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Influence of the shrink and swell cycle on soil physical properties of loam and clay soils in the Netherlands

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Influence of the shrink and swell cycle on soil physical properties of loam and clay soils in the Netherlands

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Foreword

"A nation that destroys its soils, destroys itself"
Franklin D. Roosevelt. 1882-1945

These words should everyone who works in, on or with soils keep in their minds. A destroyed soil is not easy to restore. With the increasing food and feed demands, water shortages and extreme weather conditions it's an increasing challenge to aggravate our soils without over aggravate them.

I got the chance to work with people who understood these words very well

By this foreword I would like to spread my gratitude to those people who have helped me very much along the way to reach this final report. First of all Jan van den Akker, who was my supervisor during the research. I would like to thank him a lot, he guided me very well along the way and had useful answers and feedback for me when I had questions or some data which I wasn't sure about. Together with him Manuel Seeger, who also guided me through this process.

Also I would like to thank Eduard Hummelink. He was with me all three days in the field, arranged transportation of the material and that all the material was available. Also during the lab work he helped me a lot with explaining the methods and the devices to be used.
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Erik Roelfsema
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Abstract

Soil compaction is an increasing problem throughout the world. It is caused by the increasing weight of machinery and working on soils in the wrong conditions. Especially soils with a high moisture content are susceptible to compaction. Clay and loam soils have the ability to hold water and therefore in this research loam and clay soils are used.
Also the European Union recognizes soil compaction as a problem. In the Thematic Strategy for Soil Protection from the European Union, soil compaction is mentioned as one of the threats for the soils in Europe. The purpose of the strategy is protection of the soil and sustainable use of the soil.

Clay soils are known for their shrink and swell capacities. These capacities can also result in recovery of the soil after compaction. This research tries to find out if the shrink and swell capacities of a soil influence soil recovery and how shrink and swell influences the physical characteristics of the soil. On three locations in the Netherlands, where there are loam or clay soils, this research has been conducted. Two locations in the Hoekse Waard, the southwest of the Netherlands, were chosen, namely Zuid-Beijerland and Mijnsheerenland. The third location is located in the north of the Netherlands, Nieuw Beerta. From these three locations is tried to establish the recovery potential of clay soil after compaction.

The recovery potential is determined by using several field and laboratory methods. In the field, the infiltration rate and the penetration resistance were measured. Next to that, a soil description was made and earthworms were counted. For the laboratory methods, several soil samples were taken with different sample ring sizes. The laboratory methods that were done: dry bulk density, air filled pore volume, saturated hydraulic conductivity, air permeability shrink characterization, and shrink and swell height measurements.
For all methods threshold values were determined which a soil minimal has to have to be capable of providing the right environment and physical properties for plant growth.

The results indicate that for all soils applies that there can occur problems with aeration in case of extreme wet periods. Especially with the low amounts of biological activity this problem is strengthened.
But the low amounts of air filled pores do not necessarily have to end up in problems. This is because the transportation, of air as well as water, has no trouble to be transported through the soil. Which means that when extreme conditions occur water can be easily transported away from the soil surface. Because of the fast transportation of water through the soil, there might appear no aeration problem.

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Introduction

Agricultural areas face problems related with soil compaction already for many years (Soane and van Ouwerkerk, 1994). Soil compaction is known as a problem which appears all around the world, but especially in areas where heavy machinery is used, soil compaction can cause problems (Oldeman, 1991).

In literature soil compaction is defined as compaction, densification and distortion of the structure of the soil. This results in less amount of air filled porosity in the soil and permeability of the soil. Compaction can also results in less productivity of the soil and biological activity. Due to the decreased infiltration capacity and permeability of the soil there is an increased risk that erosion occurs and nutrients are lost due to denitrification and runoff (van den Akker, 2006;).

The problem of soil compaction gets worse with the increasing size of farms and with the increasing size and weight of agricultural machines. Due to the increasing size of farms, farmers have less time to harvest their crops. This results in that farmers sometimes have to work on their fields despite the fact that the soil is too wet. A second element of increasing farm sizes is that the farmers buy large machines which can do more work in the same time span as a smaller machine. Especially soils with a high moisture content are sensitive for soil compaction (Canarache, 1991).

The European Commission presented the Thematic Strategy for Soil Protection in 2006. The purpose of this strategy is protection of the soil and sustainable use of the soil. In this strategy eight soil threats are formulated which are indicated as threat for the soils in Europe (Montarella, 2006; European Commission, 2006). These are:

- Soil erosion by water and wind
- Soil contamination
- Loss of soil organic matter
- Soil sealing which is caused by infrastructure and housing
- Soil compaction
- Decline in soil biodiversity
- Salinisation
- Floods and landslides

This research will mainly look at soil compaction and also the decline in biodiversity will be taken into account.

Within this strategy the European Commission wants to classify the areas in Europe according to their risk to compaction.

Objective
The main objective of this study is to quantify the physical and biological recovery potential of clay and loamy soils.

Research question

Can clayey and loamy soils in the Netherlands recover from (sub)soil compaction?

De Leeuw (2009) developed a method to determine the recovery potential of clay and loam soils in the Netherlands. This method will be followed during this research and if needed improved as well as the method which van den Akker *et al*(2008) used during their research will we followed.

The research took place on two privately owned fields and one field belonging to an experimental farm.

In chapter one a review is presented of available literature related to the subject of (sub)soil compaction. Chapter two describes the material and methods which were used during this research to continue in chapter three with threshold values for the different measurements which were done. The results of all the measurements will be explained in chapter four. Finally the discussion in chapter five and a conclusion in chapter six.

Theoretical background

Within the subject of compaction a distinction can be made between topsoil compaction and subsoil compaction. Topsoil compaction takes place above the ploughpan, which mostly is till ± 20 - 35 centimeter below soil surface. Subsoil compaction is the compaction which starts in the ploughpan. The ploughpan is the top part of the subsoil. The ploughpan is a result of one front tire and one back tire of a tractor which drives through the furrow while plowing as well due to the increasing wheel loads of farmers' equipment (van den Akker, 2006).

In literature several options are mentioned on how to prevent subsoil compaction.

- Lowering contact pressure of the tyres. This can be done by mounting larger tyres which have a larger contact area or inflate the tyres with less pressure which also increases contact area. Another solution is lower the wheel load or a combination of these three.
- Minimize number of passes on the field; try to combine multiple tillage and/or sowing/harvesting activities.
- Adapting practices and cropping to avoid soil which is moist
- Good crop rotation, different crops have different influences on soil properties which can improve the structure of the soil
- Improve drainage; dry soil is stronger than wet soil, topsoil and subsoil carrying capacity will improve.
- Multiple axes to decrease wheelload per axle
- Arrangement of tillage equipment
- Using four wheel drive to reduce slip
- Using tracks in stead of tyres which have a large contact area and have almost no slip and low pressure on the soil
- Make use of radial tyres in stead of diagonal tyres which have better capacities to increase contact area.

The compaction of the top layer of the soil can be dissolved by freeze- drying- and wetting-cycles. Also with (increasing) biological activity and with different cultivation techniques a compaction can be made undone (van den Akker, 2006).
Undoing the compaction of subsoil is not easy because subsoiling is often not the right way to repair the soil as Gregory *et al* (2007) mention. It can also make the conditions worse. Some soils have the capacity of recover (partially) from compaction by making use of the shrink and swell cycle. Research that has been conducted in the Netherlands on clay and loamy soils pointed out that clay and loam soils have the capacity to recover partially with the help of the shrink and swell cycle (de Leeuw, 2009).

Shrink and swell of clay soils

Clay refers to the size of the particles which is smaller than 0,002 millimeters but clay also refers to secondary clay minerals. These secondary clay minerals are

synthesized from chemical weathering. Those minerals have collodial properties which means that the very small particles carry an electric charge.
The clay minerals consist of alumino-silicates which are formed from the melting together of alumina and silica. Figure 1 represents different kind of clay structures. Clay soils consists of small amounts of Illite, Kaolonite, Montmorolite, Vermiculite, Smectite or Chlorite.

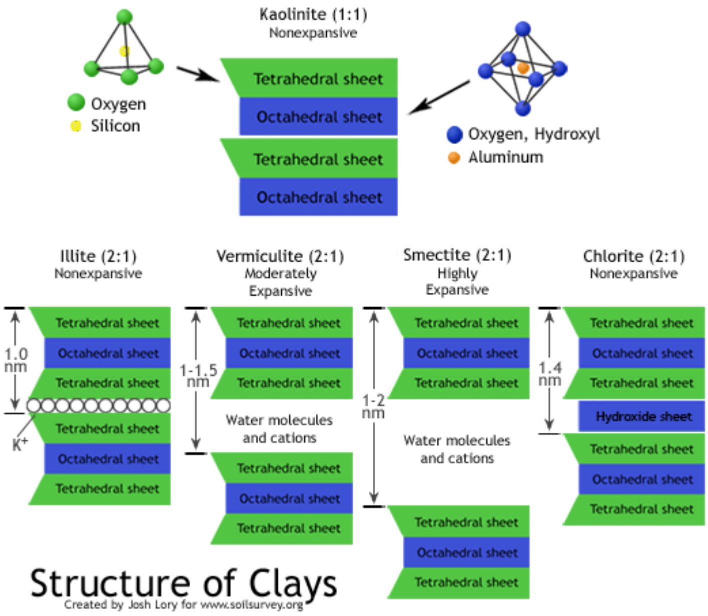


Figure 1 Structure of clay minerals (Source: Cooperative Soil Survey)

Around the clay surface cations are attracted by the negative charge of the surface. These cations are influenced by two forces. The first are the electrical forces which pull the positive ion to the negative surface and the second one are the thermal forces which stimulate the cations to move away from the clay surface. Between these two forces a balance consists. In this balance there are possibilities for cations to distribute in water adjoining the clay surface. This distribution is called electric double layer. It consists of the negative clay surface and distributed counter ions.
In the soil the electric double layer resides the space between the clay surface and the soil solution.

The soil solution around clay particles is present as thin films if there are low soil water contents. The electric double layer can then not reach its full extent. This is called a truncated double layer. The concentration of ions is higher and because of this it has a lower osmotic potential. This results in the fact that the truncated double layer can absorb water by osmosis and thus result in swelling.

The amount of swelling depends on the potential extent of the double layer. This potential is influenced by several factors:

- Clay type
- The types of counterions
- Salt concentration of the bulk solution (influences the osmotic potential)

Upon wetting the distance between the clay surfaces increases and upon drying the distance decreases which results in shrinking (Lecture notes Physical aspects of land management, 2007).

The volume decrease of aggregates can be described in three phases:

- Normal shrinkage: The aggregates remain fully saturated and the volume decrease is equal to water loss.
- Residual shrinkage: The volume of the aggregates still decreases but water which is lossed is greater than the volume decrease. In this phase air is starting to enter the pores from the aggregates.
- Zero shrinkage: If water is still extracted from the aggregate, the volume stays the same. Also the water which is lost will be replaced by air. The soil particles have reached their most dense situation.

In a field situation often a fourth type of shrinkage occurs, which is called structural shrink. In this phase macro pores and large cracks are emptied. This phase occurs before the normal shrinkage phase.

The shrink characteristic used in this research is based on the relation between void ratio (1) and moisture ratio (2) (Bronswijk, 1987). These two are defined as:

Void ratio $e = \frac{V_p}{V_s}$ (1)

Where V_p is volume of pores and V_s is volume of solids

Moisture ratio $\upsilon = \frac{V_w}{V_s}$ (2)

Where V_w is volume of water and V_s is volume of solids

Earthworms

Besides the physical elements also the biological elements in the soil can contribute to the rate of which a soil can recover from compaction.
Earthworms create pores in the soil through which the roots of the plants can grow and water can be transported away from the soil surface (Capowiez *et al*, 2009). Many laboratorial experiments conclude that earthworms are capable of digging through compacted layers creating pores (Capowiez *et al*, 2009; Langmaack, 1999). These pores play a vital part in soil structure, rooting of plants and water transportation (Kuyper, 2008). Research done by Larink *et al* (2001) found that soil with sufficient amount of earthworms has 50% higher swelling values than comparable aggregates.

Biodiversity in the soil is very important for the growth of the plant. As an indicator for life in the soil the earthworm is often used.
Baker (2006) established in his research that there are three types of earthworms with different characteristics and different contributions to the soil.

The first type is the endogeïc group. These earthworms go up and done from topsoil to the subsoil and vice versa. They spent most time in the subsoil but they eat decomposed organic matter mixed with much soil which is mostly available in the topsoil. This group creates the macro pores which run vertical to deeper layers. This group is most important regarding transportation through the soil. These earthworms are characterized by a flat tail.
Next to the endogeïc group there's one group which stays in the topsoil and decomposes litter from the soil surface in the topsoil. This is the epigeïc group. These earthworms have a grayish color.
The third kind of earthworms are the anecic worms. These worms eat the litter which is available on the soil surface. The color which characterizes them is red (Koopmans and Brands, 1999; European Commission, 2010; Kuyper, 2008)

Methods to determine the rate of soil compaction

De Leeuw(2009) and van den Akker (2006) described in their research some methods on how to estimate and calculate soil recovery compaction (Table1).

Table 1 Methods to measure soil physical properties

1	Infiltration rate
2	Penetration resistance
3	Dry bulk density
4	Packing density
5	Saturated hydraulic conductivity (Ksat)
6	Air filled pore volume
7	Shrink and swell measurement
8	Shrink characteristic

<u>*Air permeability*</u>
During this research one method is added to this list. This method is to calculate the air permeability.

Air permeability is defined as an estimate of the intrinsic permeability of the soil when gas is used as the flowing fluid. Intrinsic permeability is the ability of porous material to conduct a fluid movement in response to a pressure gradient (Reeve 1953).

Researches, which have been conducted on the subject air permeability, concluded that air permeability gives a good characterization of macro pores (Roseberg, 1990; Blackwell *et al.*, 1990).
When low pressures are applied the flow of air through the sample can be compared to the flow of a fluid through the sample.

Multiple devices have been developed in past 50 years. Both for in-situ experiments as for laboratory experiments. One note has to be made. The outcomes of these methods cannot be compared with each other without converting the data.
One of the apparatus to measure air permeability was developed by professor Kmoch at the Rheinischen Friedrich-Wilhelms Universität in Bonn. This apparatus works according to the principle that underneath a swimmer, which floats on a water surface, air is compressed through the soil or soil sample. The rate at which the swimmer sinks is a rate of soil permeability (Kmoch.1961).

Material and methods

This chapter describes the material and methods, which were used during this research. Also a little literature study is included about the air permeability and the question if it can replace the saturated hydraulic conductivity measurements.

Locations of research

The research is done on three locations in the Netherlands. Two of these locations were in the province of Zuid-Holland and the third was in Groningen (Figure 2)

Figure 2 Locations of this research in the Netherlands (Source: Alterra Geo Informatie, Wageningen)

The owners of the two locations in Zeeland were participating in a project called Hoekse-WodKa (Hoekse Waard op de kaart). In this project farmers try to increase their productivity. A way how they want to achieve that, is by getting insights in the soil and adapt their management style to it.

The location in Groningen is part of an experimental farm which is part of SPNA (Stichting Proefbedrijven Noordelijke Akkerbouw).

The coordinates of the three locations are in Table 2.

Table 2 Coordinates of locations for this research

Location	X- coordinate	Y-coordinate
Zuid-Beijerland	51°46'28.09"N	4°24'10.69"E
Mijnsheerenland	51°48'13.04"N	4°29'2.33"E
Nieuw Beerta	53°11'4.05"N	7°10'46.61"E

Zuid-Beijerland

The field belongs to a privately owned farm, Figure 3. The parcel is located near a dike but this has no effect the groundwater flow according to the farmer. It's a clay soil till -75 centimeter below soil surface and a lute percentage of 17% (Van der Bok, 2010)

In the growing season of 2010 potatoes were grown, in 2009 barley and in 2008 sugar beets.

Plowing takes place in autumn till a depth of 25 centimeters. Subsoiling also takes place but not deeper than the plowing depth.

Figure 3 Location of Zuid-Beijerland

Mijnsheerenland

The second location was in Mijnsheerenland (Figure 4). The field belongs to a privately owned farm. The field has as nickname, called the 'Kikkershoek'. This means it lies in a lowness and that it's a wet field (Van der Bok, 2010). The soil type is light clay till 45 centimeter below soil surface. From 45 centimeter it is heavy loamy soil(Van der Bok, 2010).

In growing season 2010 winter barley is grown. Three years before grass seed was grown.

Plowing is done in autumn till a depth of centimeters. Autumn 2009 it was a dry autumn and the field was grubbed with a 3 toothed subsoiler. This was done till a depth of 40 centimeter and in two directions across the field.

Figure 4 Location of Mijnsheerenland

Nieuw-Beerta

The field in Nieuw-Beerta is property of an experimental farm called 'Ebelsheerd' (Figure 5). The field on which the research was done belonged to a larger field on which they do experiments with conventional tillage, no tillage and mulching. The field we chose was the field where conventional tillage was applied since this research is focusing on the ploughpan.

Plowing takes place in autumn and is done to a depth of 20 centimeter.

During the growing season 2010 winter wheat was grown as also in 2009.

Figure 5 Location of Nieuw Beerta

Measurements

There are three elements on which a the recovery potential of a soil can be quantified. These are physical, biological and chemical. This research will focus on the physical and biological elements but recognizes also the chemical elements.

To determine the shrink and swell potential several field and laboratory measurements were carried out. These measurements are done according to the method which De Leeuw (2009) used during his research and which van den Akker (2006) used. The biological component and the air permeability will be added to this method. Hereunder the measurements will be explained.

Field measurements

Soil description and photographs of the soil profile
To take the photographs a hole was dug till about 70-80 centimeter below soil surface. A description was made of the structure and the profile. Roots and pores were also counted.

Infiltration rate
To measure the infiltration rate the double ring infiltrometer concept was used. The outer ring of the meter has a diameter of 66 centimeter and the inner ring 30 centimeter and a height of 25 centimeter. The measurement was done in the ploughpan at ± 30 centimeters. Both rings were placed on top of the ploughpan to establish the infiltration rate of the subsoil. (Eijkelkamp, 2003)

Penetration resistance
A number of 25 measurements were done per plot. This was done in a straight line across the field perpendicular to the sowing direction and at the head end of the field. In clusters of five measurements on five places the measurements were done, which resulted in 25 measurement per part of the field.
These measurements went to a depth of 80 centimeters. The cone of the apparatus was 1 cm^2 and had a top angle of 60º (Eijkelkamp, 2010).

Earthworms
A sample was taken with a size of 20 centimeters times 20 centimeters till the depth of the ploughpan. This sample is sorted out by hand and the amount of earthworms and earthworm species was counted and the different types of earthworms were determined.
To determine how many of which group live in the subsoil a formalin solution (0.2%) was added to the hole. The earthworms which live in the lower subsoil were bound to appear within twenty minutes (USDA, 1999; Capowiez, 2009[2]).

Soil samples
In the field multiple soil samples were taken for the laboratory measurements.

- To get an indication of the amount of topsoil, one sample from the head end of the field and one from the middle part of the field was taken. This was done with a ring with a diameter of 10 centimeter and a height of 32 centimeter. This ring was pushed into the topsoil till the ploughpan and then dugged out.
- For the dry bulk density five samples were taken per plot. These five rings were taken equally distributed across the head end of the field and in the middle part of the field. The samples were taken from the ploughpan to determine whether the compaction is equally distributed across the fields. These rings have a volume of 100cc.
- For the air filled pore volume three samples per layer were taken. This was also done with rings, which have a diameter of 7,5 centimeter and a height of five centimeter. Three samples were taken in the ploughpan layer, three samples 10 centimeters below the ploughpan layer and three samples 20 centimeters below the ploughpan layer.

- The saturated hydraulic conductivity (Ksat) was measured using five samples. These samples were taken in the layer just below the top layer in the upper 10 centimeter of the subsoil (ploughpan). The rings which were used have a diameter of 19 centimeter and a height of 10 centimeter.
- To measure the shrink and swell potential the samples which were taken for the Ksat were used.
- For determining the air permeability the same samples were used which were also used for the air filled pore volume determination.

Laboratory measurements

Formulas used to calculate the specific characteristics are in chapter 4.

Dry bulk density
The dry bulk density was measured according to the description made by Alterra, E4503. In this method the filled 100cc rings have to be weighted. After weighing they were put in an oven (105 °C) for 24 hours. Once out of the oven they were weighted again as also the empty rings. And with the help of the Excel file belonging to E4503. This method is based on NEN 5781 (Alterra, 2007).

Organic matter content
The organic matter content was measured according to Alterra E0100. In this method a quantity of 20 gram was taken from each sample which was put in a melting pot and weighted. After the weighing the samples were dried in an oven (105 °C) for 24 hours. After 24 hours the samples were weighted again an put in an oven (550 °C) for 8 hours. Once they come out of the oven they were cooled down in an oven at 45°C for two hours and after the two hours they were weighted again. This method is based on NEN 5754.

Saturated Hydraulic Conductivity (Ksat)
The Ksat is determined as described by Alterra E4500. The samples from the field were first placed in plastic boxes to let them saturate. This can take for clay from one week up to four weeks and for loamy soils from one till three weeks. Once the samples were saturated they were placed on the Ksat apparatus. After placement the samples were saturated again till a water head appeared above the samples. Once this water head was formed the Ksat was measured.
The sample rings in this measurement may be different in size from other researches. The rings which Alterra uses are larger (19 centimeter diameter and 10 centimeters in height) than other countries or researchers (5 – 10 centimeter diameter and 5 centimeter in height). The reason why they use these larger rings is that they also include the effect of macro pores such as cracks. If smaller rings are used these effects can be ignored (Van den Akker and de Groot, 2008). Information from this method is based on NEN 5791 (Alterra,2006).

Air permeability
The 8 centimeter rings taken in the field at different depths, which also were used to determine the air filled pore volume, were also used to establish the air conductivity.

This was done according to the method developed by Kmoch (1961). The sample ring was placed in the apparatus and the air conductivity was measured with the help of a timer. The measurement was repeated two times with each sample. With the help of Table described in Chapter 4 the air conductivity was determined.

Air filled pore volume

The samples taken from the field were placed on a pF-box. This is a box with fine sand and which has a range of pF curve till -150 centimeter water suction. Several days have to be waited to let the internal moisture content to become stable (Van den Akker & de Groot, 2008). Once the moisture content was stable at five water suction levels the weight of the samples was measured. These levels were 0, -5, -30, -50 -60 and -100 centimeters water suction. After the weight had been measured in all levels, the samples were dried in the oven at 105°C and weighted after 24 hours. Once this was done the diameter of the rings and the weight of these rings was measured. With this obtained data the air filled pore volume was calculated.

Shrink and swell measurements

After measuring the saturated hydraulic conductivity the samples were dried out. This was done in a controlled environment of 16 °C. The samples were weighted every two days to determine the weight loss. At the same time steps the height was measured with the help of a sample ring with two height measure devices connected to it. The difference between two measurements is the shrink. Also the pressure was measured with the help of tension meters which were installed in the sample after the Ksat. There was measured till the pressure of -800 kPa.

Once the samples had reached that pressure they were put in a box with a layer of water again to saturate. Also now, every two days the weight and height was determined till the soils are saturated again.

Shrink characteristic

The method that was used to determine the shrink characteristic was done according to Bronswijk.

From each location three aggregates were taken. These samples have to be more or less fully saturated. The best way is to place them on sandbox at a height of 0 centimeter. From the samples aggregates were be taken with a size around 3-5 centimeters. Around these aggregates a rope was tied to hang them. Once the rope was connected the samples were weighted, both the normal weight as the weight under water. After the weighing, all the samples were put in a SARAN-solution which was standing on a scale.

SARAN is a Poly Vinyl Ideen Chloride. A solution of SARAN F310 synthetic resin and methyl-ethyl keton (MEK). It's has a characteristic that the aggregates, which are covered with SARAN, have the ability to breath and evaporate, but for moisture it is almost impossible to penetrate through the coverage of SARAN.

The weight difference of the jar with SARAN was noted down before and after the immersion. The weighted difference is the amount of SARAN around the aggregate. The aggregates then dried for 20 minutes and immersed for the second time. Again the weight was noted down before and after the immersion. Once the samples are done twice they were hang up and were weighted at several times. These are after 1 hour, 6 hours, 1 day, 3 days, 5 days, 10 days and 14 days. The weighing each time consisted of a normal weighing and an under water weighing. After the weighing sessions the samples were dried in an oven (105 °C) for 24 hours and weighted again. At all the under water measurements has to be made sure that the samples are no longer than a few seconds under water because they might absorb some water, especially after the oven (Bronswijk 1986).

Threshold values

To determine whether the outcomes of the field and laboratory measurements are good or bad, threshold values have to be established. This was done by reviewing literature and with help of the report by van den Akker (2008).

Infiltration rate

United States Department of Agriculture developed some values regarding infiltration. This values holds for unsaturated infiltration. To have a moderate infiltration at least 0,366 m\d water has to infiltrate in the soil.

Table 3 Infiltration rate classification

m/d		Class
from	till	
> 12,192		Very rapid
3,658	12,192	Rapid
1,219	3,658	Moderately rapid
0,366	1,219	Moderate
0,122	0,366	Moderately slow
0,037	0,122	Slow
0,001	0,037	Very slow
< 0,001		Impermeable

Penetration resistance

Ten Cate *et al* (1995) established that the critical value for roots to penetrate through the soil lies between 2,5 – 3 MPa. This will shift to higher values if there is a well established pore system.

Critical threshold value for penetration resistance for rooting: Pr = 2,5 - 3 MPa.

For this research an average value of 3 MPa is used a threshold value. This value can only be used if the penetration resistance is measured with a cone which has a cross-sectional area of 1 cm^2 and a top angle of 60°. Penetration resistances measured with other cones cannot be compared because top angle and size of the cone has large influence on the penetration resistance.

Earthworms

To determine the quality of soils regarding biological activity Louis Bolk Instituut developed guidelines for farmers. In these guidelines there is also a classification system for the number of earthworms in a soil. These are visualized in Table 4. In a soil at least 20 earthworms per m^2 have to appear.

Table 4 Biological activity

Number of earthworms per m^2		Class
from	till	
< 20		Bad
20	100	Moderate
> 100		Good

Packing density (PD)
To establish the threshold for packing density the following formula (3) can be used

$$PD = D_b + 0{,}009C \qquad (3)$$

Where D_b is dry bulk density in g/cm^3
C = clay content (in mass %) of the location in the field
PD = packing density in g/cm^3

No fixed threshold can be maintained. The threshold depends on the bulk density and on clay content.

Within the packing density three classes can be divided:

Low <1,75 g/cm^3
Medium 1,40 – 1,75 g/cm^3
High > 1,75 g/cm^3

Dry bulk density (Db)
Dry bulk density can be calculated according to the formula (4):

$$Db = \frac{m_s}{V} \qquad (4)$$

To come to a threshold value for dry bulk density the formula (5) used for packing density can be rewritten into a comparison:

$$Db < 1{,}75 - 0.009C \qquad (5)$$

For light loamy soils (C <17,5) the threshold value for pore volume can be recalculated into a threshold value for dry bulk density.

$D_b < 1{,}6$ g/cm^3

Saturated hydraulic conductivity(Ksat)
The Cultuurtechnische Vereniging established some threshold values for the saturated hydraulic conductivity (Ksat). They classified a Ksat of less than 10 cm.d^{-1} as 'low'. Also Lebert found in his research that a Ksat value of 10 cm.d^{-1} is a suitable value for the subsoil (Cultuurtechnische Vereniging, 1988; Lebert *et al*, 2003).

Table 5 Classification for saturated hydraulic conductivity (Ksat)

Classification	K (m/d^{-1}) from	till
Very low	<0,01	
Low	0,01	0,1
Average	0,1	0,5
Above average	0,5	1
High	1	10
Very high	>10	

Ksat > 10 cm day^{-1} or 0,1 m day^{-1}

The saturated hydraulic conductivity is both an indicator for physical quality of the soil as for the functioning of the soil itself.

When the subsoil is compacted this has most influence on the continuity of the macro pores and also on the amount of macro pores which results in a lower infiltration capacity.

If the soil is compacted and has a low infiltration capacity the soil can take up less water if rain is falling. This can result in saturation of the soil which then can results in surface flow and erosion. One of the other threats as mentioned in the Thematic Strategy for Soil Protection (European Commission, 2006).

Pore volume
If a soil has a pore volume (n) of less than 40%, plant roots face problems of penetrating through the soil (Hidding, 1961).

n > 40%

In the Netherlands clay soils have pore volumes which are larger than 40% (van den Akker, 2006).

The pore volume can be calculated according to the equation (6):

$$\phi_{\rho} = 1 - \frac{\rho_d}{\rho} \qquad (6)$$

Where:
ρ_d = Packing density in gram/cm^3

ρ = particle density in gram/cm^3

ρ can be calculated with the formula (7)

$$\rho = \frac{100}{0.3H + 38} \qquad (7)$$

Where:
H = 100f_h
f_h = mass fraction of organic matter of solid parts

Air filled pore volume (n_g)
Air filled pore volume can be calculated according to the following equations (8,9):

$$\theta = \frac{m_0 - m_s}{V_{ring}} \qquad (8)$$

Where

θ is the volumetric water content
m_0 is the mass of the soil sample at 0 cm water tension in gram
m_0 is the mass of the soil sample after drying 24 hours at 105°C
V_{ring} is the volume of the sample ring

For each next step with increasing water tension the equation will be:

$$n_g = m_{1,2,3..} - m_0 \qquad (9)$$

Where:

$M_{1,2,3..}$ is the mass of the soil sample at the different water tension levels

The threshold value for the pore volume which has to be preferably filled with air is depending in the structure of the soil.

Table 6 Classification for air filled pore volume

Soil structure	Air filled pore volume	
	Minimal	Preferable
Very good	> 2 %	> 14 %
Good	> 5 %	> 15 %
Average	> 8 %	> 17 %
No, Bad	>12 %	> 21 %

For this research a minimal air filled pore volume of 10% is taken. This means that is assumed that the soil have an average to bad structure.

Air permeability

For air permeability two classifications will be used. One which is developed by Kmoch (1961) which is in Table 7 and the second one by Horn (2003) which is in Table 8. The outcomes will be compared with each other and see what the differences are.

Table 7 Classification for air permeability by Kmoch

Classification	Class value	Air conductivity Kl ($*10^{-4}$ cm s^{-1})
Very low	1	<10
Low	2	10-22
Mean	3	22-46
High	4	46-100
Very high	5	>100

Table 8 Classification for air permeability by Horn

Classification	Class value	Air conductivity Kl ($*10^{-4}$ cm s^{-1})
Very low	1	<5,5
Low	2	5,5-12
Mean	3	12-25
High	4	25-55
Very high	5	>55

To give a short summary of all the thresholds which were mentioned in this chapter Table 9 is enclosed.

Table 9 Overview of the different threshold values

Aspect	Threshold	Unit
Packing density	1,75	g/m^3
Biological activity	20	per m^2
Penetration resistance	3	Mpa
Pore volume	40	%
Afpv (-50 cm H2O)	10	%
Afpv (-100 cm H2O)	10	%
Air permeability	22	cm^{-4} / s^{-1}
Ksat	0,1	m/day

Results

Profile description

Zuid-Beijerland
In the subsoil little amount of pores were visible and also little organic matter, even though the previous growing season barley was grown on the field which . There is a compacted layer at 24-25cm but there was no clear ploughpan. But this compacted layer could indicate that this soil has a low infiltration rate and a high penetration resistance. The particle size distribution is visualized in Table 10.

Table 10 Particle size distribution for Zuid-Beijerland

Zuid-Beijerland	Depth cm	<3 µm (clay %)	3-20 µm (silt %)	>20 µm (sand %)	< 16 µm (afslibbaar %)
Head end	0-28,5	17,7	27,8	54,5	40,4
	28,5-33,5	16,8	26,9	56,3	38,5
	38,5-43,5	15,8	24	60,2	35,3
	48,5-53,5	12,1	17	70,9	26
Middle	0-29,5	19,4	31,7	48,9	45,1
	29,5-34,5	22,6	36,7	40,7	52,5
	39,5-44,5	25,1	39,2	35,7	57,2
	49,5-54,5	23,7	37,4	38,9	54,5

Mijnsheerenland
The field was subsoiled in the autumn of 2009. It was clearly visible in the soil. There were a lot of cracks and pores visible. This subsoiling also resulted in undoing of the ploughpan. Due to the growing of grass seed in 2009 in the soil were a lot of roots visible. The particle size distribution is visualized in Table 11.

Table 11 Particle size distribution for Mijnsheerenland

Mijnsheerenland	Depth cm	<3 µm (clay %)	3-20 µm (silt %)	>20 µm (sand %)	< 16 µm (afslibbaar %)
Head end	0-25	23,5	37,5	39	54,7
	25-30	21,4	36,6	42	51,8
	35-40	20,7	35,8	43,5	50,4
	45-50	20,1	35,7	44,2	49,6
Middle	0-24	21	34,8	44,2	50
	24-29	20,4	35,4	44,2	49,7
	34-39	19,6	34,8	45,6	48,4
	44-49	17,3	30,4	52,3	42,3

Nieuw Beerta
This location was the only location where a clear ploughpan was visible. On top of the ploughpan were some undigested crop residues visible which clearly indicated that wheat was grown on the field previous year. And below a dark layer of compacted soil was visible. The density of the soil is estimated at 1500kg/m^3 with an

organic matter content of 2%. Rooting depth is up to 80 centimeter indicated by hairs from previous crops. The particle size distribution is visualized in Table 12.

Table 12 Particle size distribution for Nieuw Beerta

Nieuw Beerta	Depth cm	<8 µm (clay %)	8-20 µm (silt %)	>20 µm (sand %)	< 16 µm (afslibbaar %)
Head end	0-24,5	39,1	22,9	38	55,1
	24,5-25,5	36,5	22	41,5	51,8
	34,5-39,5	36,8	22,6	40,6	52,2
	44,5-49,5	46,1	26,1	27,8	64,6
Middle	0-23	37,7	22,5	39,8	53,3
	23-28	39,6	22,6	37,8	55,2
	33-38	48,4	25,4	26,2	66,7
	43-48	42,5	22,5	35	58,5

Infiltration measurements

Table 13 shows the values for the measured infiltration. For all three locations can be seen that between the three measurements a large difference occurs of more than 10% difference. This is due to cracks and macro pores in the soil. These cracks and macro pores resulted in high infiltration values because the water was easily transported away from the surface.

Table 13 Results for infiltration measurements in meters/day

Location	1	2	3	Log average	Class
ZB Head end	0,034	0,005	0,020	0,015	Very slow
ZB Middle	0,036	0,059	0,008	0,026	Very slow
ML Head end	1,478	0,007	1,142	0,228	Moderately slow
ML Middle	0,032	1,653	15,216	0,930	Moderate
EB Head end	0,216	0,006	0,070	0,045	Slow
EB Middle	0,410	0,031	0,019	0,062	Slow

Noticeable is that the infiltration rates on the head ends of the field are lower than on the middle part of the field. In Zuid-Beijerland the difference is the smallest and in Mijnsheerenland the highest. For Mijnsheerenland there is a large distribution visible for both the head end as the middle part of the field. Looking towards the logarithmic average and the thresholds for Zuid-Beijerland can be concluded that the head end and the middle part have very slow infiltration. For Mijnsheerenland the head end has moderate slow infiltration and the middle part moderate. Nieuw Beerta has on the head end slow infiltration as well as on the head.

Penetration resistance

Figure 6 represents the penetration resistance of the soils till a depth of 80 centimeter. For all thee fields can be concluded that the resistance in the middle part of the field stays below or around 2 MPa. For Zuid-Beijerland and Mijnsheerenland no clear compacted layer is visible. The resistance keeps increasing with depth. For Nieuw Beerta a compacted layer is visible. Around a depth of 20-30 centimeters the resistance suddenly increases till 35 centimeters of depth and then decreases again.

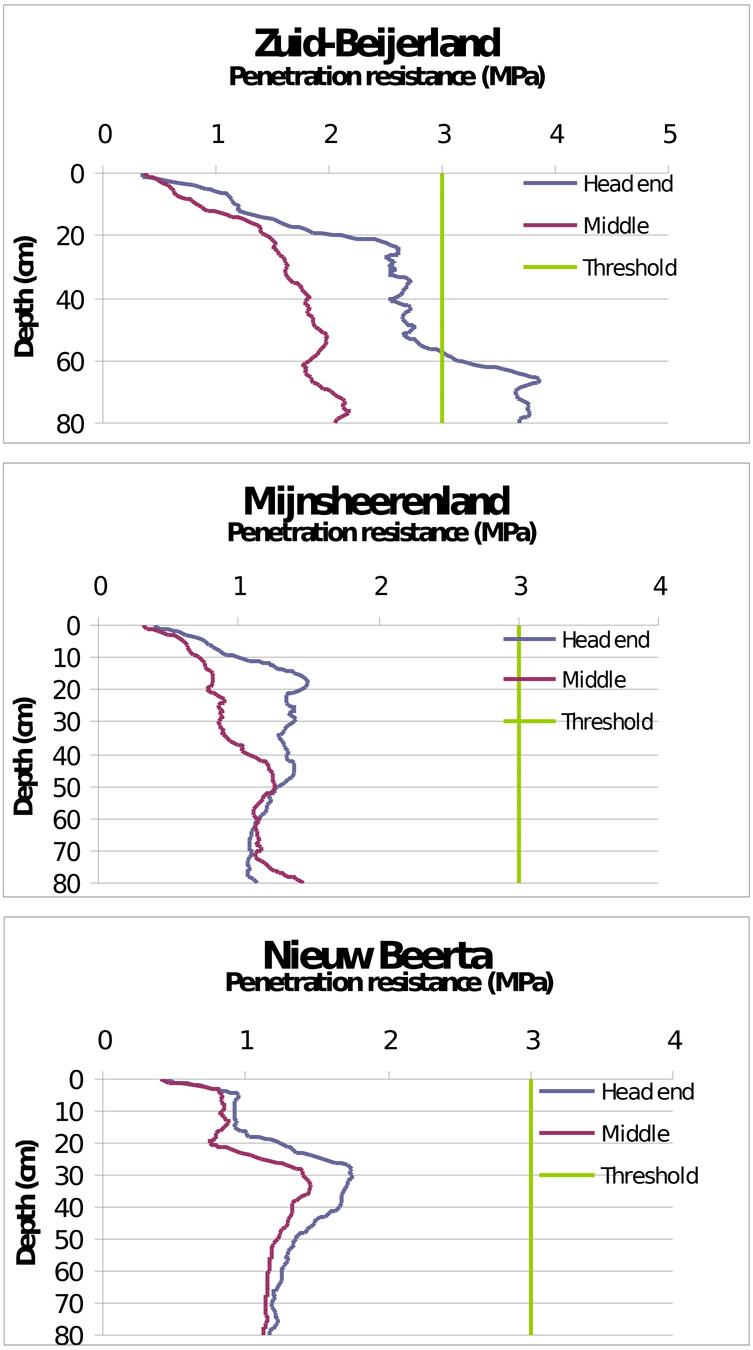


Figure 6 Measured penetration resistances for Zuid-Beijerland, Mijnsheerenland and Nieuw Beerta

For the head end of the fields the results are not the same. For Mijnsheerenland and Nieuw Beerta the resistance stays well below the threshold. Mijnsheerenland shows an unclear compacted layer while Nieuw Beerta has a clear compacted layer between 20-40 centimeters.

The resistance in Zuid-Beijerland keeps increasing from 0 centimeter till 80 centimeter. At 58 centimeter the resistance exceeds the threshold of 3 MPa.

Earthworms

Table 14 and 15 represents the number of earthworms counted in the soil and the subsoil. For the head end the two out of three soils have sufficient earthworms in the topsoil. In the middle part of the field only one soil has enough earthworms, Mijnsheerenland.

For the head end subsoil only in Nieuw Beerta live more than 20 earthworms while in the subsoil of the middle part two out three have more than 20 earthworms.

Table 14 Counted number of earthworms in the topsoil

Location		Number of worms per m^2	Class
Zuid-Beijerland	Head end	0	Bad
	Middle	0	Bad
Mijnsheerenland	Head end	225	Good
	Middle	125	Good
Nieuw Beerta	Head end	25	Moderate
	Middle	0	Bad

Table 15 Counted number of earthworms in the subsoil

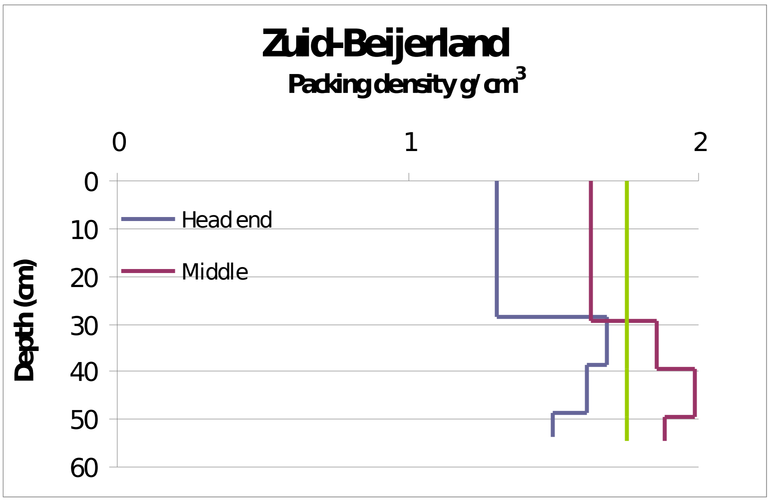
Location		Number of worms per m^2	Class
Zuid-Beijerland	Head end	0	Bad
	Middle	0	Bad
Mijnsheerenland	Head end	0	Bad
	Middle	25	Moderate
Nieuw Beerta	Head end	25	Moderate
	Middle	25	Moderate

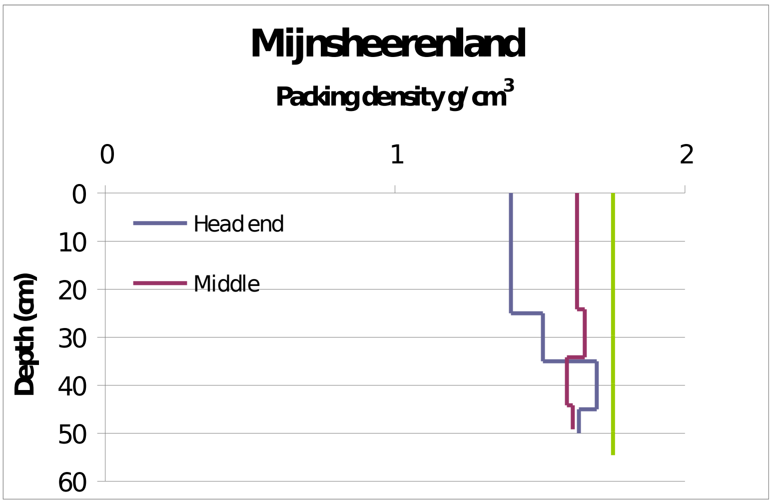
Packing density

Figure 7 represents the packing density for all three locations. When reviewing Zuid-Beijerland can be seen that the density increases for the head end part in the compacted layer and below decreases. The density of the head end part of Mijnsheerenland shows an increase in density with increase in depth. For Mijnsheerenland holds the same as for Zuid-Beijerland. There is an increase in density in the compacted layer and underneath the density decreases.

When looking at the middle part of the field three different observations can be made for all three locations. For Zuid-Beijerland can be said that the density is increasing with increasing depth. Only at the deepest layer density decreases again. From the depth of the ploughpan density exceeds the threshold of 1,75 g/cm^3. In Mijnsheerenland density stays around the same amount (1,45 g/cm^3).

In Nieuw Beerta the density decreases in the compacted layer and immediately underneath it, density decreases again.





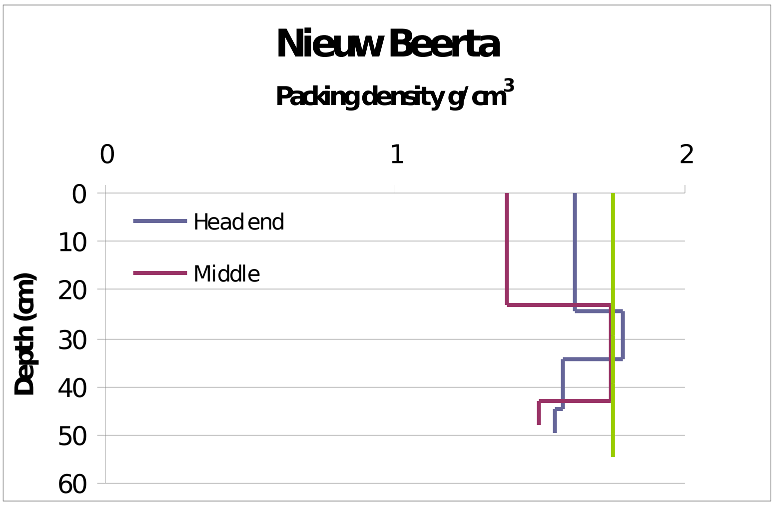


Figure 7 Packing density (g/cm3) for Zuid-Beijerland, Mijnsheerenland and Nieuw Beerta

Dry bulk density

In Figure 8 the dry bulk density is described. Regarding the middle part of Zuid-Beijerland bulk density gets higher with increasing depth. For Mijnsheerenland the bulk density stays around the 1450 kg/m^3 till a depth of 50 centimeter. And in Nieuw Beerta the highest bulk density is in the compacted layer and underneath the density gets less.

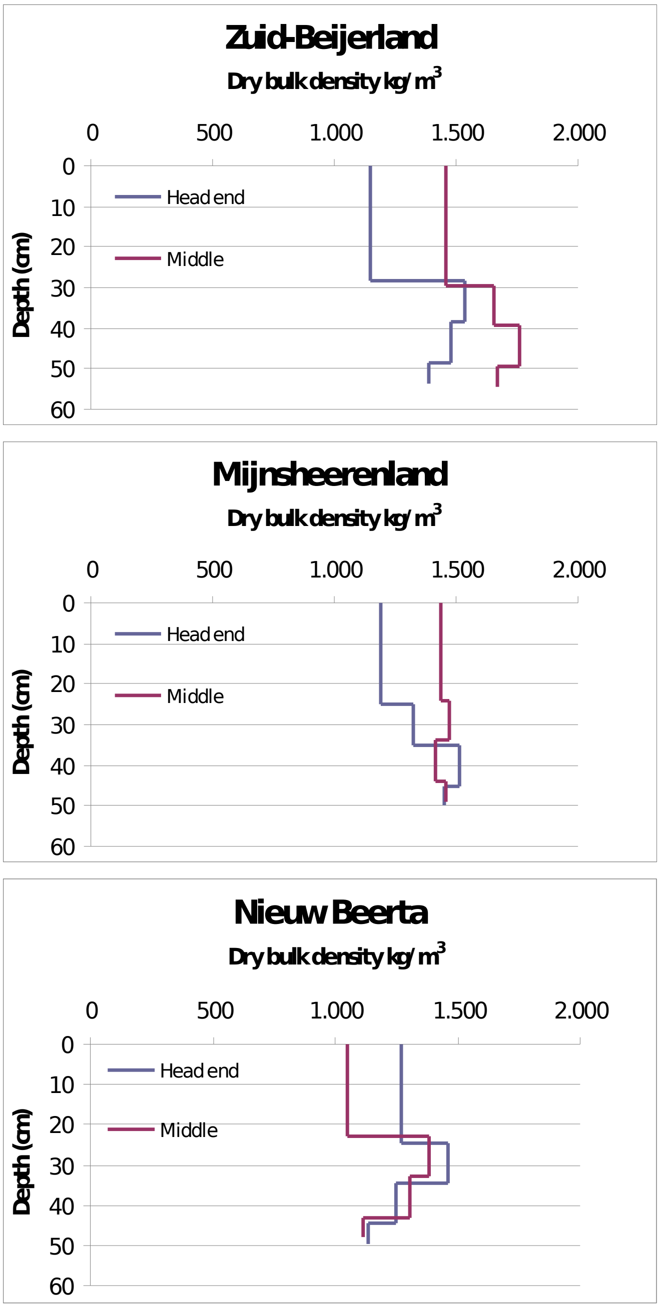


Figure 8 Dry bulk densities for Zuid-Beijerland, Mijnsheerenland and Nieuw Beerta

For the head ends can be concluded that in Zuid-Beijerland the bulk density increases in a compacted layer (1535 kg/m^3) and underneath the density slightly decreases (1389 kg/m^3). The bulk density in Mijnsheerenland keeps increasing from the topsoil (1190 kg/m^3) into the subsoil (1513 kg/m^3). The situation in Nieuw Beerta on the head end is the same as in middle part of the field. The bulk density increases in the compacted layer,1459 kg/m^3 and decreases underneath it, 1134 kg/m^3

For two out of three situations, Zuid-Beijerland and Mijnsheerenland holds that the bulk density is higher in the middle part of the field than on the head end. This is surprising because machinery goes more often across the head end which therefore is more susceptible for higher densities.

Saturated hydraulic conductivity

Figure 9 represents the values for the saturated hydraulic conductivity (Ksat). Regarding the middle part of the field Zuid-Beijerland and Nieuw Beerta have values below the threshold value. All three values for Zuid-Beijerland are below 0,1 m/d, for Nieuw Beerta one value. For Mijnsheerenland all three values are well above the threshold.

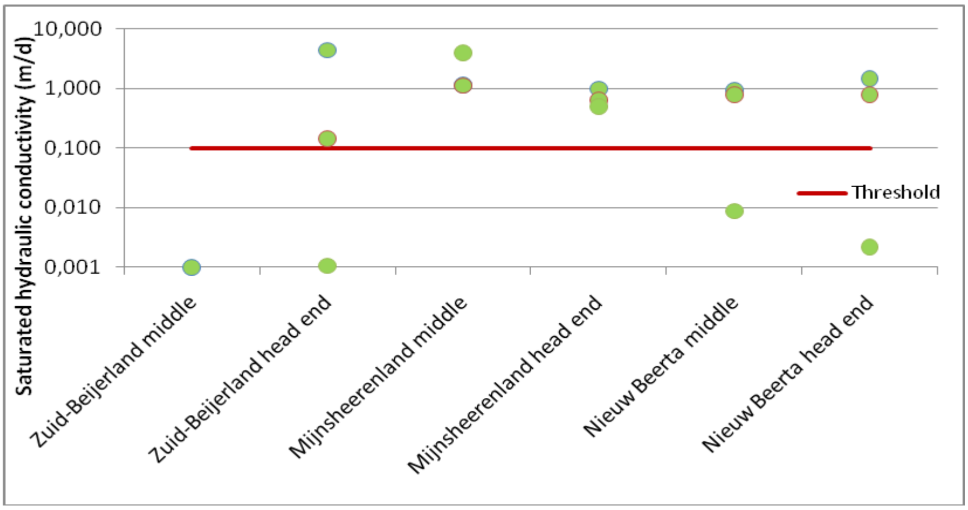


Figure 9 Measured saturated hydraulic conductivity

For the head end Zuid-Beijerland and Nieuw Beerta had one out of three below the 0,1 m/d. and Mijnsheerland were all three well above the 0,1 m/d. This was mainly because there were a lot of large cracks in the soil which resulted in that water was fast transported through the soil.

Pore volume

The pore volumes in Figure 10 of the head end of the fields show two different trends. The first trend is a decrease in pore volume in the compacted layer and underneath the compacted layer a slight increase in pore volume. This holds for Zuid-Beijerland and Nieuw Beerta. The decrease in pore volume is larger for Zuid-Beijerland (14%) than in Nieuw Beerta (6%).
For Mijnsheerenland the pore volume keeps increasing with depth and only in the deepest layer which was measured the pore volume slightly increases.

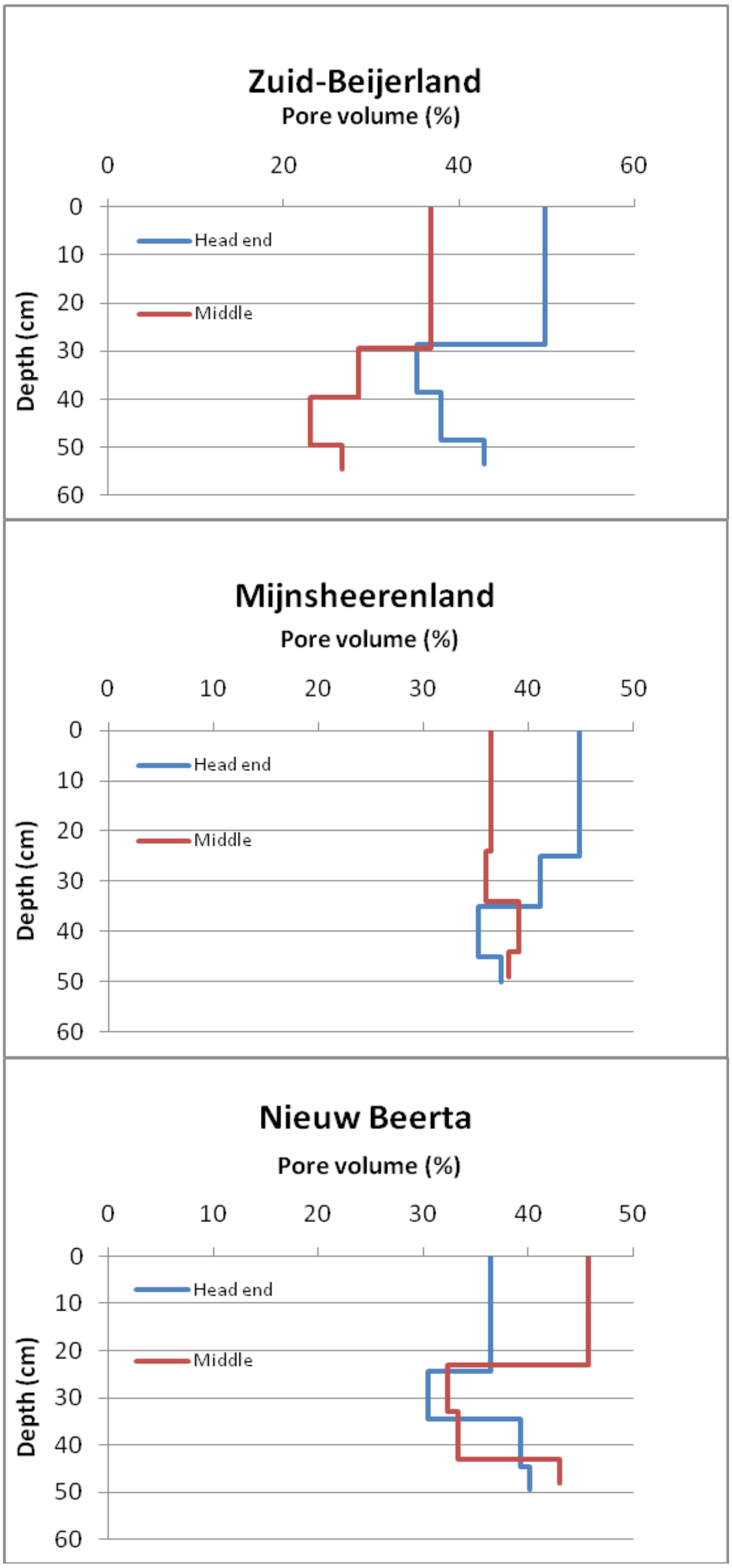


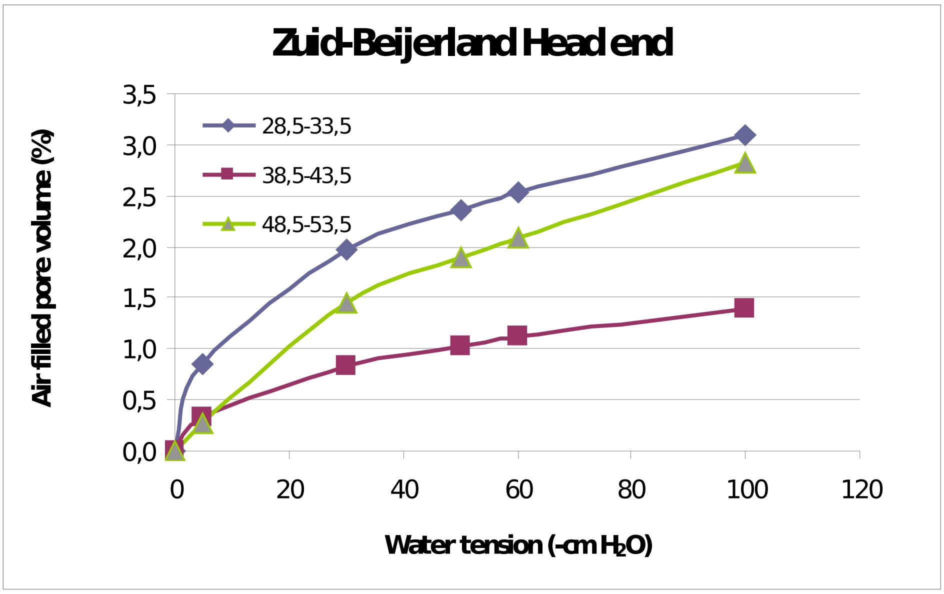
Figure 10 Calculated pore volumes for Zuid-Beijerland, Mijnsheerenland en Nieuw Beerta

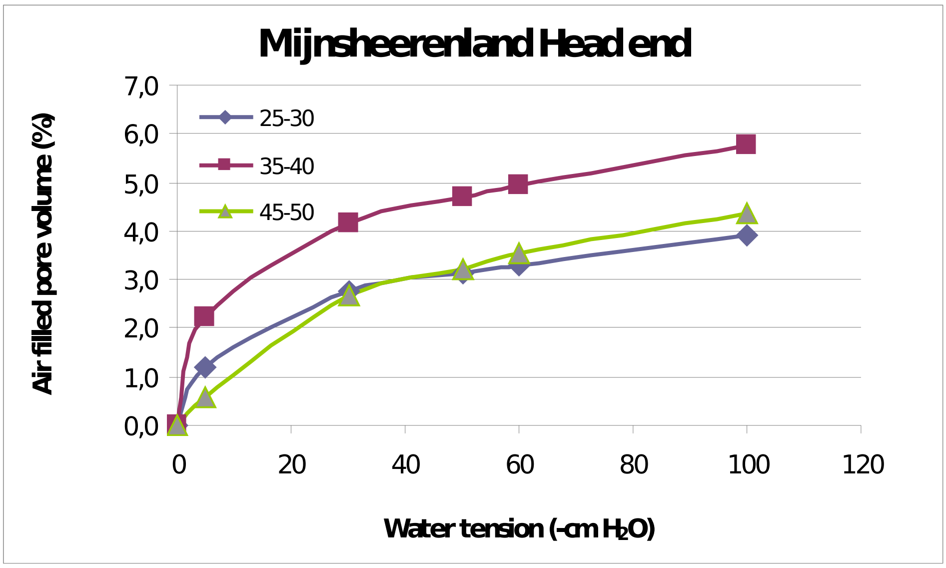
The pore volumes in the middle part in Zuid-Beijerland decrease from 36,7 till 23% with increasing depth. In Mijnsheerenland the pore volumes stay around the same level till 35 centimeters depth and increase till 39%. The middle part of Nieuw Beerta shows more or less the same as the head end with the difference that the pore volume increases at a deeper layer. In the compacted layer the pore volume decreases from 45,6% till 32,4%.

Air Filled Pore Volume

The air filled pore volume are represented in Figure 11 for the head end and Figure 12 for the middle part of the fields. For the middle part of the field the results are different for the three locations looking at the compacted layer (blue line in the graph) at a water tension level of -50 centimeters. Nieuw Beerta has the highest air filled pore volume (4,68%), followed by Mijnsheerenland (3,12%) and Zuid-Beijerland (2,36%).

For -100 centimeters water tension the air filled pore volumes are increased. Nieuw Beerta now has 5,11%, Mijnsheerenland 3,90% and Zuid-Beijerland 3,10%.


Zuid-Beijerland Head end
Air filled pore volume (%)
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
0
20
40
60
80
100
120
28,5-33,5
38,5-43,5
48,5-53,5
Water tension (-cm H2O)


Mijnsheerenland Head end
Air filled pore volume (%)
7,0
6,0
5,0
4,0
3,0
2,0
1,0
0,0
0
20
40
60
80
100
120
25-30
35-40
45-50
Water tension (-cm H2O)

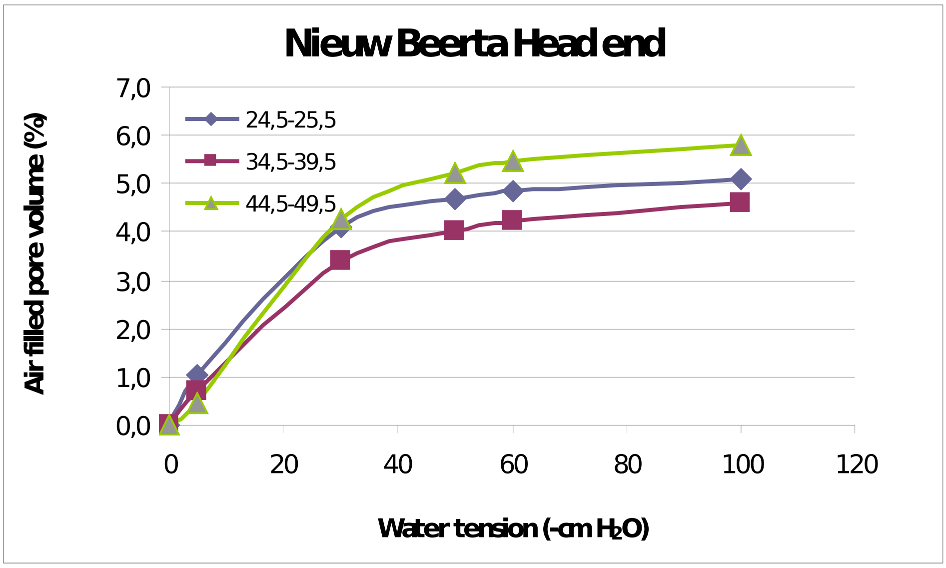
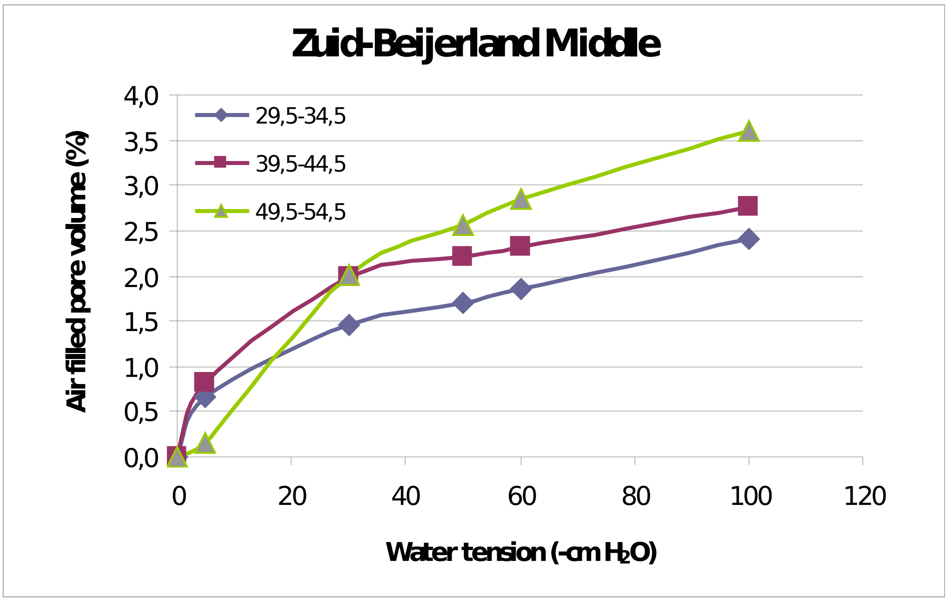
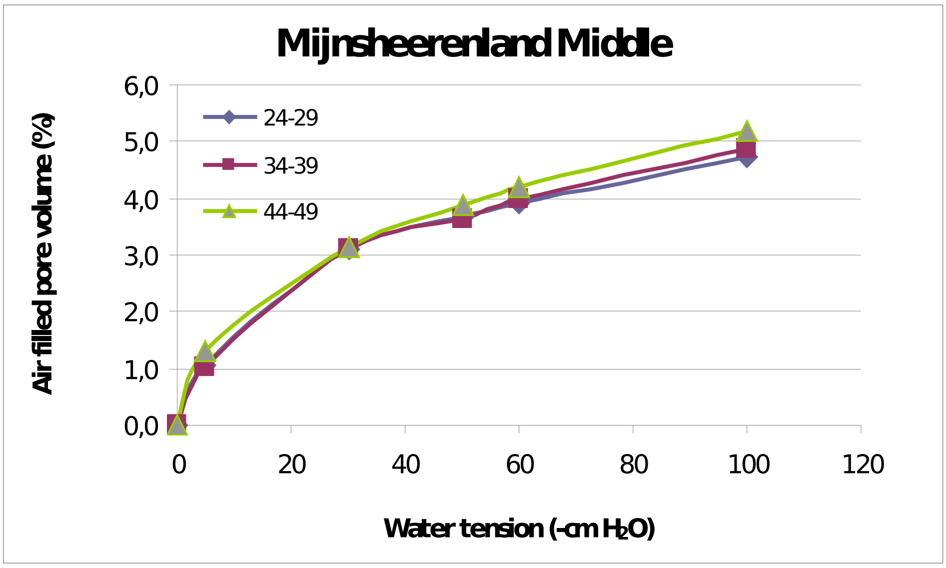


Figure 11 Air filled pore volume at different water tension levels for Zuid-Beijerland, Mijnsheerenland and Nieuw Beerta on the head end of the field

Looking at the head ends of the field the results are not the same. At a depth of -50 centimeters for the compacted layer (blue line in the graph) there's a difference of more than 2%. Mijnsheerenland has the highest percentage (3,69%), followed by Nieuw Beerta (1,75%) and Zuid-Beijerland has the lowest air filled pore volume at the depth with the compacted layer (1,71%). When the suction is decreased till -100 centimeters, the air filled pore volumes increase.

Mijnsheerenland now has 4,71%, Zuid-Beijerland 2,40% and Nieuw Beerta 2,05%. The levels for the air filled pore volume increase in the situations of Zuid-Beijerland and Mijnsheerenland, but for Nieuw Beerta the air filled volume stays below the 2,05%.





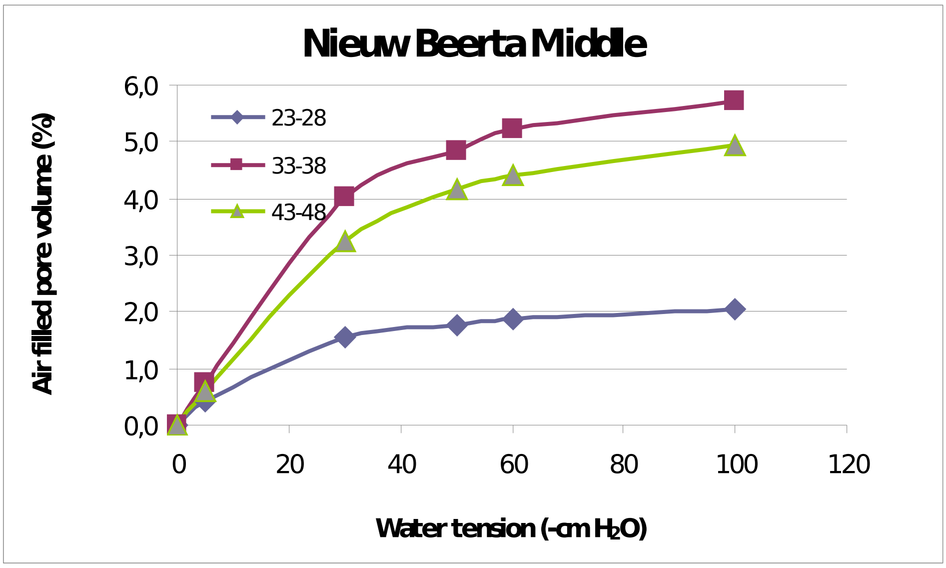


Figure 12 Air filled pore volume at different water tension levels for Zuid-Beijerland, Mijnsheerenland and Nieuw Beerta on the middle of the field

Air permeability

The air permeability was only measured for the samples which came from Mijnsheerenland and Nieuw Beerta. The samples from Zuid-Beijerland were taken in sample rings which were a few millimetres too large for the apparatus.

The results for Mijnsheerenland show that on that location there is a very high air conductivity. This means that the air travels through the soil with a speed of more than 100 cm^{-4} / s^{-1}.

Table 16 Classifications for air permeability at 3 different water tension levels for Mijnsheerenland

Location Mijnsheerenland	Depth cm	-50 cm -ss	-60 cm -ss	-100 cm -ss
Middle	24-29	Very high	Very high	Very high
	34-39	Very high	Very high	Very high
	44-49	Very high	Very high	Very high
Head end	25-30	Very high	Very high	Very high
	35-40	Very high	Very high	Very high
	45-50	Very high	Very high	Very high

Looking at the results fro Nieuw Beerta, Table 17, the classes differ a lot compared to those from Mijnsheerenland. For the middle part of the field the compacted layer has very low permeability but underneath the permeability improves till the classification high. Which means the speed of which air travels through the soil increases from < 10 cm^{-4}/s^{-1} till 46 - 100 cm^{-4}/s^{-2}. The head end on the contrary has a high permeability in the compacted layer. This decreases in the layer underneath it (34,5-39,5) and increases again till the classification very high.
No significant differences can be found between the pressure depth and the air permeability.

Table 17 Classifications for air permeability at 3 different water tension levels for Nieuw Beerta

Location Nieuw Beerta	Depth cm	-50 cm -ss	-60 cm -ss	-100 cm -ss
Middle	23-28	Very low	Very low	Very low
	33-38	High	High	High
	43-48	Mean-High	High	High
Head end	24,5-25,5	High	Very high	High
	34,5-39,5	Low-Mean	Mean	Mean
	44,5-49,5	Very high	Very High	Very high

Shrink and swell measurement

The average shrinkage for the middle part of Zuid-Beijerland is 1,95 mm, with a maximum of 3,58 mm. The average swell is 1,26 mm (Table 18).
For Mijnsheerenland the average shrinkage is 2,40 mm for the middle part with a maximum of 2, 7mm. The average swell is 1,97 mm with a maximum of 2,87 mm (Table 19).

Shrinkage in Nieuw Beerta is average at 4,06 mm with a maximum of 5,6 mm. This is also the largest shrinkage of the three soils in this research. Average swell is 3,15 mm with a maximum of 4,65 mm (Table 20).

The results of the head ends of the fields indicate the same trend. Average shrinkage in Zuid-Beijerland is 2,30 mm and swell 0,61 mm (Table 18).
Measured values for Mijnsheerenland give an average of 0,96 mm shrinkage and 0,98 mm swell (Table 19).
Nieuw Beerta has also on the head end the largest shrink and swell capacities with an average shrinkage of 3,15 mm and a maximum of 4,18 mm. Swelling gives an average of 2,46 mm (Table 20).
The results for shrink and swell indicate that for Zuid-Beijerland and Nieuw Beerta the soil shrinks more than it swells.
Mijnsheerenland is the only soil where the original state is reached after drying and wetting.

Table 18 Height differences after shrinkage and swelling for Zuid-Beijerland

Zuid-Beijerland	Shrink mm	Swell mm
Middle 1	3,58	2,7
Middle 2	1,34	0,35
Middle 3	0,92	0,72
Head end 1	1,05	0,94
Head end 2	3,02	0,21
Head end 3	2,84	0,68

Table 19 Height differences after shrinkage and swelling for Mijnsheerenland

Mijnsheerenland	Shrink mm	Swell mm
Middle 1	2,53	1,16
Middle 2	2,7	2,87
Middle 3	1,97	1,89
Head end 1	0,17	0,29
Head end 2	1,8	1,59
Head end 3	0,9	1,07

Table 20 Height differences after shrinkage and swelling for Nieuw Beerta

Nieuw Beerta	Shrink mm	Swell mm
Middle 1	1,69	2,34
Middle 3	4,91	4,65
Middle 4	5,59	2,47
Head end 2	4,18	3,06
Head end 3	2,96	2,95
Head end 5	2,32	1,36

Shrink characteristic

The number of shrink graphs was too large to place them all in the report. That is why a selection is made. The graphs of the compacted layer are in this section and described while the graphs from the other layers are in annex 6.

For the head ends can be concluded that Zuid-Beijerland has a little less void ratio moisture ratio. Also the normal shrinkage phase cannot clearly be distinguished. For Zuid-Beijerland as well as Mijnsheerenland holds that zero-shrinkage starts at 0,1 moisture ratio with 0,5 moisture ratio (Figure 13).

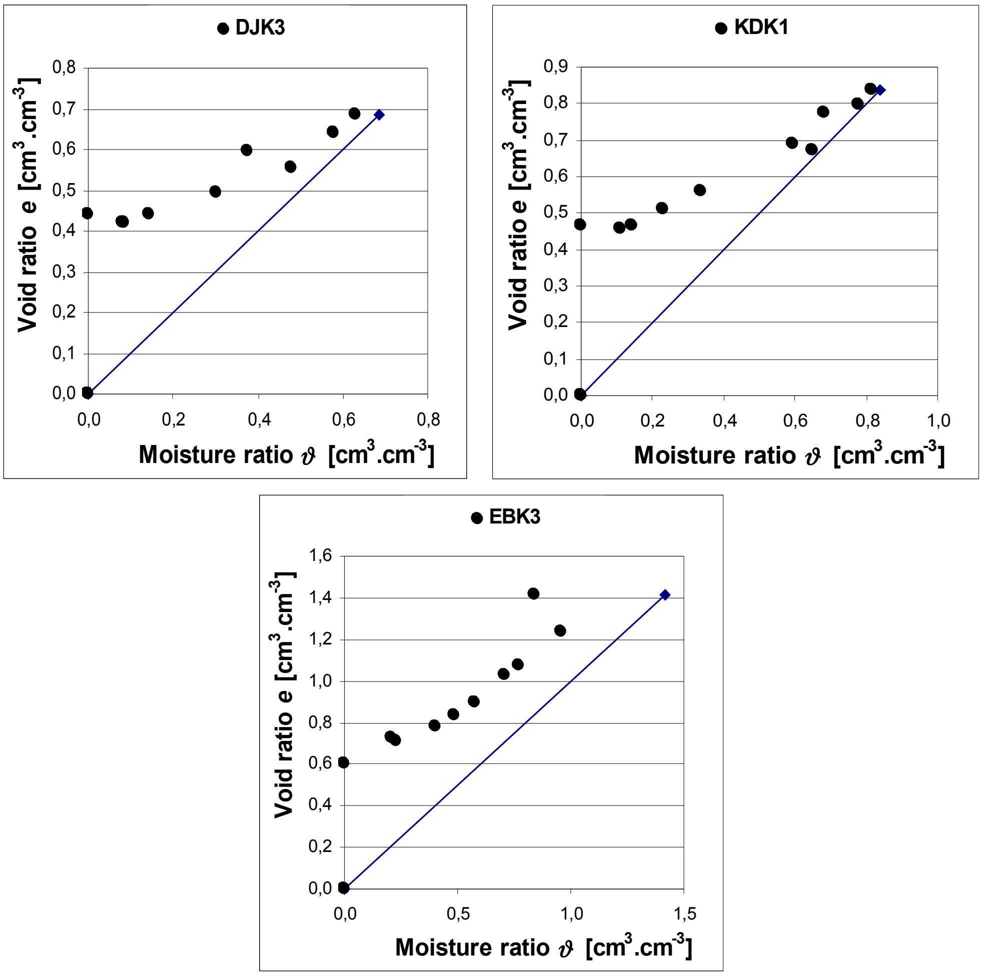


Figure 13 Shrink characteristics of the compacted layer on the head end for Zuid-Beijerland, Mijnsheerenland and Nieuw Beerta

The shrink characteristic for the middle part of the fields are represented in Figure 14. The differences between the three soils here are considerably. Both Mijnsheerenland and Zuid-Beijerland have a relative smooth curve where normal shrinkage becomes residual shrinkage and finally zero shrinkage. For Nieuw Beerta the curve is much more steep. The border between normal and residual shrinkage and between residual and zero shrinkage is not clear.

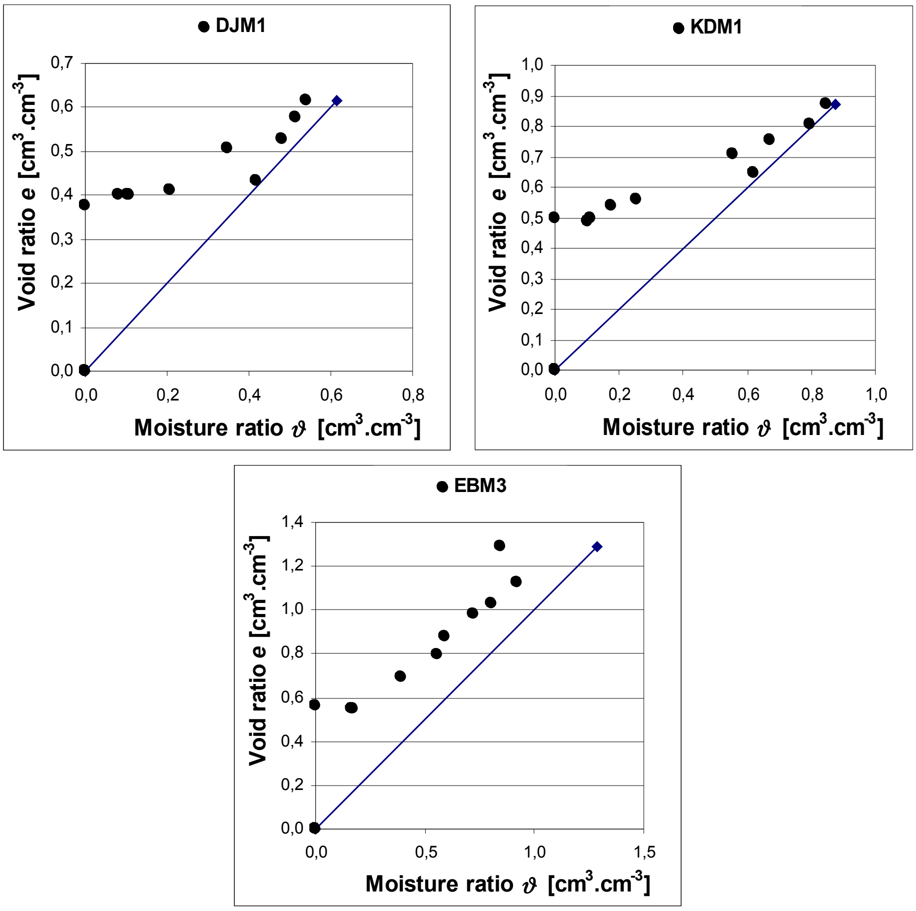


Figure 14 Shrink characteristics of the compacted layer on the middle for Zuid-Beijerland, Mijnsheerenland and Nieuw Beerta

Discussion

Table 22 and 23 show the results for respectively the middle part of the field and the head end of the field. For each location the results are graded in higher (+), around (0) or lower (-) than the threshold value. The methods which are used to grade are bulk density, biological activity, pore volume, air filled pore volume at -50 and -100 centimeters, air permeability, saturated hydraulic conductivity and penetration resistance.

The depth for which this is done is the layer which represents the ploughpan.

To give a short overview on which the classification is based, Table 21 shows the aspects for which is graded together with their threshold value.

Table 21 Threshold values for this research

Aspect	Threshold	Unit
Packing density	1,75	g/m^3
Biological activity	20	per m^2
Penetration resistance	3	Mpa
Pore volume	40	%
Afpv (-50 cm H2O)	10	%
Afpv (-100 cm H2O)	10	%
Air permeability	22	cm^{-4} / s^{-1}
Ksat	0,1	m/day

Table 22 Physical quality of the middle of the field

Location	Soil type	Packing density	Biological activity	resistancePenetration	Pore volume	Afpv (-50 cm H2O)	Afpv (-100 cm H2O)	Air permeability	Ksat
Zuid-Beijerland	Light Clay	-	-	+	0	-	-		0
Mijnsheerenland	Light Clay	+	0	+	+	-	-	+	+
Nieuw-Beerta	Heavy clay	0	0	+	+	-	-	-	+

Table 23 Physical quality of the head end of the field

Location	Soil type	Packing density	Biological activity	resistancePenetration	Pore volume	Afpv (-50 cm H2O)	Afpv (-100 cm H2O)	Air permeability	Ksat
Zuid-Beijerland	Light Clay	+	-	+	-	-	-		+
Mijnsheerenland	Light Clay	+	-	+	+	-	-	+	+
Nieuw-Beerta	Heavy clay	-	0	+	+	-	-	+	+

<u>Physical condition of the middle part of the fields</u>

From Table 22 can be concluded that none of the three soils reach all the thresholds. They have all unique weak points but also common points. For all three soils biological activity is a weak point. Two out of three reach the threshold but having more biological activity can still improve the physical condition of the soil. Also the

volume filled by air is a common weakness. For all soils at all depths the air filled pore volume doesn't reach the threshold value.
Note that N-critical > 40%. Calculate threshold value for porosity with equation 1 for Pd = 1,75 g/cm^3.
A positive point is that the penetration resistance stays below the threshold. This can be seen as an indicator for root growth. Also the pore volume at all three soils reaches the threshold. Even for Zuid-Beijerland it reaches the threshold value despite the fact that there's a high bulk density.

<u>*Physical condition of the head end part of the fields*</u>
Results in Table 23 show bit more negative results than Table 22. What is striking is that the permeability to air as well to water is above the threshold value for all soils. This can mean that even though the density is high the subsoils have a good structure through which air and water still can be transported at sufficient speed.
Biological activity in the head end parts are low and only Mijnsheerenland reaches the threshold. Also for penetration resistance only one soil stays below the three MPa. In this case Zuid-Beijerland. For Mijnsheerenland and Nieuw-Beerta pore volume is more than 40%.
All three soils have problems which supplying enough pores which are filled with air. This makes no difference between the different pressure depths (-50 and -100 centimeters).
Another unforeseen result is that on the head ends the permeability to air and water is better than on middle part of the fields. This is unexpected because the head end part are more heavy loaded than the middle part of the field and also the number of passes is higher on the head end.

<u>*Comparison between head end and middle part of the field*</u>
When the results in Table 22 and 23 are compared some differences occur. Looking at the thresholds which are reached in the middle part, slight more positive outcomes appear than in the head end.
When reviewing the penetration resistance on the middle part of the field all soils stay below the threshold as well as on the head end part. A difference could be expected here, because the head end of the field is driven over very often during every growing season. In every growing season, with every plating, cultivation and harvesting, the head end is under load, multiple times per treatment. While the middle part is loaded far less per treatment and per season.
Also the load per axle is mostly higher on the head than on the middle part of the field. This is because most farmers use carried machinery instead of pulled machinery. On the head end this machinery has to be lifted to give the tractor free way to turn. But because the machinery is lifted, the weight increases significantly on the axles of the tractor, especially on the rear axle.
In annex 3 the graphs for penetration resistance are represented again with here added the distribution of the measured resistance for all 25 measurements. For Mijnsheerenland and Nieuw Beerta holds that the distribution of the measured values decreases with depth. This means that compaction gets to a point where no further compaction can take place. At this depth the soil has reached almost a steady state. This is a problem because when a soil is in such state, it's very difficult to undo this compaction and also very difficult to attain the potential yield.

Biological activity is one element with which all soils struggle. No difference between head end and middle part. A better management of the biological activity can improve the physical properties and maybe reduce problems in the future which might occur.
Also air filled pore volume is a problem which occurs as well on the head end as in the middle part of the field. None of the soils at all three locations reached the threshold of 10% air filled pore at a depth -50 and -100 centimeter tension. Because of this rooting problems might occur in wet periods because of aeration problems (Van den Akker, 2006).

Visual assessment of the soils
In the material and method is mentioned that a profile description would be made of the soils. But because the fieldwork was done in a period that a lot of people with experience to make a soil map, were in the field, only for the soil of Nieuw Beerta a soil map was made. These are added in annex 1.

The bulk density of 1500 kg/m^3 is 120 kg to high for the head end and 150 kg/m^3 for the middle part of the field compared with the measured densities. Organic matter is estimated at 2% for the complete subsoil. From laboratory test organic matter is starts around 7,2% for the head end and 6,8 for the middle part in the ploughpan decreasing till 2% in the soil layers underneath.
The ploughpan is also in the visual assessment clearly visible and mapped as compacted.

The rooting depth of this soil goes up to 80 centimeter. The evidence for this are root hairs which were visible at a depth of 80 centimeters.

A visual assessment is difficult to make and only trained people can do that. But it is helpful to get an insight in how a soil is built. Also rough estimations can be made of soil characteristics. But aspects like bulk density, lute content and organic matter is better to do it in the laboratory because there appears a rather large difference between the visual aspect and the laboratory tests.

Comparison with research done by de Leeuw in 2009
Figure 15 represents the measured values for the Ksat before shrinkage and swell and after shrinkage and swell. The first figure is from this research, the second one from research done by de Leeuw (2009). Clearly visible is that the values for this research are much higher than from de Leeuw. In the research of de Leeuw the values don not go over 0,6m/d, while in this research a lot of values have a higher Ksat than 0,6m/d. This is probably caused by large macro pores and cracks in the soil samples.

De Leeuw concluded in his research that after shrinkage and swelling 60% of the soil samples had a higher Ksat. For this research 78% had a higher Ksat after shrinkage and swelling.

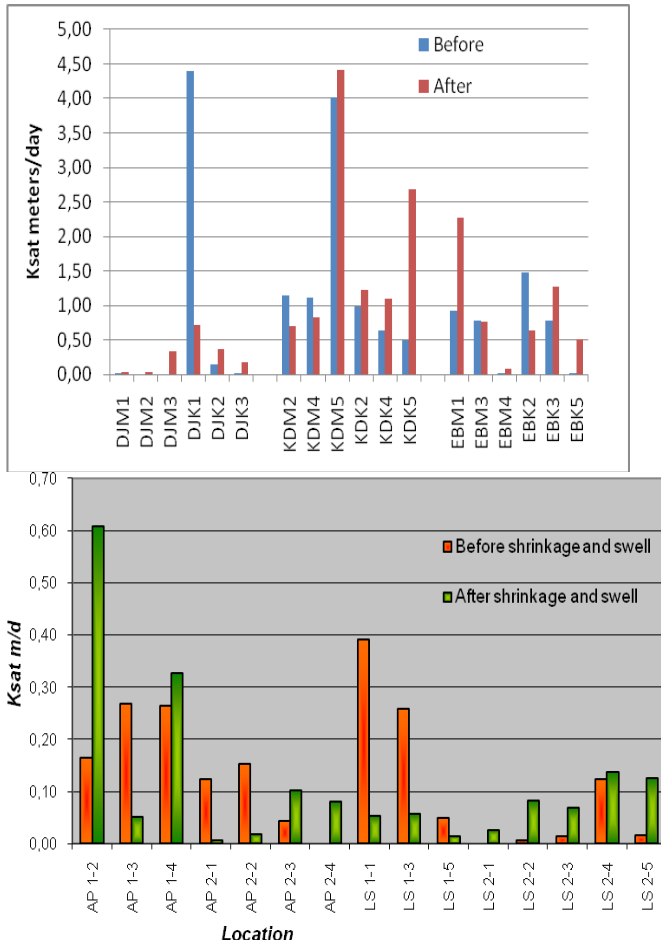


Figure 15 Measured Ksat from this research (above) and from research done by de Leeuw (under)

When reviewing the shrink and swell measurements also some differences appear. De Leeuw concluded that the clay soil in his research had the ability to swell more than it shrunk while the loamy soil did not reach it original state again and shrunk more than it swell. This research concluded for all three soils that none of the soils had the ability to reach its original state again. An explanation can probably be found in the clay content. For the research of de Leeuw this is not known so no comparison can be made.

Comparison with research done in the past

In the past several researches have been carried out in or around the same area as this research. These researches also included the physical state of the soil. This data is compared with the data which is gathered in this research. The results of the comparison can indicate whether the state of the soil is decreasing or that there is no visible trend.

Mijnsheerenland and Zuid-Beijerland

Mijnsheerenland and Zuid-Beijerland are both located near the experimental farm of Westmaas. On this experimental farm researches have been carried out during the seventies. During this researches three cropping systems were compared. But also

several soil measurements were done (Westmaas Research Group on New Tillage Systems, 1984).
During these two researches the pore volume of the soil were determined (Boone *et al*[a,b], 1984). Also Bakker (1987) did a research in Westmaas regarding diffusion of gasses in the soil. Bakker measured also some physical properties including pore volume. Together with the data of this research they are in Table 20.

Table 24 Comparison pore volumes 1973, 1978, 1979 and 2010 for Zuid-Beijerland and Mijnsheerenland

Westmaas					Zuid-Beijerland		Mijnsheerenland	
Depth	1973	Depth	1978	1979	Depth	2010		2010
cm -ss	%	cm -ss	%	%	cm -ss	%	cm -ss	%
10-15	42-46	2-7	47,1	47,1	0-29,5	36,77	0-24	36,49
30-35	38-43	12-17	46,4	46	29,5-34,5	28,61	24-29	35,95
35-40	41-44	22-27	45,9	45,1	39,5-44,5	22,99	34-39	39,07
45-50	43-47	32-37	39,3	40,1	49,5-54,5	26,72	44-49	38,16

Comparing the data measured by Bakker with the data from 2010 can be said that the pore volume of the soils decreased over time. Although the depths are not completely the same that conclusion still stand.
Looking to the pore volumes measured by Boone the conclusion can be drawn that for the soil of Zuid-Beijerland and Mijnsheerenland, the pore volume in the topsoil and the compacted layer is lower than in 1979.
A big comment has to be made here because the locations are not close together. A few kilometers differs the three locations from each other. So comparing these data is a big risk and cannot be generalized without further research. Note that clay content differ.

Also the penetration resistance has been measured by Boone. In the spring of 1978 the measured resistance from the ploughpan till a depth of 80 centimeters was between 2,5 and 2,7 MPa. In 2010 the resistance on the middle part was significantly lower both for Zuid-Beijerland as for Mijnsheerenland, respectively 2,2 and 1,5 MPa. For the head end has Mijnsheerenland the same resistance in 2010, 1,5 Mpa while Zuid-Beijerland exceeds the values measured by Boone. But also in this situation it is not desired to compare the data with each other because of the topographic locations of the fields.

Nieuw Beerta

Also for Nieuw Beerta research has been done in the past regarding soil physics. Bronswijk *et al* (1987) determined shrink characteristics for several clay soil in the Netherlands including Nieuw Beerta. But also Beuving(1987) did research in Nieuw Beerta. His research embraced the moisture- and permeability characteristics, density and composition of soil profiles in sand, loamy, clay and peat soils.

Beuving measured on the soil in Nieuw Beerta the bulk density (Table 21) and pore volumes (Table 22). Comparing the historic data with recent data can be concluded that the top soil of the head is more compacted, but the biggest difference is the compacted layer. This layer has become much more compacted. The deepest layer (43-48 cm) on the other hand has become less compacted, compared with 1987. For the middle part the conclusion is a bit different. The topsoil has become less compacted than in 1987 and the compacted layer is not as much increased in compaction as the head end. For the deeper layer the same can be said as about the deeper layer in the head end.

Regarding the pore volume can be concluded that for the head end as well as for the middle part of the field the pore volume has decreased in time. This ranges from a decrease of 14% till 24% on the head end and from 10 till 22% for the middle part.

Table 25 Comparison of bulk density for 1987 and 2010 for Nieuw Beerta

1987		2010 Head end		2010 Middle	
Depth	P_{db}	Depth	P_{db}	Depth	P_{db}
cm -ss	kg/m^3	cm -ss	kg/m^3	cm -ss	kg/m^3
4-10	1177	0-24,5	1267	0-23	1049
26-32	1214	24,5-29,5	1559	23-28	1386
40-50	1248	34,5-39,5	1251	33-38	1306
		44,5-49,5	1134	43-48	1112

Table 26 Comparison of pore volumes for 1987 and 2010 for Nieuw Beerta

1987		2010 Head end		2010 Middle	
Depth	Pores	Depth	Pores	Depth	Pores
cm -ss	%	cm -ss	%	cm -ss	%
4-10	55,40	0-24,5	36,43	0-23	45,67
26-32	54,40	24,5-29,5	30,41	23-28	32,35
40-50	54,00	34,5-39,5	39,27	33-38	33,31
		44,5-49,5	40,17	43-48	42,96

An overall conclusion is that the conditions of the topsoil and the subsoil has decreased over time. The packing density has become higher and also the pore volume has decreased over time.
The shrink characteristics made by Bronswijk and the one from this research are represented in Figure 16. The two shrink characteristics differ on a few points. In1987 the moisture ratio / void ratio has a higher starting point in the graph 1,45 to 0,5. Also the zero shrinkage phase is different. In 1987 this phase was at 0,45 and in 2010 at 0,58. This means that soils has less capacities to absorb water and that the pore volume has become greater.
In this comparison is assumed that the locations of the two researches are the same but this is just based on coincidence.

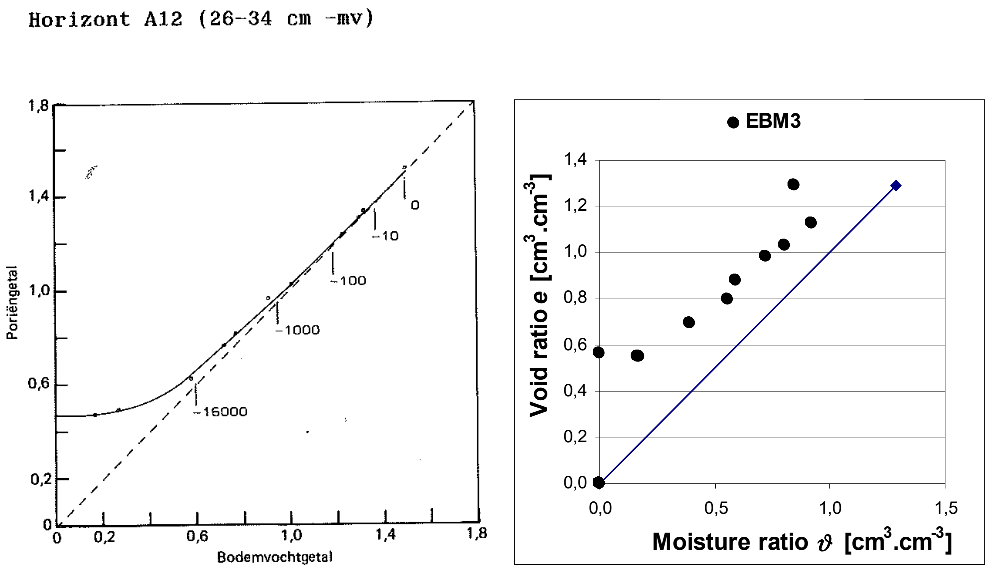


Figure 16 Comparison for shrink characteristic for the compacted layer in Nieuw Beerta

Conclusion

The measurements done in the field and in the laboratory show that the difference in the state of head end and the middle of the field is considerable. The penetration resistance is a problem for head ends while on the middle part no problems occur.

For all soils applies that there can occur problems with aeration in case of extreme wet periods. Especially with the low amounts of biological activity this problem is strengthened.
But the low amounts of air filled pores do not necessarily have to end up with problems. This is because the permeability, air as well as water, has no trouble to be transported through the soil. Which means that when extreme conditions occur water can be easily transported away from the soil surface. Because of the fast transportation of water through the soil, there might appear no aeration problem.

The soil of Mijnsheerenland was the only soil in this research where in 2009 subsoiling took place. Throughout most of the measurements on the middle part of the field, Mijnsheerenland reached the threshold values. Also on the middle part of the field the soil reached the threshold with the exception that biological activity was not sufficient.
Also when reviewing the Ksat results the values for the Ksat increase after shrinkage and swelling. This is striking because subsoiling often results in the opposite effect of what farmers want to achieve. In this case can be concluded that subsoiling was done at the right time and condition.

Regarding the recovery potential, the conclusion for this research can be that 78% of the measured soil samples has a better permeability to water after shrinkage and swelling. Here no difference can be distinguished between a ploughed soil and a subsoiled soil.
This means for the Soil Protection strategy that areas which are classified as areas vulnerable for compaction or compacted areas, can improve in quality through which they can be classified in a different class.

This research, together with the research of van den Akker 2008 and de Leeuw(2009) is the third research done on the state and shrinkage and swelling of loamy and clay soils in the Netherlands. These three researches combined do not cover the complete area of loamy and clay soils in the Netherlands. But this research has the same conclusion as the other two, which is that soils and in particular subsoils in more or less extent are under degradation.

Recommendations
A point of attention is the method which during this research is used to collect the earthworms from the subsoil. In the field, the conditions of the subsoil were moist. This resulted in low or no infiltration of the solution. After waiting 30 minutes there were little or no earthworms visible while there were some worms visible in the subsoil when the profile pitch was dug.

Make sure that before the research all the materials and methods which are used are known. By doing that the problem doesn't occur that for instance one type of soil sample rings is too large too fit in the holder for air permeability measurements.

For laboratory experiments take good care of the kind of tension meters which are used. In this research large tension meters have been used for which a hole to be drilled in the samples to install them. When a soil has large macro pores and cracks it is difficult to get a good connection between the soil and the tension meter which is essential.
A second comment regarding the tension meters used if that is worked with soils with high lute contents, which take a lot of time to shrink, the water filled tension meters may be dried out before the maximum tension is reached.
Better is to use smaller samples rings with holes which can be placed in an installation in the lab which can measure tensions without the risk of drying out.

In this research the only physical aspect which is used to prove if soils have better physical properties after shrinkage and swelling is Ksat. Other aspects where planned to use, but because of the underestimated length of shrinkage and swelling there was no time left to test on other aspects. For future research it's recommended that extra time is scheduled in case of long shrinkage and swelling times.

The soil for Mijnsheerenland was subsoiled in 2009. The results of the measurements were positive for 2010. But because soil needs some time to restore and reach a steady state, a following research would measure the soil again, to find out if subsoiling really succeeded or whether the soil has fallen back to its initial stage before the subsoiling.

Finally a critical look has to be made on some threshold values. Especcially the threshold for air filled pore volume. In this research all the measured air filled pore volumes were in a low class although the permeability's for air and water were sufficient.
The threshold value was established for soils with bad or average structure. This could be an under estimation for clay soils. If the clay soils have a good structure the threshold value can decrease from 10% to a lower value.

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Annexes

Annex 1 profile description of middle of Nieuw Beerta

Kop		Plaats	Nieuw Beerta		coordinaten	274750	579101	
Datum	19-5-2010		Grondwatertrap	GHG	GLG	meting	Bodemgebruik	Akkerland/wintertarwe
Kaarteenheid			VI	60	150		Bewortelbare diepte	100
Mn45A-VI								
Opmerkingen		beworteling tot min. 70 cm						

Laagnr	Horizontcode	Horizontdiepte	Grens		Kleur		Org. stof	Textuur				Grind/knip	Kalkklasse	Rijpingsklasse	Mate verkitting
		cm		vorm	Hue	Value	%	veensoort	% lutum	% leem	M50				
1	1Ap1	0-10	duidelijk	vlak			2		45				2	5	0
2	1Ap2	10-23	duidelijk	vlak			2		45				3	5	0
3	1Ap3	23-33	duidelijk	vlak			2		45				3	5	0
4	1Cg1	33-45	geleidelijk	vlak					33				3	5	0
4	1Cg2	45-80	geleidelijk	vlak					33				3	5	0
5	1Cg3	80-115	geleidelijk	vlak					20				3	5	0
6	1Cg4	115-150	duidelijk	vlak	grijs		15		14				3	5	0
7	1Cg5	150-170	duidelijk	vlak	grijs		10		10				3	5	0
7	2Cw	170-180	geleidelijk	vlak	bruin		30	DK					1	4	0
8	1Cr	160-220		vlak	grijs		5		9				1	3	0

Vlekken

roest	overige	Vochtigheid	Structuur			zichtbare porien	schatting	wortels	aantal/dm2					
aantal	soort		type	grootte	graad	%	Dichtheid	aantal	1	2	3	verdeling	geologische formatie	opmerkingen
o		v	sb	1	s	1	1,5	z	58	60	50	1	692	
o		v	sb	2	s	1	1,5	v	58	60	50	1	692	
o		v	sb	2	m	1	1,5	m/v	22	19	11	2	692	plastischer, fysisch licht gestoord, stro op "ploegzool" van ondergeploegde graanstoppel
m	gr	v	ab	1	m	1	1,5	m	4	11	11	2	211	gelaagd
b	gr	v	ab	1	m	1	1,4	m	5	3	2	2	211	gelaagd
b	gr	v	sg										211	gelaagd
o		v											211	moerige bandjes
o		n											211	gelaagd
o		n											110	onherkenbaar veen
o		n											211	met riet, slap

Annex 2 Profile description of head end of Nieuw Beerta

Midden		Plaats	Nieuw Beerta		coordinaten	274822	578947			
Datum	19-5-2010		Grondwatertrap	GHG	GLG	meting		Bodemgebruik	Akkerland/wintertarwe	
Standaardpunten code			VI	75	180			Bewortelbare diepte	100	
Mn45A-VI								Kritieke z-afstand (cm)		
Opmerkingen		beworteling tot min. 60 cm								

Laagnr	Horizontcode	Horizontdiepte cm	Grens	vorm	Kleur Hue	Value	Org. stof %	veensoort	Textuur % lutum	% leem	M50	Grind/knip	Kalkklasse	Rijpingsklasse	Mate verkitting
1	1Ap1	0-10	duidelijk	vlak			2		45				3	5	0
2	1Ap2	10-26	duidelijk	vlak			2		45				3	5	0
3	1Ap3	26-35	duidelijk	vlak			2		45				3	5	0
4	1Cg1	35-60	geleidelijk	vlak					28				3	5	0
5	1Cg2	60-120	geleidelijk	vlak					22				3	5	0
6	1Cg3	120-150	geleidelijk	vlak					16				3	5	0
7	1Cg4	150-170	geleidelijk	vlak	grijs		10		10				3	5	0
8	2Cw	170-180	geleidelijk	vlak	bruin		30	DK					1	5	0
9	1Cr	180-220	geleidelijk	vlak	grijs		5		9				1	3	0

Vlekken

roest aantal	overige soort	aantal	Vochtigheid	Structuur type	grootte	graad	zichtbare porien %	Dichtheid	wortels aantal	aantal/dm² verdeling				geologische formatie	opmerkingen
o			v	sb	2	s	1	1,5	z	54	57	53	1	692	kalkarm, bruist nauwelijks (schuimaarde-gebruik steeds nodig om pH op peil te houden (blijkbaar onderhevig aan ontkalking, weinig vrije kalk))
o			v	sb	2	s	1	1,5	z	31	18	28	1	692	intensief beworteld rond structuurelementen
o			v	sb	2	m	1	1,5	v	11	8	17	2	692	plastischer, intensieve beworteling, enige blauwkleuring rond (oude) wortelgangen, stro op "ploegzool" van ondergeploegde graanstoppel
m	gr		v	ab	2	m	1	1,5	m	7	2	7	2	211	gelaagd, roestig brokkelig soms, in kleine structuurelementen (afgerond) op te delen, zandige tussenlaagjes en humeuze laagjes wisselen elkaar af.
b	gr		v	ab	1	m	1	1,4						211	gelaagd, roestig brokkelig soms, in kleine structuurelementen (afgerond) op te delen, zandige tussenlaagjes en humeuze laagjes wisselen elkaar af.
b	gr		v	sg										211	gelaagd, roestig brokkelig soms, in kleine structuurelementen (afgerond) op te delen, zandige tussenlaagjes en humeuze laagjes wisselen elkaar af.
o			v											211	gelaagd, moerige bandjes
o			n											110	onherkenbare plantenresten
o			n											211	met riet, slap

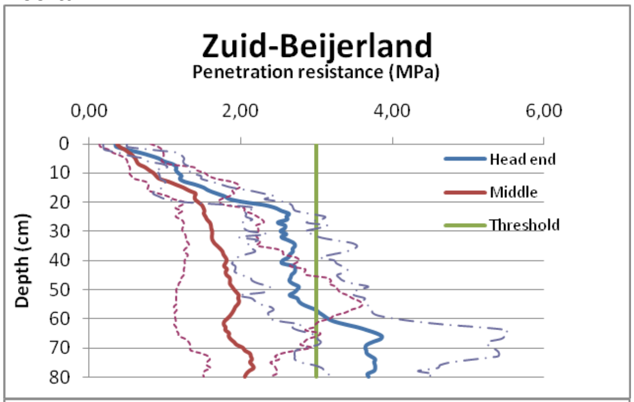
Annex 3 Overview of the bulk densities, pore volume and organic matter content per soil layer of 7,65 and 8 cm sample rings

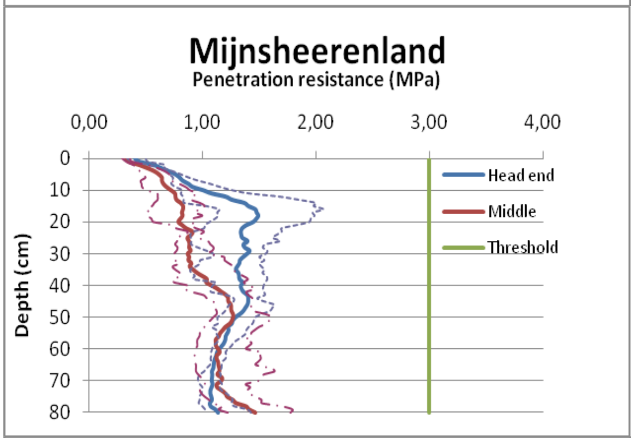
	Depth	Db	Pd	OM	Φ
Zuid-Beijerland	cm -ss	g/cm^3	g/cm^3	%	%
Middle	0-29,5	1,46	1,63	5,62	44,74
	29,5-34,5	1,65	1,86	4,77	39,22
	39,5-44,5	1,76	1,98	2,69	42,72
	49,5-54,5	1,67	1,88	3,07	45,96
Head end	0,28,5	1,15	1,31	3,97	54,50
	28,5-33,5	1,54	1,69	3,85	37,28
	38,5-43,5	1,48	1,62	1,32	32,47
	48,5-53,5	1,39	1,50	0,87	36,08
Mijnsheerenland	Depth				
Middle	0-24	1,44	1,63	6,40	53,54
	24-29	1,47	1,65	5,57	46,09
	34-39	1,41	1,59	2,15	41,55
	44-49	1,46	1,61	0,86	44,46
Head end	0-25	1,19	1,40	7,52	43,25
	25-30	1,32	1,51	6,01	45,41
	35-40	1,51	1,70	1,57	45,62
	45-50	1,45	1,63	2,84	43,31
Nieuw Beerta	Depth				
Middle	0-23	1,05	1,39	6,85	50,16
	23-28	1,39	1,74	5,62	45,06
	33-38	1,31	1,74	1,56	51,87
	43-48	1,11	1,49	1,70	56,33
Head end	0-24,5	1,27	1,62	7,23	64,58
	24,5-25,5	1,46	1,79	5,83	46,96
	34,5-39,5	1,25	1,58	1,37	49,83
	44,5-49,5	1,13	1,55	2,22	56,99

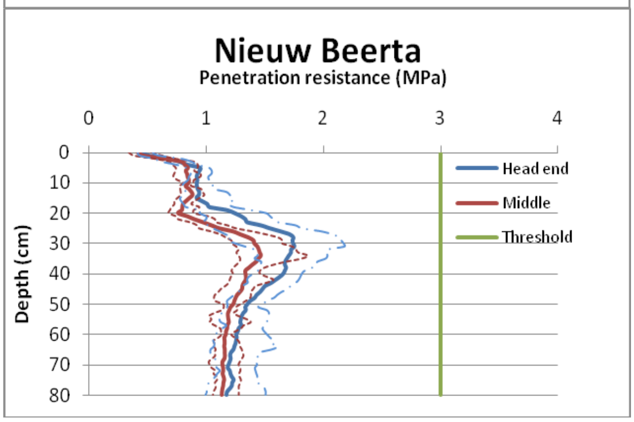
Annex 4 Overview of the lute content, dry bulk density and packing density per soil layer of 7,65 and 8 cm sample rings

	Depth	<2	Db	Db	PD	
Zuid-Beijerland	cm	µm (clay %)	kg/m^3	g/cm^3	g/cm^3	Class
Head end	0-28,5	12,8	1149	1,15	1,26	Low
	28,5-33,5	12,1	1535	1,54	1,64	Medium
	38,5-43,5	11,4	1476	1,48	1,58	Medium
	48,5-53,5	8,86	1389	1,39	1,47	Medium
Middle	0-29,5	13,9	1456	1,46	1,58	Medium
	29,5-34,5	16,2	1652	1,65	1,80	High
	39,5-44,5	18	1759	1,76	1,92	High
	49,5-54,5	16,9	1671	1,67	1,82	High
	Depth					
Mijnsheerenland	cm					
Head end	0-24	16,5	1190	1,19	1,34	Low
	24-29	15	1321	1,32	1,46	Medium
	34-39	14,4	1513	1,51	1,64	Medium
	44-49	14	1452	1,45	1,58	Medium
Middle	0-25	14,7	1439	1,44	1,57	Medium
	25-30	14,1	1471	1,47	1,60	Medium
	35-40	13,6	1414	1,41	1,54	Medium
	45-50	12,1	1459	1,46	1,57	Medium
	Depth					
Nieuw Beerta	cm					
Head end	0-24,5	15,9	1267	1,27	1,41	Medium
	24,5-25,5	14,8	1459	1,46	1,59	Medium
	34,5-39,5	15,3	1251	1,25	1,39	Low
	44,5-49,5	18,6	1134	1,13	1,30	Low
Middle	0-23	15,5	1049	1,05	1,19	Low
	23-28	16	1386	1,39	1,53	Medium
	33-38	19,4	1306	1,31	1,48	Medium
	43-48	17,4	1112	1,11	1,27	Low

Annex 5 Penetration resistance with distribution for Zuid-Beijerland, Mijnsheerenland and Nieuw Beerta







Annex 6 Number of earthworms found in the soils also divided by type

Topsoil	Worm		Epigeic	Endogeic	Anecic	Total	Per m2	Class
	Zuid-Beijerland	Head end	0	0	0	0	0	Bad
		Middle	0	0	0	0	0	Bad
	Mijnsheerenland	Head end	7	2	0	9	225	Good
		Middle	3	2	0	5	125	Good
	Ebelsheerd	Head end	0	1	0	1	25	Moderate
		Middle	0	0	0	0	0	Bad

Subsoil			Epigeic	Endogeic	Anecic	Total	Per m2	
	Zuid-Beijerland	Head end	0	0	0	0	0	Bad
		Middle	0	0	0	0	0	Bad
	Mijnsheerenland	Head end	0	0	0	0	0	Bad
		Middle	0	0	1	1	25	Moderate
	Ebelsheerd	Head end	0	0	1	1	25	Moderate
		Middle	0	0	1	1	25	Moderate

Annex 7 Results of measured saturated hydraulic conductivity measurements, before and after shrinkage and swell.

Location	Ksat	Depth	Before m/d	Class	After m/d	Class
Zuid-Beijerland middle	DJM 1	29,5-34,5	0,001	Very low	0,032	Low
	DJM 2	29,5-34,5	0,000	Very low	0,029	Low
	DJM 3	29,5-34,5	0,000	Very low	0,331	Average
Zuid-Beijerland head end	DJK1	28,5-33,5	4,402	High	0,719	Above average
	DJK2	28,5-33,5	0,143	Low	0,376	Average
	DJK3	28,5-33,5	0,001	Very low	0,171	Average
Mijnsheerenland middle	KDM 2	25-30	1,141	High	0,703	Above average
	KDM 4	25-30	1,120	High	0,833	Above average
	KDM 5	25-30	4,015	High	4,406	High
Mijnsheerenland head end	KDK 2	24-29	0,992	Above average	1,227	High
	KDK 4	24-29	0,639	Above average	1,091	High
	KDK 5	24-29	0,500	Above average	2,690	High
Nieuw Beerta middle	EBM 1	23-28	0,930	Above average	2,265	High
	EBM 3	23-28	0,787	Above average	0,758	Above average
	EBM 4	23-28	0,009	Very low	0,086	Low
Nieuw Beerta head end	EBK2	24,5-25,5	1,483	High	0,646	Above average
	EBK3	24,5-25,5	0,786	Above average	1,269	High
	EBK5	24,5-25,5	0,002	Very low	0,519	Above average
	EBK5	24,5-25,5	3,520	High		

Annex 8 Air filled pore volume at different water tension levels for Zuid-Beijerland, Mijnsheerenland and Nieuw Beerta

Location	Depth cm -ss	Water tension cm -ss					
Zuid-Beijerland		0	-5	-30	-50	-60	-100
Middle	29,5-34,5	0,00	0,66	1,46	1,71	1,85	2,40
	39,5-44,5	0,00	0,83	1,99	2,21	2,33	2,75
	49,5-54,5	0,00	0,16	2,00	2,57	2,86	3,60
Head end	28,5-33,5	0,00	0,85	1,97	2,36	2,54	3,10
	38,5-43,5	0,00	0,33	0,82	1,03	1,12	1,39
	48,5-53,5	0,00	0,27	1,45	1,89	2,09	2,83
Mijnsheerenland	Depth	0	-5	-30	-50	-60	-100
Middle	24-29	0,00	1,06	3,10	3,69	3,91	4,71
	34-39	0,00	1,01	3,12	3,62	4,00	4,86
	44-49	0,00	1,32	3,14	3,88	4,20	5,20
Head end	25-30	0,00	1,18	2,74	3,12	3,30	3,91
	35-40	0,00	2,21	4,15	4,70	4,96	5,75
	45-50	0,00	0,58	2,69	3,21	3,52	4,37
Nieuw Beerta	Depth	0	-5	-30	-50	-60	-100
Middle	23-28	0,00	0,44	1,54	1,75	1,86	2,05
	33-38	0,00	0,76	4,03	4,85	5,23	5,71
	43-48	0,00	0,60	3,25	4,18	4,41	4,93
Head end	24,5-25,5	0,00	1,02	4,11	4,68	4,85	5,11
	34,5-39,5	0,00	0,70	3,41	4,02	4,21	4,61
	44,5-49,5	0,00	0,45	4,27	5,21	5,45	5,81

Annex 9 Weight decrease of Ksat samples during shrinkage

Zuid-Beijerland										
Days after start	0	2	4	6	8	9	12	15	17	21
Date	23-jun	25-jun	27-jun	29-jun	1-jul	2-jul	5-jul	7-jul	9-jul	13-jul
Weight	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg
Kop 1	5,45	5,43	-	5,36	5,34	5,33	5,29	5,25	5,22	5,17
Kop 2	5,47	5,46	-	5,39	5,36	5,35	5,31	5,26	5,22	5,17
Kop 3	5,69	5,67	-	5,60	5,57	5,55	5,52	5,47	5,43	5,47
Mid 1	5,66	5,65	-	5,58	5,54	5,53	5,50	5,45	5,41	5,36
Mid 2	5,74	5,70	-	5,63	5,59	5,58	5,55	5,51	5,47	5,42
Mid 3	5,47	5,42	-	5,35	5,35	5,31	5,28	5,23	5,20	5,15

Mijnsheerenland								
Days after start	0	2	5	7	9	12	14	20
Date	30-jun	2-jul	5-jul	7-jul	9-jul	12-jul	14-jul	20-jul
Weight	kg	kg	kg	kg	kg	kg	kg	kg
Kop 1	5,48	5,45	5,41	5,36	5,31	5,26	5,24	5,16
Kop 2	5,19	5,16	5,11	5,05	5,01	4,95	4,93	4,84
Kop 3	5,43	5,40	5,36	5,32	5,27	5,22	5,20	5,12
Mid 1	5,15	5,12	5,08	5,02	4,98	4,92	4,89	4,82
Mid 2	5,37	5,34	5,30	5,24	5,20	5,14	5,12	5,05
Mid 3	5,21	5,18	5,14	5,08	5,04	4,98	4,96	4,88

Nieuw Beerta							
Days after start	0	2	4	7	9	15	20
Date	20-jul	22-jul	24-jul	27-jul	29-jul	4-aug	9-aug
Weight	kg	kg	kg	kg	kg	kg	kg
Kop 2	5,16	5,11	5,09	5,02	4,99	4,90	4,83
Kop 3	5,12	5,08	5,06	4,99	4,96	4,87	4,80
Kop 5	5,26	5,22	5,20	5,13	5,10	5,02	4,94
Mid 1	4,86	4,82	4,81	4,74	4,71	4,62	4,55
Mid 3	5,04	4,99	4,97	4,90	4,87	4,78	4,71
Mid 4	5,15	5,11	5,10	5,13	5,10	4,92	4,85

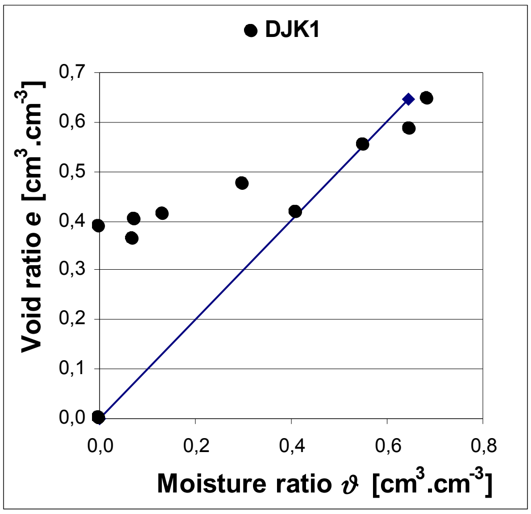
Annex 10 Weight increase of Ksat samples during swelling

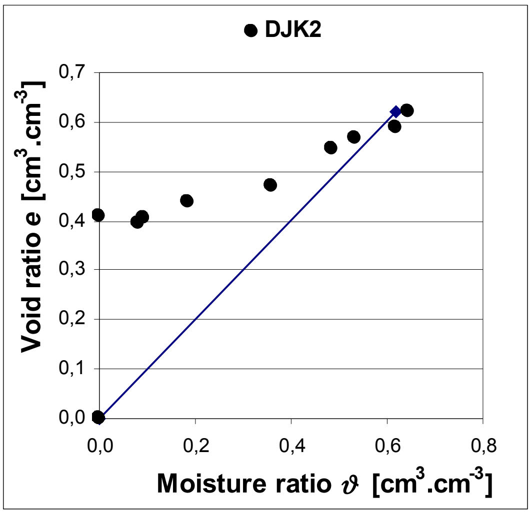
Zuid-Beijerland		13-jul	16-jul	20-jul	27-jul
Weight		kg	kg		kg
	Kop 1	5,24	6,10		6,12
	Kop 2	5,16	6,02		6,07
	Kop 3	5,53	6,30		5,82
	Midden 1	5,35	6,13		6,19
	Midden 2	5,47	6,25		6,31
	Midden 3	5,68	6,50		6,56

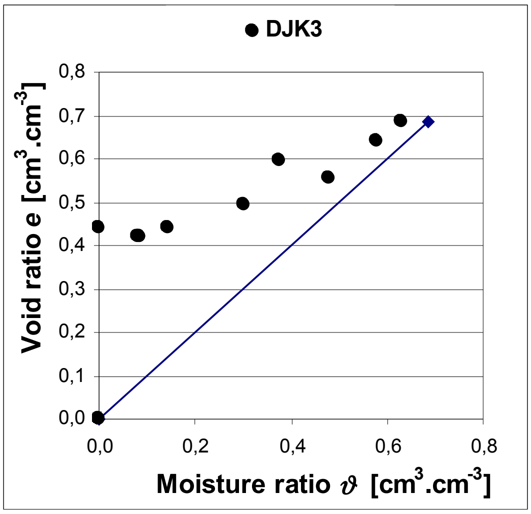
Mijnsheerenland		20-jul	23-jul	4-aug	10-aug
Weight		kg	kg	kg	kg
	Kop 2	5,22	5,57	5,98	6,01
	Kop 4	4,83	5,27	5,68	5,78
	Kop 5	5,18	5,52	6,00	6,03
	Midden 2	4,88	5,25	5,68	5,72
	Midden 4	5,11	5,45	5,94	5,97
	Midden 5	4,93	5,30	5,78	5,80

Nieuw Beerta		9-aug	28-aug
Weight		kg	kg
	Kop 2	4,82	5,24
	Kop 3	4,80	5,21
	Kop 5	5,01	5,34
	Mid 1	4,61	4,95
	Mid 3	4,70	5,13
	Mid 4	5,39	5,21

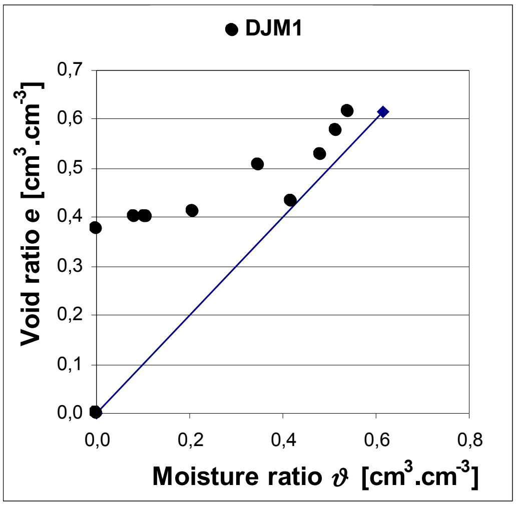
Annex 11 Shrink characteristic for the head end of Zuid-Beijerland (3 repetitions)

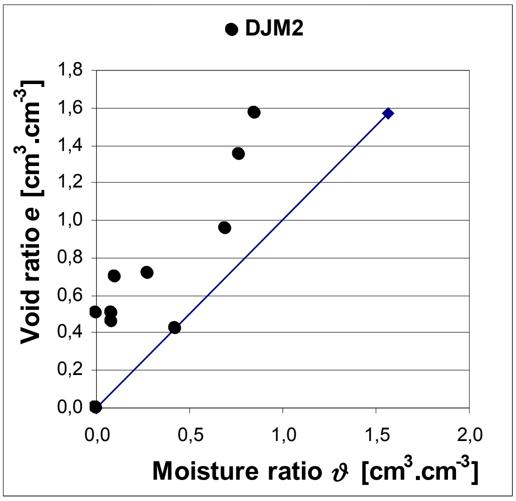


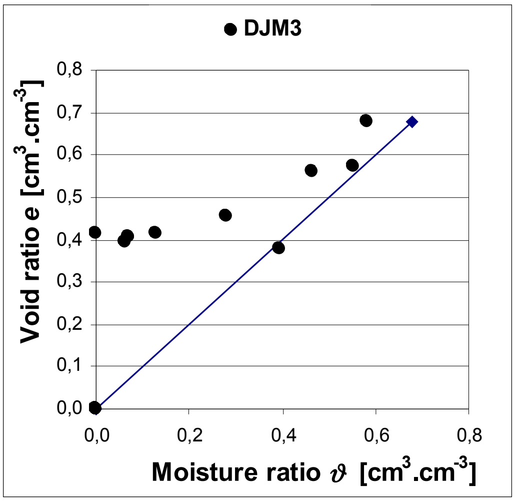




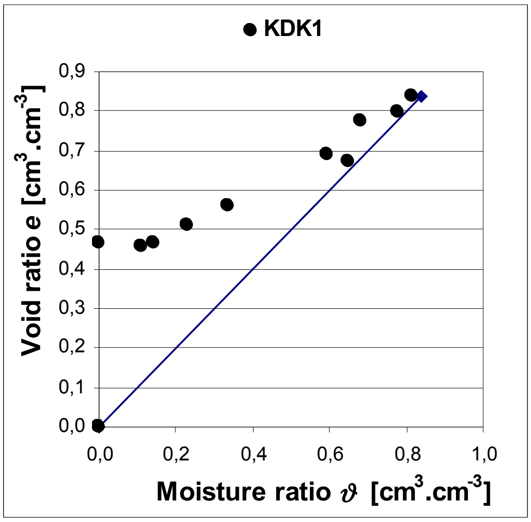
Annex 11 Shrink characteristic for the middle of Zuid-Beijerland (3 repetitions)

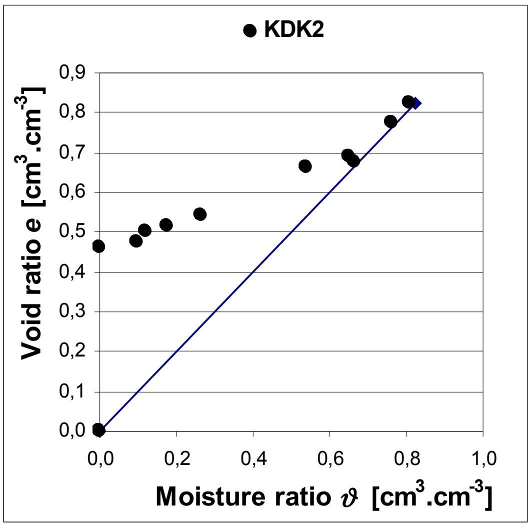


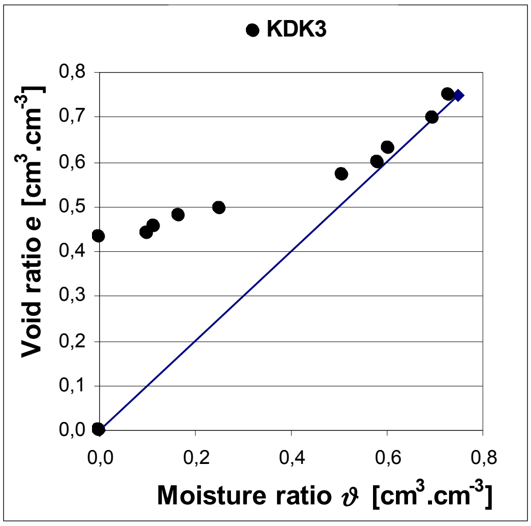




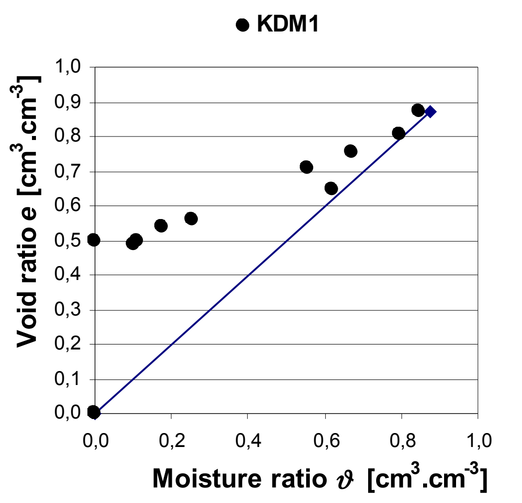
Annex 12 Shrink characteristic for the head end of Mijnsheerenland (3 repetitions)

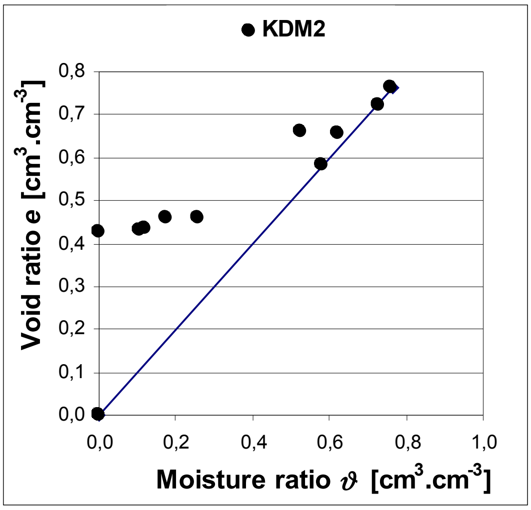


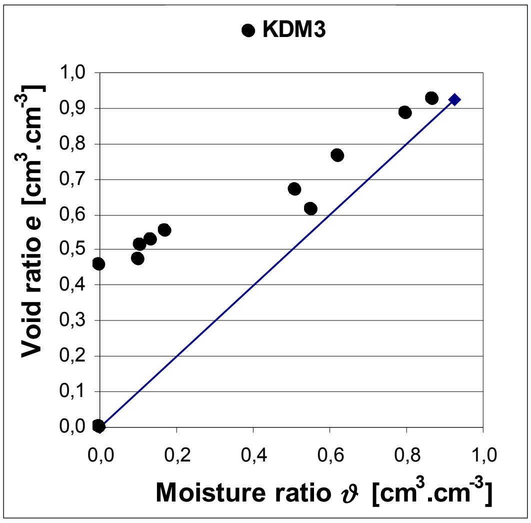




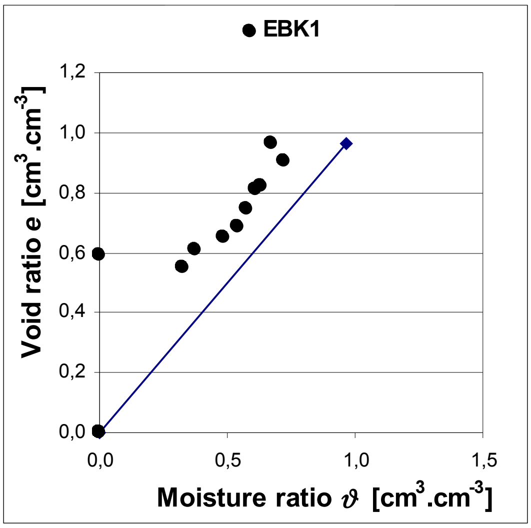
Annex 13 Shrink characteristic for the middle part of Mijnsheerenland (3 repetitions)

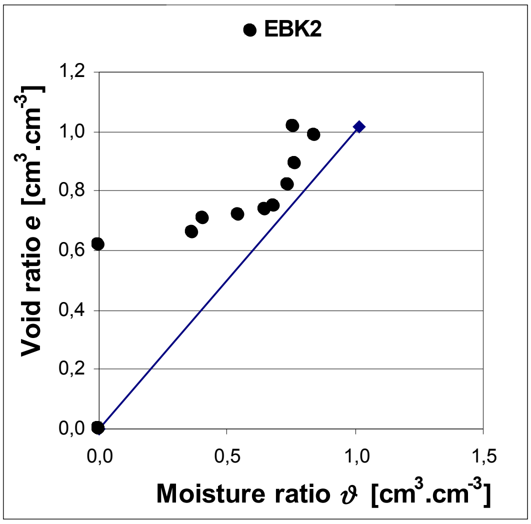


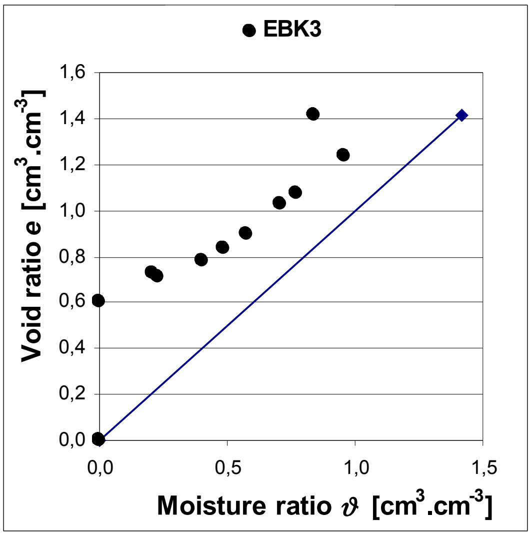




Annex 14 Shrink characteristic for the head end of Nieuw Beerta (3 repetitions)







Annex 15 Shrink characteristic for the middle part of Nieuw Beerta (3 repetitions)