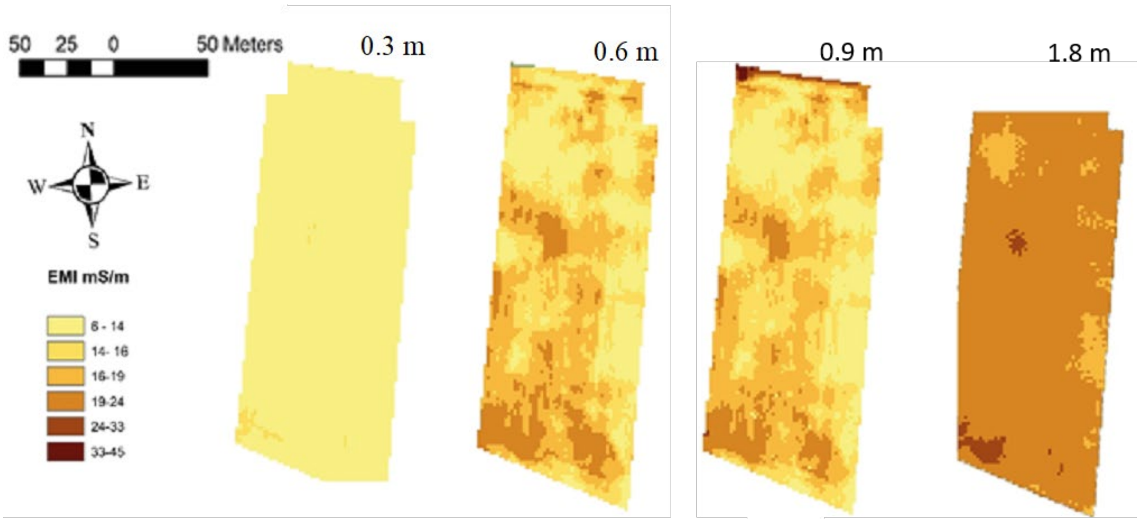

***Figure 7.2**. Results of the electrical conductivity mapping of the Lund field site using the DUALEM21s sensor.*

7.2.2 DC resistivity

In the Multi-Electrode Profiling (MEP) method for 2D resistivity mapping an array consisting of 96 electrodes is set up, in this case across the field site. Each electrode is connected to a switch unit, which transmits current through two transmitter electrodes and simultaneously records the potential between two other electrodes. By varying the distance between the transmitting and receiving electrodes data points at different depths along the array can be obtained (Dahlin and Zhou, 2004). The longest distance between current and potential electrodes, yields the deepest data point and vice versa. At the field site in Lund we obtained MEP data along five lines, the length of which were chosen so the investigation depth was sufficient to be able to delineate the top of the limestone below the tills. The spacing between electrodes was 1.5 m and measurements were collected using an IRIS SYSCAL Pro Switch 96 system with 10 channels (IRIS Instruments, Orleans, France), which was made available by the Department of Geosciences and Natural Resource Management, University of Copenhagen. Inversion of resistivity data was performed using the Res2Dinv software (Geotomo Software, Malaysia).

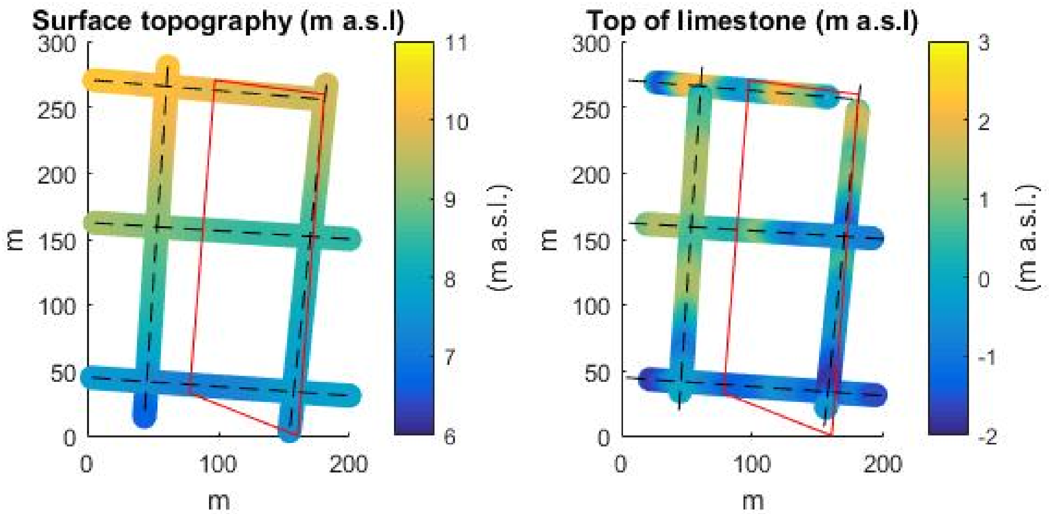

Figure 7.3. Surface topography (left), elevation of top of limestone (middle), and thickness of "transition zone" between till and limestone (right) based on MEP data. The shape of the field is outlined by the red polygon.

The profiles show that the upper approximately 9 m of soil have characteristic resistivities corresponding to clayey till (25-50 Ωm), and below this, the resistivity values correspond to limestone (> 80 Ωm) (Jørgensen et al., 2003). In Figure 7.3, the MEP data have been converted to maps showing the topography of the surface topography and the bryozoan limestone. The highest elevation of the surface as well as of the limestone surface is found in the northwestern corner, and both the ground surface and limestone surface slopes gently towards the south-southeast. This corroborates the common assumption that the surface topography of Stevns in general follows that of the top of the limestone. Since the till thickness is only 5-6 m at the coastal cliff south of the field site (Figure 5.6), it seems the limestone surface has a slightly higher slope than the ground surface, although this is not entirely evident from the MEP data. In the piezometer well P3, the transition zone between till and limestone was reached at a depth of approximately 9 m, which also fits well with the MEP data.

7.3 Ground Penetrating Radar

During establishment of the other PLAP fields Ground Penetrating Radar (GPR) was used for detection of soil anomalies such as sand or gravel lenses, and internal structures in the sediments. GPR can also be used for delineating drainpipes (Koganti et al., 2020), and it was attempted to use GPR for this purpose at the Lund field site. The results, however, show that this was not possible due to high attenuation and low penetration depth of the signal from the surface.

Prior to making the six-meter-deep excavation west of the field, three boreholes for cross-hole GPR measurements were installed by the Department of Geosciences and Natural Resource Management, University of Copenhagen. With this method, the antennae are lowered into the boreholes. In recent years, cross-hole GPR has been successfully used for mapping and characterizing sand lenses within clayey till (Looms et al., 2018), and it was therefore decided to use the method at the Lund field site before excavating the area. As was evident from the excavation, however, there were no significant sand lenses within the clayey till in that area. Interestingly, the data does show that the two tills found at the site can be delineated in the cross-hole GPR data. The transition from the upper to the lower till is found at approximately 2.5 m depth as a decrease in both amplitude and electromagnetic velocity of the GPR signal, which is interpreted to be caused by the lower porosity and sand content of the lower till. This fits well with the findings in the excavation, in which the transition between the two tills is at approximately 2.3 m depth.

8 Concluding remark

With the addition of the Lund field site to the Pesticide Leaching Assessment Programme it is our hope that we will be able to shed further light on the nature of pesticide leaching and thereby be able to more effectively protect the groundwater and nature in general. Since results from PLAP have shown that clayey till soils seems to be more prone to transport of many compounds than sandy soils, it is of great importance that more knowledge about the mechanisms at play is gained. Although there is already 20 years of data from the Pesticide Leaching Assessment Programme, there are still many lessons to be learned and compounds to test, and with the addition of the Lund field site, we are even better prepared for the future.

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11 Appendix A. Cultivation and pesticide application history

Year	Crop	Date	Pesticide brand	Dose per ha
2012/13	Winter wheat	10.10.12	Stomp	1.200 l
		10.10.12	Boxer	0.800 l
		10.10.12	DFF	0.030 l
		25.04.13	Ally ST	0.380 tab
		25.04.13	Starane XL	0.450 l
		25.04.13	Ceando	0.150 l
		25.05.13	Fastac 50	0.125 l
		25.05.13	Viverda	0.400 l
		15.06.13	Fastac 50	0.150 l
		15.06.13	Viverda	0.450 l
2013/14	Winter rape	20.08.13	Command CS	0.250 l
		20.08.13	Stomp	0.500 l
		18.05.14	Cyperb 100	0.250 l
		18.05.14	Amistar	0.380 l
		18.05.14	Folicur EC 250	0.500 l
2014/15	Winter wheat	11.10.14	Legacy 500 EC	0.100 l
		11.10.14	Express SX	7.000 gr
		18.04.15	Starane XL	0.500 l
		01.05.15	Bumper 25 EC	0.200 l
		01.05.15	Rubric	0.200 l
		20.05.15	Viverda	0.600 l
		20.05.15	Bumper 25 EC	0.100 l
		10.06.15	Mavrik 2F	0.050 l
		10.06.15	Proline EC 250	0.350 l
		10.06.15	Rubric	0.100 l
2015/16	Winter wheat	05.10.15	Boxer	1.000 l
		05.10.15	DFF	0.100 l
		05.10.15	Oxitril CM	0.150 l
		05.05.16	Starane XL	0.400 l
		05.05.16	Express SX	7.500 gr
		06.05.15	Proline EC 250	0.120 l
		22.05.16	Mavrik 2F	0.070 l
		22.05.16	Maredo 125 EC	0.100 l
		22.05.16	Proline EC 250	0.150 l
		22.05.16	Comet Pro	0.100 l
		28.05.16	Viverda	0.500 l
		28.05.16	Orius 200 EW	0.100 l