SNOWMAN NETWORK
Knowledge for sustainable soils

Project No. SN04-03

PROJECT RAI-SOILCOMP

Raising Awareness on the Impact of subSOIL COMPaction

Final Report

February 2015

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Project description

The project 'Raising Awareness on the Impact of subSOIL COMPaction' (RAI-SOILCOMP) aims at

1. raising awareness on the (economic and environmental) impact of soil compaction and thus

2. preventing (further) soil degradation as caused by compaction related to land use, soil type and climate.

Specific objectives that have been defined for this project are:

a) To assess the economic and environmental impact of soil compaction at farm and regional level, based on specific key indicators; related to soil functions and ecosystem services;
b) To extend the soil compaction tool TERRANIMO® with innovations in machinery related to caterpillar tracks;
c) To extend the applicability of TERRANIMO® for Dutch, Belgian and Swedish soils;
d) To raise awareness among relevant stakeholders in the Netherlands, Belgium and Sweden on the risks related to soil compaction;
e) To actually reduce the risk of soil compaction, through both practice (e.g. farmers) and policy (e.g. regional administration), using the soil compaction tool TERRANIMO.

Problem description

Research has established that in European countries high wheel load traffic causes deep and persistent subsoil compaction. This subsoil compaction reaches a depth at which conventional ploughing techniques can no longer restore the compacted layer. As such subsoil compaction has a permanent character (e.g. Berisso et al., 2012) and with the trend of continuously increasing wheel loads, European agricultural soils are facing a serious threat of increased subsoil compaction.

Subsoil compaction generally causes a reduction in through flow of water and air and forms a barrier for root development. In case of heavy rainfall, subsoil compaction in agricultural soils may cause limited infiltration, ponding, and increased runoff, which in turn increases risks of flooding and losses of nutrients and agrochemicals to surface water, resulting in reduced water quality. Furthermore, soil compaction increases the risk of reduced harvests, both due to the fact that the frequent stagnation of water limits the aeration of the root zone and accessibility of the fields by machinery for harvest purposes, and because the subsoil compaction reduces rooting depth and capillary rise, limiting water availability in dry periods.

Predicted climate scenarios for Europe indicate an increase in weather extremes, i.e. increase in number and intensity of heavy rainfall events and number and extent of dry spells. To adequately anticipate on these extremes in both water management and agricultural production a good soil structure is essential.

Investigations in The Netherlands (Van den Akker and Hoogland, 2011) and in Belgium (Verbist et al., 2007; Van De Vreken et al., 2009) show that bulk densities in the subsoil increase and in several cases exceed critical threshold values. Vermang (2012) demonstrated that weather conditions and hence soil-water status during harvesting greatly affects subsoil compaction, which cannot be corrected by tillage in the following crop season. Topsoil hydraulic conductivities of a loamy soil measured by a constant-head dropped from more than 160 mm/h in the growing season preceding compaction induced by harvesting to less than 6 mm/h. Similar results have been obtained in Sweden: for example traffic with heavy sugarbeet harvesters reduced hydraulic conductivity in the subsoil by around 90% (Arvidsson, 2000). A national survey of the physical quality of Swedish subsoils was started in 2003. Measurements in 30 soils have shown that most subsoils have a hydraulic conductivity < 10 mm/h, which is often used as a critical limit, with many soils having even values around 1 mm/h. http://www.slu.se/sv/fakulteter/nl-fakulteten/om-fakulteten/institutioner/institutionen-mark-och-miljo/forskning/jordbearbetning-och-hydroteknik/miljoovervakning

Subsoil compaction is a hidden form of soil degradation without clear visible exposure. About 32% of the subsoils in Europe are highly vulnerable to subsoil compaction and another 18% are moderately vulnerable to subsoil compaction (Fraters, 1996). Soil compaction is acknowledged by the European Commission (COM, 2006) as one of the main threats to soils in the EU. However, so far wide awareness on the threats of subsoil compaction and potential avoidance strategies are not yet established and assembled information on the extent of the economic impact both at farm and regional (provincial) level is still lacking.

Most farmers and other land owners have (distantly) heard of ‘soil compaction’ but are not aware of the potential problem and do not link this problem to their own farm or soil management. Becoming aware of especially long term risks is crucial and this should be accompanied with knowing how to prevent subsoil compaction and how to recognize first signals or effects of compaction.

Most regional governments are becoming aware of the consequences of subsoil compaction, but often lack insight into the gravity of the problem and actual occurrence. These regional authorities are looking for effective measures and policy instruments to combat further soil compaction.

Question addressed:

How to raise awareness on the (economic and environmental) impact of soil compaction and how to ensure prevention of (further) soil degradation caused by compaction?

Stakeholders and their involvement

Different groups of stakeholders are relevant for this project. We intend to identify these different groups and their incentives. It is important to know how to motivate or stimulate stakeholders in order to become interested in the topic or come into action to prevent subsoil compaction or ultimately change their practices towards more sustainable land management. The largest group, the farmers, will be involved in workshops and will receive direct and also indirect information (for instance in magazines and extension flyers). In the Netherlands and in Belgium regional government (e.g. provinces) is already involved in projects related to subsoil compaction and fully support this proposal. During the project we will try to get other groups involved (e.g. contractors and farm machinery companies). In Sweden, dissemination of the results will be in cooperation with ‘Focus on Nutrients’ (in Swedish: ‘Greppa Näringen’), which is a governmentally funded advisory service aiming at reducing losses of nutrients from soil to air and water. It also includes a programme that aims at avoiding soil compaction. Focus on Nutrients has 9500 farmers as members.

Methodology

A. **Impact assessment study (WP3)** of economic and environmental effects. This study starts with literature study and an inventory of indicators related to the economic and environmental effects of soil compaction, both on-site and at farm level, as well as off-site and at regional level. Based on selected key indicators the impact assessment study will be carried out for 50 farmers in each country, providing important comparative insights. Economic impact will deal with costs and benefits such as labour/time, soil productivity, machinery (at farm level), as well as flood damage and agricultural production at regional level. Considered environmental effects will deal with ecosystem services and their valuation at farm and regional level (hence, for each specific farmer and for society in general). The methodology aims principally at using the impact assessment study as an awareness raising tool, including scenarios (20-50 years ahead) about sustainable agriculture and food production for several soil compaction trends and related machinery use. Related to this assessment is the identification of relevant stakeholders and their incentives in WP 2. The combination of WP2 and WP3 will help us to address relevant issues for raising awareness on the problems of subsoil compaction for different stakeholders.

B. **Field work and soil analysis (WP 4)** and **model development (WP 5)**. The tool involved is Terranimo®, which is a web-based decision support tool that facilitates the evaluation of the risk of compaction in field traffic (www.soilcompaction.eu ; Lassen et al., 2012; Stettler et al., 2012). Terranimo® incorporates a database of several hundred agricultural tyres and a database of the most common soil types of some countries (currently: Denmark, Finland, Switzerland), and includes pedo-transfer functions for estimation of (i) the tyre-soil contact properties (contact area, stress distribution) from tyre properties and (ii) soil strength from easily-available soil attributes and soil moisture. The tool will be refined by incorporating a) functions for estimation of the contact area and the contact stress distribution at the rubber track-soil interface, b) a database of common soil types in the Netherlands, Belgium and Sweden and c) a model that describes the track-soil contact area and the stress distribution at the track-soil interface along the lines of the tyre-soil model of Keller (2005). This will improve the model as a decision-making tool for farmers.

C. **Awareness raising and dissemination (WP2 and 6)** will focus on three groups: farmers/contractors, industry/machinery companies and policy makers. These three groups in each country will be invited to participate in practical workshops. Communication and discussion material will be provided and spread via farming and innovation networks. At least 5.000 farmers per country will be reached by articles in magazines and journals.

The impact assessment tool will be applied both at farm level and regional scale so that participants (farmers and policy makers) will become aware of the economic and environmental costs of soil compaction and 2) the use of the model TERRANIMO® will be promoted to make participants familiar with the measures to prevent soil compaction.

Project partners

1. Alterra, The Netherlands (coordinator; WP 1)
2. Ghent University, Belgium (Flanders) (leader of WP 4)
3. Swedish University of Agricultural Sciences, Sweden (leader of WP 5)
4. Inagro Onderzoek & Advies in Land-en Tuinbouw, Belgium (Flanders) (leader of WP 2)
5. CLM centre for Agriculture and Environment, The Netherlands (leader of WP 6)
6. Wageningen University, Department of Environmental Sciences, The Netherlands (leader of WP 3)

State of the art

Research has established that European agricultural soils are facing a serious threat of increased subsoil compaction. Subsoil compaction generally causes a reduction in through flow of water and air (oxygen) and forms a barrier for root development, causing for instance limited infiltration, increased runoff, reduced harvests, etc. Subsoil compaction is a hidden form of soil degradation without clear visible exposure, but scientists estimate soil compaction to be responsible for the degradation of an area of 33 million ha (roughly the size of Germany) in Europe (Van Ouwerkerk and Soane, 1994). However, awareness of the threats of subsoil compaction and potential avoidance strategies are not established. One of the reasons that subsoil compaction does not get the required attention is that it is invisible, and that the economic impact of subsoil compaction is not well determined and documented, although yield reductions of more than 35% in extreme dry or wet years are mentioned (COM 231, 2006).

Recent research on subsoil compaction has a strong emphasize on the effects on the structure and quality of subsoil and on prevention of subsoil compaction. We know from long term experiments that subsoil compaction has a long term detrimental effect on crop yields (Håkansson & Reeder, 1994; Alakukku, 2000). Hanse et al. (2011) showed that there is a relation between sugar beet yield and the saturated hydraulic conductivity of the plough pan (upper subsoil): typically, farm fields with an up to 20% better yield had a higher saturated hydraulic conductivity of the plough pan. In 2003, the Swedish Environmental Protection Agency initiated and financed an environmental assessment of physical properties of soils. Totally thirty soils are included, every year five soils are investigated. Measurements until now show that saturated hydraulic conductivity is below critical levels on most of the investigated soils. Whalley et al. (2012) improved our knowledge on the detrimental effects of compaction and shear on the saturated hydraulic conductivity Ksat. Decrease of the amount of larger pores by compaction without shear results in a strong decrease of Ksat Shear proves to have a very high impact on of soils with a high porosity, where Ksat was reduced to 5% of its original value. In dense soil the effects of shear deformation on Ksat were smaller but still high. In the topsoil and in many cases also in the ploughpan both compaction and shear deformation occur and the impact on Ksat of both processes can be multiplied resulting in a sometimes extreme low Ksat.. In the inter-Nordic project “Persistent effects of subsoil compaction on soil ecological services and functions (POSEIDON)”, long-term compaction effects on water flow, gas and solute transport, and microbial populations were investigated (see also: www.poseidon-nordic.dk). In this project Berisso et al. (2012) concluded that commonly used agricultural machinery can compact the soil to 0.9 m depth with negative effects on soil porosity and gas transport properties. Furthermore, these effects seemed to persist for more than a decade.

The mechanisms responsible for the natural amelioration of soil compaction proved to be nearly absent in subsoil layers under central and northern European conditions (e.g. Etana and Håkansson, 1994; Schjønning and Rasmussen, 1994; Voorhees, 2000). This demonstrates the urgent need to avoid subsoil compaction.

Prevention of subsoil compaction requires well founded advice for farmers and contractors on the maximum allowable wheel loads on a certain soil: what is possible by using wide and flexible tires? and what should be the tire inflation pressure? Knowledge on the distribution of stresses in the subsoil is increasing (a.o. Lamandé and Schjønning, 2011) and the importance of the stress distribution in the tire–soil contact surface is better understood (Keller and Lamandé, 2010). The obtained insights improved the confidence in the performance of rather simple and easy-to-use analytical models to predict stresses in the soil (Van den Akker, 2004, Keller et al., 2007). Measurements and model calculations show that the use of rubber tracks can reduce soil stresses and potentially prevent subsoil compaction (Arvidsson et al., 2011). This Swedish research is still going on and in 2012 stresses were measured at 15, 40 and 60 cm depth under a fully loaded combine harvester, and similar measurements for tractors were carried out in 2013. These measurements are very well suited to validate models of soil stress distribution. To prevent subsoil compaction the exerted soils stresses in the subsoil should not exceed the strength of that subsoil (Van den Akker and Schjønning, 2004, Schjønning et al., 2012). Simple equations for estimation of soil strength have recently been presented by Rücknagel et al. (2012). A map on risk areas of subsoil compaction of the Netherlands was constructed, showing that the major part of Dutch subsoils have a high risk on subsoil compaction. In Flanders also such a map has been constructed and actual measurements show that bulk densities at a depth of 40 cm increased considerably the last 40 years (Van De Vreken et al., 2009)

The development of Terranimo® (www.soilcompaction.eu ; Lassen et al., 2012; Stettler et al., 2012) in the project "Preparing for the EU Soil Framework Directive by optimal use of Information and Communication Technology across Europe (PredICTor)" (see: www.ict-agri.eu) is the result and promoter of research on subsoil compaction. A conclusion and recommendation of two European Concerted Actions on subsoil compaction was that subsoil compaction should be prevented and made more easily recognized by farmers and other involved people (Van den Akker et al., 2003). The SNOWMAN project that includes refinement of Terranimo® is an answer to that request.

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Final report

In this report you can read what we have achieved within the Work Packages (WPs). Each of the next chapters is dedicated to one of the WPs, except WP 1.

WP 1 is the work package for project management and coordination, led by Alterra (project coordinator Mirjam Hack-ten Broeke). We organized a project start up video conference in September 2013, prepared and attended the kick-off meeting on November 20 in Paris and organized a project meeting on November 19 plus a meeting with Simon Moolenaar from the SNOWMAN network. Regular contact between project partners on project matters and progress was established. On April 11 2014 the midterm meeting was held in Ghent, Belgium. The discussions and progress reports of the midterm report were discussed at that meeting. With the midterm report WPs 2 and 3 were finalized. Between April and November we had several contacts and discussions on WPs 4, 5 and 6.

Finally we had a videoconference meeting on December 4 2014. We discussed the draft final report and agreed on some further details for the report that you are reading right now.

In general we agreed amongst ourselves that this project was very straightforward and that we achieved what we had planned. Furthermore we concluded that all partners were equally involved and dedicated and that we will try to cooperate further on raising awareness on subsoil compaction, on preventing subsoil compaction, but maybe also on restoration of compacted soils.

ACHIEVEMENTS WP 2: DISSEMINATION AND EXPLOITATION; IDENTIFICATION OF STAKEHOLDERS AND INCENTIVES

WP 2 was led by Inagro (Martijn De Naegel and Annelies Pollentier)

General

Within the framework of the SNOWMAN project RAI-SOILCOMP different stakeholders were interviewed about soil compaction in the autumn of 2013. The principal stakeholders are farmers, machine constructors, contractors, public authorities and knowledge centers. The intention of the interviews was to compare the different visions on the approach of soil compaction in Belgium, the Netherlands and Sweden, thus enabling the different countries to learn from each other's experiences. It must be pointed out however that the interviews have not been analyzed scientifically and are consequently a mere impression of the vision of the different stakeholders.

The results of WP2 were used in WP6.

	Milestones and expected results	How reached	
	overview of committed stakeholders and incentives in The Netherlands, Belgium and Sweden		
1	identification of the stakeholders in the different countries	partnerschip	
2	drawing up different questionnaires per group of stakeholder	partnerschip	
3	identification of the incentives per group of stakeholder	per region	
			questionnaire for farmers (by phone, by mail, at fairs, at demonstration days)
			questionnaire for machine constructors (by phone, by mail, at fairs, at demonstration days)
			questionnarie for contractors (by phone, by mail, at fairs, at demonstration days)
			questionnaire for public authorities and knowledge centers (by phone, by mail, at fairs, at demonstration days)
4	compare the different visions on the approach of soil compaction		
		per region	comparing the results within the region
		partnerschip	comparing the results between the Nederlands, Belgium and Sweden

Vision on soil compaction

The farmers from the three countries are aware that soil compaction is a serious problem. But they aren't always aware that they can have that problem on their own farm. This is mostly the case on Belgian farms. Most of the Belgian and the Swedish farmers believe that the rate of compacted soils increases. In the Netherlands, half of the farmers think the rate is increasing, the other half thinks the rate stays equal. There were no farmers who believed that the rate of compacted soils decreased.

The machine constructors share the opinion of the farmers and believe that soil compaction is a serious problem. The Swedish constructors mention that their farmers take less measures against soil compaction than before. According to them the reason is that they now have more timeliness costs than previously.

Swedish contractors do not agree with the previous. According to them the rate of compacted soils has decreased because of the farmers that are more aware of the problem and because there are now more technical solutions than before. It's striking that this opinion isn't shared by other stakeholders like farmers, constructors, governments.

The governments from the three countries also believe there is more compaction than before. In Sweden they remark that the awareness of the farmers increases, but that it could be interesting that financers and researchers also become aware of the problem.

Causes of soil compaction

The farmers in the three countries see the heavy machines as the main cause of soil compaction. In Belgium these are the harvest machines and carts, in the Netherlands these are the harvest machines and the fertilizers and in Sweden these are mainly the harvest machines. In Belgium and Sweden the wet harvest conditions were also mentioned as a big cause. Because of the late harvest of maize, beets or potatoes there is a greater risk to have wet conditions during the harvest and more compaction.

The machine constructors of the three countries also see the heavy machines as the biggest cause of compaction. The Swedish constructors also mention that farmers have less time and therefore they drive on their fields in bad (wet) conditions. The heavy tractors make this possible, but they cause a lot of damage.

The contractors of the three countries also see the heavy machines as the main cause of compaction.

In Belgium, governments see the heavy machines and wet harvest conditions as the main causes of compaction. The Dutch governments add the up scaling of the farms. Because of the up scaling the farmers have less time and drive more often on the fields in bad conditions. The Swedish governments see the bad way of cultivation as a cause of soil compaction.

Consequences of soil compaction

In all three countries the farmers notice that their soil is workable later and stays wet longer as a consequence of soil compaction and that the yields are lower (in Belgium there are less farmers that are aware of that). In Belgium and the Netherlands farmers experience problems with the harvest because of the wet conditions. In Sweden they also notice that the soil is less workable, that the drainage doesn't seem to work and that there's a nitrogen shortage and lower growth.

Avoiding and repairing of soil compaction

The farmers of the three countries say that they subsoil regularly. This is an action to repair compacted soils. Besides that they also take measures to prevent compaction. The most used measure is adapted tire equipment. This measure is applied in all three countries, but the least in Belgium. For reduced tillage we observe the same. It's applied in all three countries, but the least in Belgium. A possible explanation is that Belgian farmers are less aware of the problem on their farm. The Swedish farmers also mention the following measures: front plow (needs a lighter tractor), extra drainage, light machines and removing the slurry spreader by pumping out the slurry to a tractor with spreader.

The machine constructors in the three countries try to take the choice of tires (or tracks) into account in dialog with the farmer. The machines are made as light as possible, but must stay functional. For the constructors, preventing compaction isn't a main objective. The durability of the machine comes in the first place.

The efforts of the contractors are highly variable. If they take measures it's mostly adapted tire equipment. Swedish contractors also mention reduced tillage as a good measure. In Belgium generally contractors don't take a lot of measures because the investment is too big and farmers aren't willing to pay the extra cost. In the Netherlands contractors usually take measures if they're asked by farmers. In Sweden it's also the customer (farmer) that stimulates the contractor to take measures.

Some Flemish governments invest in research and studies about soil compaction. Especially reduced tillage and organic matter get a chance. In the Netherlands co-funding of projects is possible. The Swedish governments mention the importance and usefulness of internet tools. There already exist 2 tools that are used (one to calculate the total amount of traffic in Mgkm/ha, one to calculate stresses under tires) but they are not user-friendly. Terranimo is still new but seems user-friendly. There is still need for a tool that calculates weight transfer from implements to tractors, to estimate wheel load correctly. Weight given by manufacturers is often not precise enough or even incorrect. All three countries think subsidies or obligation of certain practices aren't realistic because it's difficult to check. In Flanders VLIF-support could be interesting. That is financial support for certain investments like certain tire equipment. In Sweden they think it would be useful to financially stimulate drainage and green covers. The Dutch governments mention that it could be interesting to put the consequences and measures in a business-economic perspective. This could be a strong argument to convince farmers.

Knowledge exchange and advice about soil compaction

Swedish and Belgian farmers think that the agricultural press is the most important source for information about soil compaction, demonstrations come in the second place. In the Netherland advisors and study groups are the most important source of knowledge. Swedish farmers are stimulated to take measures by the government (focus on nutrients), research and the agricultural press.

Belgian farmers seldom ask machine constructors for advice (the constructors say that advice is better given by PCLT, research centers and the own experience of the farmers). In Sweden farmers also don't ask a lot of questions to machine constructors. In the Netherlands constructors give information about soil compaction to their customers during winter conversations, meetings and demonstrations. The Dutch constructors also mention that there's a task for the government.

In all three countries there are few questions and/or demands for the contractors. However according to the Belgian contractors the farmers are aware of the problem. In the Netherlands the lack of questions is explained by the fact that the immediate effect of compaction on the yield isn't visible. The Swedish contractors say that farmers know the machines already well enough. Swedish farmers are willing to register problems with compaction to the contractors. The Swedish contractors mention that it helps to raise the awareness if you can demonstrate the yield losses caused by soil compaction.

According to the Flemish governments the biggest advising role is put aside for the research centers. The farmer are best informed by demonstrations or study moments. LNE is also making a guide about compaction. In the Netherlands the governments think that the best way to inform and stimulate the farmers is by demonstrations. According to them it's important to put the attention on the yield losses. They believe that contractors and machine constructors should also be involved. In Sweden the advisors say that there is a need for a basic textbook on soil compaction. Advisors and researchers should be where the farmers are to discuss these issues. They also say that they need good tools for site-specific advice to farmers. According to the Swedish governments the best way to communicate is by websites and study moments.

Conclusions

Most of the stakeholders in the three countries say that they are aware of the problem of soil compaction and think that it is an increasing problem. Swedish farmers are more aware of the problem than the Belgian farmers. The Dutch farmers are somewhere in between. The main reasons for compaction according to most stakeholders are the heavy machines and wet field conditions while driving on it.

The farmers in all three countries subsoil regularly. Next to that there are a lot of farmers that use adapted tire equipment and reduced tillage as a measure against soil compaction. Most measures are taken in Sweden, least in Belgium. Governments point out that it's not realistic to oblige good agricultural practices. It's more realistic to financially support certain investments.

Swedish and Belgian farmers think that the agricultural press is the most important source for information about soil compaction, demonstrations come in the second place. In the Netherland advisors and study groups are the most important source of knowledge. Swedish governments also point out the importance of good tools.

It’s important to stimulate the communication about soil compaction. Especially farmers and contractors should talk more with each other. In Sweden the farmers are already willing to report problems with soil compaction to their contractors.

Multiple stakeholders agree that soil compaction should be placed in a business-economic perspective. If the farmers see that they can increase their yield by taking measures, they would be more motivated to take those measures.

ACHIEVEMENTS WP 3: IMPACT ASSESSMENT

WP 3 was led by Wageningen University (Lucrezia Caon and Aad Kessler)

Objectives

The objectives of WP3 were to gain insight in economic and environmental impact of soil compaction at farm and regional level and obtain ready to use knowledge for workshops of WP 6.

The expected results to be achieved were
- A list of key-indicators related to the economic and environmental effects of soil compaction;
- Impact assessment studies carried out in each of the three countries;

Results

The deliverable of WP3 is a report on the economic and environmental effects of soil compaction and its prevention, including a comparison between the three countries. The report has been finalized and is as such part of the report. It is included as annex 1.

Based on the results of the study, it was possible to conclude that:
- The percentage (%) of arable farmers declaring to have soil compaction considerably differs between the countries. The lowest percentage of farmers perceiving soil compaction problems is in Belgium, the highest is in Sweden;
- Dutch farmers consider topsoil and subsoil compaction negative or less important as causing a decrease in agricultural production. Otherwise, Swedish farmers are the ones giving less importance to those. Belgian farmers do not have a clear opinion on the importance of compaction on agricultural production;
- Although the majority of the farmers recognized the harvester and the harvesting cart as the most harmful machineries for the subsoil, only 27% of them stated that these pass on the same track. As those farmers were mainly the ones declaring not to have soil compaction problems, soil compaction can be counteracted by adopting a controlled traffic system especially in presence of heavily load machineries such as the harvesting cart;
- The majority of the farmers did not have an opinion on soil quality parameters related to the presence of soil compaction such as soil porosity and soil water infiltration capacity. The presence of soil compaction did not affect the amount of surface runoff in Holland and Sweden especially;
- The majority of the interviewed blamed soil compaction for causing water-logging;
- The majority of the interviewed stated that the amount of agrochemicals and fertilizers applied on the crops did not change over the last 10 years;
- Although the majority of the interviewed blamed soil compaction to affect their income, it was not easy to assess the economic impacts of soil compaction. Most of the farmers do

not pay attention to the shape of the roots of deep rooting and bulb/root crops. Nevertheless, the interviewed had a better idea on the cost of increasing subsoiling activities, which was considered significant by Belgium farmers especially;

- Swedish farmers with soil compaction problems were mainly using a random traffic system. The same group of Swedish farmers is however the most willing to take soil compaction mitigation measures, much more than the Belgium and Dutch farmers;
- Farmers are generally hindered by taking mitigation measures mainly because of economic reasons such as the cost of the implements and the low economic benefits of counteracting soil compaction. Additionally, several farmers declared not to know which measures to take against soil compaction;
- While Swedish farmers were mainly hindered by taking mitigation measures because of economic reasons (the mitigation measures available nowadays are too expensive or require too many changes to the current farming system), Dutch farmers were the main ones mistrusting the efficiency of the mitigation measures available nowadays and thinking to have already done everything possible to counteract soil compaction.

ACHIEVEMENTS WP 4: FIELD WORK

WP 4 was led by UGent (Wim Cornelis)

Objectives

The specific objectives of WP4 were to:

- extend the existing soil database used in Terranimo® (containing soil data from Denmark, Finland, Switzerland) with soil data from Flanders (Belgium), the Netherlands and Sweden.
- provide soil information to evaluate, fine-tune and extent pedotransfer functions (PTF) to predict precompression stress (PCS, as a measure for risk to soil compaction) from more readily available basic soil properties as clay, silt, sand and organic matter content, and bulk density.
- better understand the role of soil-water potential and bulk density on soil compaction risk.

Summary of work and background

Datasets

A *Flemish* dataset was established at UGent, containing:

- PCS data of various soils in Flanders with contrasting texture, land use, degree of compaction and wetness (preset matric potentials of -6 kPa, -10 kPa and -33 kPa). PCS is the *response* variable for predicting the risk to soil compaction.
- Clay (0-2 µm), silt (2-50 µm), sand (50-2000 µm) and organic carbon (OC) content, and bulk density (BD) corresponding to each PCS value. These are the potential *predictor* variables.

The Flemish dataset contains in total 126 PCS values with corresponding clay, silt, sand, OC, BD and matric potential values. It covers the seven major soil textural classes, i.e., Z (sand), S (loamy sand), P (light sandy loam), L (sandy loam), A (silt loam), E (clay), and U (heavy clay).

A Dutch dataset was established at Wageningen by Alterra Wageningen UR containing:

- Stress – strain data of a series of soils in the Netherlands with contrasting texture, degree of compaction and wetness (preset matric potentials of 6 kPa, -10 kPa and -30 kPa). The stress – strain curve is the basis for the calculation of the response variable for predicting the risk to soil compaction. The PCS is one of the possible response variables that can be calculated.
- Clay (0-2 µm), silt (2-50 µm), sand (50-2000 µm) and organic carbon (OC) content, and bulk density (BD) and volumetric water content (Wv) corresponding to each matric potential of each sample and stress – strain curve. These are the potential predictor variables.

The Dutch dataset is coupled to the data base with soil hydraulic data of BIS (Bodem Informatie System, Soil Information System; www.bisnederland.wur.nl) by doing the sampling as much as possible on exactly the same locations as the sampling for the determination of the soil hydraulic properties. The sampling and determination of the soil hydraulic properties is an ongoing program and the intention is to combine this with the determination of the mechanical strenght of these soils. Up to now 12 BIS locations were sampled with soils ranging from sand to middle heavy clay. Stress – strain data were measured at preset matric potentials of 6 kPa, -10 kPa and -30 kPa.

A large *Swedish* dataset was already available.

Confined uniaxial compression test

The concept of precompression stress originated from civil engineering soil mechanics (geotechnics) to evaluate slow consolidation of saturated homogenized clay (Casagrande, 1936). This concept was later modified to evaluate risk to compaction of unsaturated soil due to agricultural operations, but several procedures have been presented in literature (e.g., Koolen, 1974; Schjønning, 1991; Arvidsson and Keller, 2004; Keller et al., 2011). Whereas e.g. Schjønning (1991) conducted a confined uniaxial compression test with strain-controlled stress application at fast rate, Keller et al. (2011) performed a confined compression test with each stress being applied for 30 minutes ('slow rate' approach). The latter procedure was applied earlier to establish the Swedish dataset (that will be used within this project), and was also applied by Van De Vreken et al. (2009) in a project funded by the Environment, Nature and Energy Department of Flemish Government on mapping risk zones to soil compaction. It was therefore decided to also use the 'slow rate' approach for Flemish soils. However, because of practical constraints, a modified version of the 'fast rate' method was applied for Dutch soils. A preliminary 'intercalibration' between both approaches was conducted on an additional set of six soil samples.

Calculation of PCS

Once stress-strain relationships have been established with a confined uniaxial compression test, PCS needs to be calculated. Several methods have been presented in literature. Lamandé et al. (2012) classified them in two groups: regression methods and fitting methods. Several of these methods were compared in this study for determining PCS (e.g., Casagrande, 1936; Dawidowski and Koolen, 1994; Arvidsson and Keller, 2004; Gregory et al., 2006; Cavalieri et al., 2008; Rücknagel et al., 2010).

It has been demonstrated that the computed PCS value further depends on how strain is expressed, i.e., as dry bulk density or void ratio (Rücknagel et al., 2010), or whether stress is expressed linearly or logarithmically (Keller et al., 2011). In this study, we plotted void ratio as a function of the logarithm of stress.

PTF to predict PCS

To predict PCS, Terranimo® uses a PTF with clay content (clay) and pF (log of matric suction in cm) as predictor variables:

$$\log10(PCS) = 1.83 - 0.059*clay + 0.0297*clay*pF \quad (1)$$

Equation 1 was derived by Schjønning and coworkers from multiple regression on a dataset of PCS values calculated by fitting the Gompertz equation to stress-strain relationships. These relationships were obtained from fast-rate confined uniaxial compression tests to a total of 584 soil cores, sampled in undisturbed condition from nine locations and four soil depths including subsoil in Denmark. The cores were drained to either of three matric potentials: -5 kPa, -10 kPa and -33 kPa (corresponding to pF 1.7, 2.0 and 2.5, respectively) (Schjønning, 2014, personal communication).

The regression model was highly significant ($P<0.0001$), as well as each individual effect. The coefficient of determination was low ($R^2 = 0.24$) (Schjønning, 2014, personal communication).

The soils on which Eq. (1) is based cover a clay content from about 4 to 17% only. Whether Eq. (1) is valid for soils in Flanders, the Netherlands and Sweden needs to be tested, and if necessary, Eq. (1) should be recalibrated.

In Terranimo® International, the PCS predicted with Eq. (1) is 'scaled' to the level of soil strength observed in a range of Swedish wheeling experiments monitoring stress and strain conducted by Keller et al. (2012) (Schjønning, 2014, personal communication).

Activities

Selection of sampling sites

Using the soil map of Belgium (www.dov.vlaanderen.be) in combination with a database with textural data from the department of Soil Management, UGent, and the Belgian Aardewerk database, seven sites that represent the seven major soil textural classes according to the Belgian textural triangle were selected in Flanders (Fig. 4-1). At each site, samples were taken from three locations on two concurrent fields, one under cropland and the other under grassland. At the cropland, samples were taken from two locations, one at the headland and one more central in the field. This sampling strategy (with different land use and location within the cropped field) aimed at some variation in degree of compaction within one textural class. Moreover, samples were taken at two depths but all from the subsoil (i.e., at 40 and 70 cm depth). In total 21 locations were thus selected for taking 126 disturbed and undisturbed soil samples.

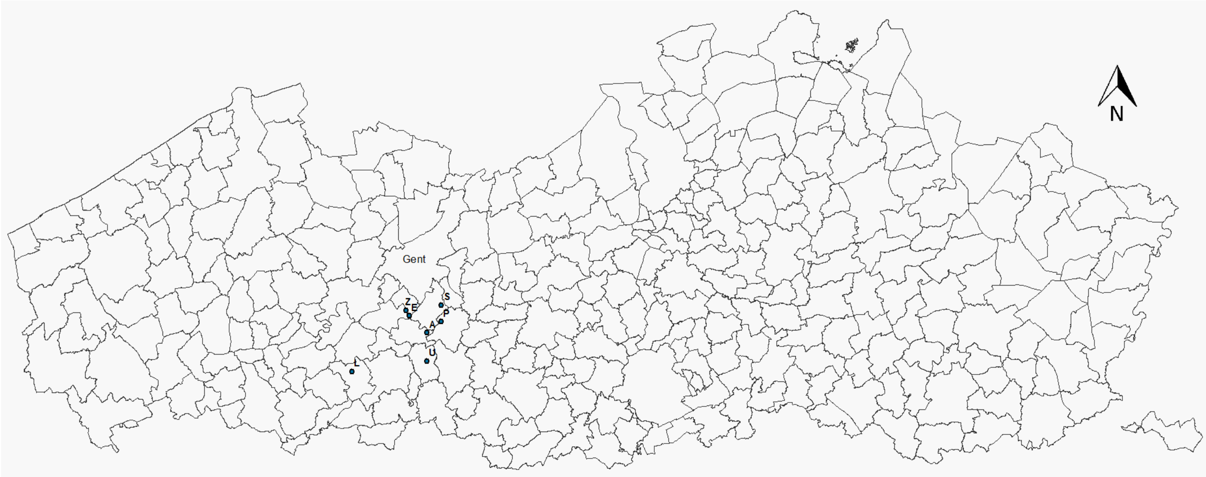

Figure 4-1. Location of the seven sampling sites within Flanders, Belgium covering, in the subsoil, the seven textural classes according to the Belgian textural triangle. At each site undisturbed and disturbed samples were taken at three locations (headland of cropland, central within cropland, grassland) from the subsoil at depths of 40 and 70 cm.

For the preliminary ‘intercalibration’ between the fast- and slow-rate confined uniaxial compression tests, samples were taken in Flanders at three locations and two depths (15 and 60 cm) in order to cover a wide clay content range.

In the Netherlands, a modified version of the ‘fast rate’ method (Koolen, 1974; Schjønning, 1991) was applied. The samples have a diameter of 10 cm and an initial height of 3 cm. The load is applied in a few seconds, comparable with the loading rate at a depth of about 30 – 40 cm by a running wheel in agriculture (figure 4.2).

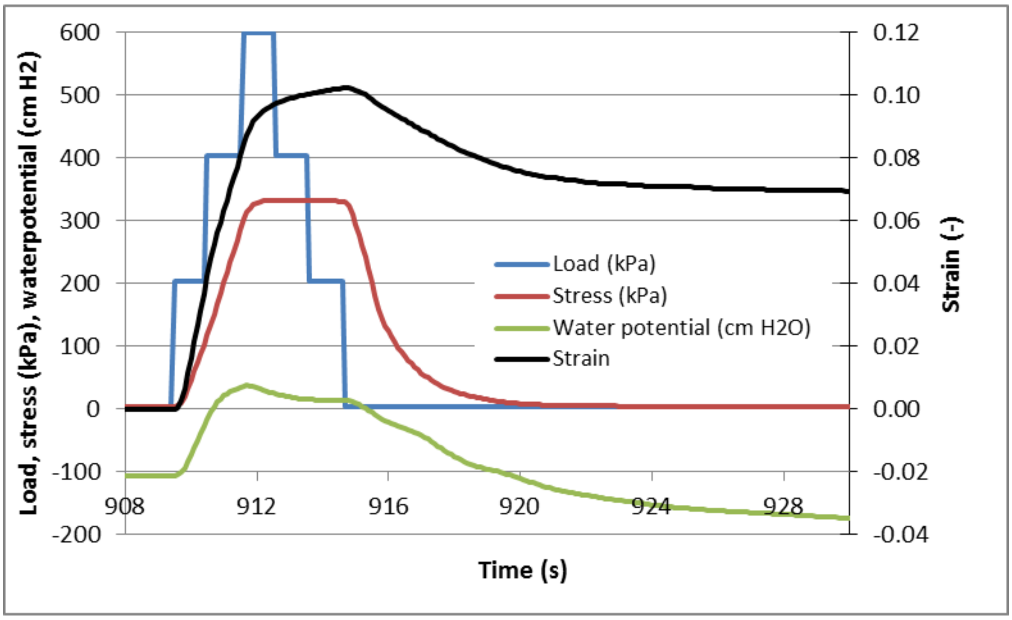

Figure 4-2. Example of a fast uni-axial test on a light clay soil (clay content 26.2%), initial dry bulk density 1.526 g.cm^{-3}, initial soil water potential -10 kPa (-100 cm H_2O).

Soil sampling

Soil samples were taken in Flanders in the period of November 2013 to February 2014, after soils had freely drained in preceding days and reached a near field capacity condition. Soil pits were dug to the desired depth and undisturbed samples were taken manually by pushing sharpened PVC cylinders (∅ = 125 mm, height 5 cm) vertically in a horizontal flat surface using a dedicated hammering holder. Samples were closed with plastic caps to avoid disturbance during transportation. Per depth and location, three cylinders were taken, resulting in a total number of 126 cylinders. Additionally, disturbed samples were taken from the soil that was sticking to the cores when digging them out, mixed and transported in bags (42 in total).

For the preliminary ‘intercalibration’, one core per depth was taken in a similar way, resulting in an additional 12 cores and 12 disturbed samples.

In the Netherlands 6 samples were taken of the subsoil at about ploughpan depth. To be sure to have a sample without mixing up of the upper soil layer we sampled at a depth of at least 30 cm and at least 5 cm below the ploughing depth. The sampling locations are combined with locations where already was sampled to determine the hydraulic properties of these soils for the Dutch Soil Information System (BIS).

Soil analysis

At UGent, the samples taken from Flemish soils were prewetted at predefined matric potentials of -6, -10 and -33 kPa on sandboxes and in pressure chambers till equilibrium. The oedemeter tests to establish the stress-strain relationships were conducted in the course of January to April 2014. Prior to each slow-rate confined axial compression tests, a subsample was taken in a metal ring of 19.99 mm height and 63.5 mm diameter from each prewetted core. The subsamples were then placed on the oedometers and subjected to predefined pressures (stresses) of 15, 29, 57, 113, 224, 447, 895 and 1786 kPa for 30 minutes.

Sand, silt and clay content was determined with the sieve-pipette method of De Leenheer (1959), OM content with the Walkley and Black method (1934) and BD from the undisturbed cylinders by oven-drying (Blake and Hartge, 1986). This was carried out from February till April 2014.

For the preliminary ‘intercalibration’ (at WUR and at UGent), the undisturbed samples were pre-wetted by subjecting them to a matric potential of -10 kPa on a sandbox for seven days. This should have ensured an equal soil moisture status for the pairwise samples. Samples were then subjected to a confined uniaxial compression tests with each stress being applied for 30 minutes at UGent using conventional oedometers, and to fast-rate confined uniaxial compression tests using Eijkelkamp’s compression test apparatus at WUR. Part of the UGent team (Adam Bezuijen, Gemmina Di Emidio, Maarten Volckaert, Wim Cornelis) visited the soil physics lab at WUR (Jan van de Akker, Piet Peters) where a demonstration with Eijkelkamp’s compression test apparatus was given on 29 November 2013. The tests were then conducted in the course of December 2013 and January 2014.

In The Netherlands samples were saturated and then subjected to predefined matric potentials of -6, -10 and -30 kPa on sandboxes and in pressure chambers till equilibrium. Per matric potential two samples were prepared and tested with the ‘fast’ uniaxial test (see Figure 4-2). One sample was tested at a maximum applied load of 600 kPa and the other sample at a maximum applied load of 200 kPa. The latter being more in the range of the soils stresses to be expected at a depth of 30 cm below a tire used in agriculture. Before the actual load was started the sample was pre-loaded during 15 minutes with a load of 4 to 6 kPa, depending on the sampling depth. This pre-load equals the weight of the soils above the sample in the field. The load of 600 kPa was built up with steps of 200 kPa during 1 second (see Figure 4-2), however, because air pressure was used with a certain delay, the really exerted stress on top of the sample could in some cases be just 55% of the 600 kPa. In general the maximum applied stress was about 500 kPa. After reaching a load (air pressure) of 600 kPa during 1 second, the load was lowered with steps 200 kPa till 4 to 6 kPa during 15 minutes to include also the rebound the sample.

Sand, silt and clay content was determined in the BIS project, in which the sieve-pipette method is used. The same accounts for the OM content, however, we used also the loss-on ignition method with a temperature of 550 ˚C. BD was determined from the tested samples by oven-drying (Blake and Hartge, 1986).

Data analysis

Fout! Verwijzingsbron niet gevonden. shows the land use, sand, silt, clay and OM content, and BD at the sampling depths and positions of the seven sampled Flemish sites. Table 4-2 to 4-4 show, for the predefined matric potentials, the corresponding strain values at the different imposed stresses.

Python scripts were written in March 2014 to automatically deduce PCS from the stress-strain relationships. Various calculation methods for deriving PCS values for such relationships were tested, including that of Casagrande (1936) using the procedure of Dawidowski and Koolen (1994) (denoted as C_DK), the four methods evaluated by Arvidsson and Keller (2004) (AK_2 – AK_5), and Gompertz’ equation suggested by Gregory et al. (2006) (for which we tested a modified three-parameter version and the original four-parameter version; Gea3 – Gea4).

In brief, C_DK is a numerical procedure for Casagrande’s graphical method where a tangent and a parallel to the x-axis are drawn at the point of the highest curvature of the stress-strain curve, and PCS then corresponds to the intersection of the bisector of the angle between these two straight lines and the virgin compression line VCL (the straight portion of the stress–strain curve). AK_2 considers PCS at the intersection of the VCL with the x-axis at zero strain, AK_3 at a predefined strain, set to 2.5%, AK_4 at the intercept of the VCL and a regression with the first two points of the curve, and AK_5 at the intercept of the VCL and a regression with the first three points of the curve. In the Gea method, a Gompertz type equation is fit to the observed stress-strain data. To derive the parameters of the Gompertz equation, several non-linear optimization methods available in the Python library were tested and we finally found Sequential Least Squares Programming (SLSQP) and an extended

Limited-memory Broyden–Fletcher–Goldfarb–Shanno algorithm (L-BFGS-B) showing the best results, for Gea3 and Gea4, respectively. C_DK was used by Rücknagel et al. (2010) among many others. AK_2, AK_4 and AK_5 were used by Dias Junior and Pierce (1995) and later by Cavalieri et al. (2008), and AK_2 by Schmertmann (1955) and McBride and Joosse (1996). The PTF used in Terranimo® is based on PCS data derived from the Gea approach, used also by Lamandé et al. (2012) (Schjønning, 2014, personal communication).

Figure 4-3 shows a box and whisker plot of the PCS values calculated with the various methods. The median value of PCS and its variation was largest with C_DK, and lowest with AK_2 and AK_3. The other methods took intermediate positions. Keller et al. (2004) also found that Casagrande's methods showed higher PCS values and more variation as compared to a regression method (similar to AK_5) where the regression line was determined from data of the initial part of the compaction curve (at stresses ≤25 kPa). Our findings might indicate that C_DK is able to capture PCS variation better than the other methods, although they might also (and most probably) imply that C_DK is most sensitive to small measurement errors hence affecting the position of the point corresponding to the smallest radius of the curvature, as also suggested by Keller et al. (2004). A comparison between the PCS values as deduced from the different methods is presented in Fig. 4-4.

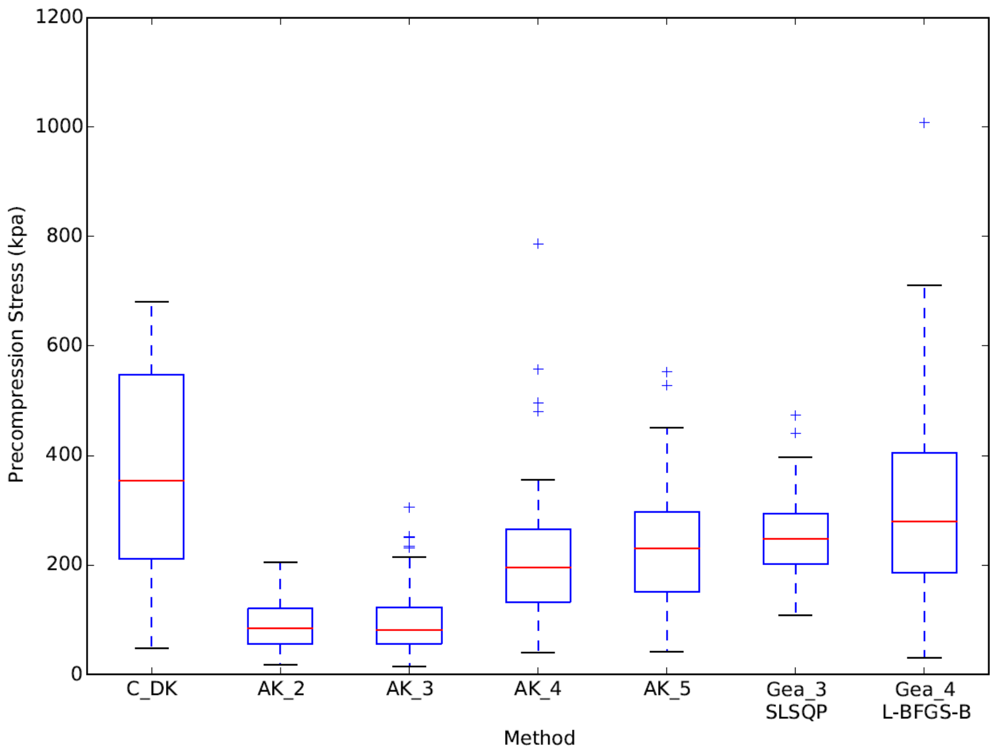

Figure 4-3. Statistical comparison (N=126) of precompression stress PCS calculated from different procedures. C_DK is Casagrande according to Dawidowski and Koolen (1994), AK_2-AK_5 are four alternatives evaluated by Arvidsson and Keller (2004), Gea_3-Gea_4 are a three- and four-parameter version of a Gompertz equation suggested by Gregory et al. (2006), SLSQP is Sequential Least Squares Programming, L-BFGS-B is Limited-memory Broyden–Fletcher–Goldfarb–Shanno algorithm

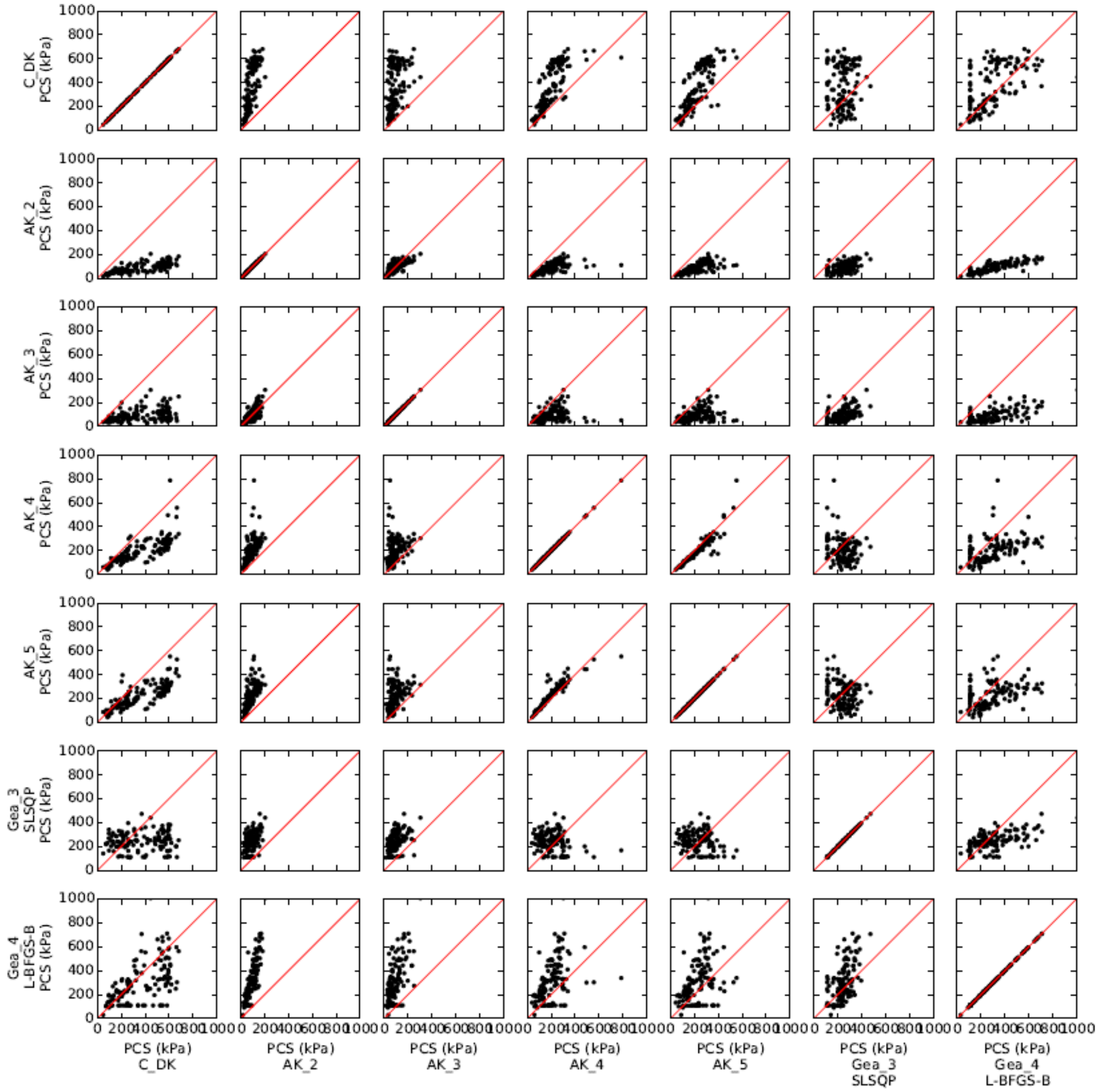

Figure 4-4. Comparison of precompression stress PCS deduced from different methods (N=126). C_DK-Gea_4 as in Fig. 4-3.

Scatter plots of PCS values against basic soil properties were made to detect trends and extreme measurements, and to provide information about the linear or nonlinear behaviour of the variables and the kind of transformation that might be needed to eliminate the nonlinearity if present. Highest correlations were found between log10 PCS (at -6, -10 and -33 kPa) as calculated from C_DK and AK_5 on the one hand, and bulk density and clay content on the other (Fig. 4-5 to 4-7), with AK_5 generally outperforming C_DK. Although PCS calculated from Gea3 resulted as well in relatively high correlations with bulk density and clay content, they were negative and positive, respectively, which is against most findings reported in literature. It is generally accepted that under given wetness conditions, PCS increases with increasing bulk density and decreasing clay content.

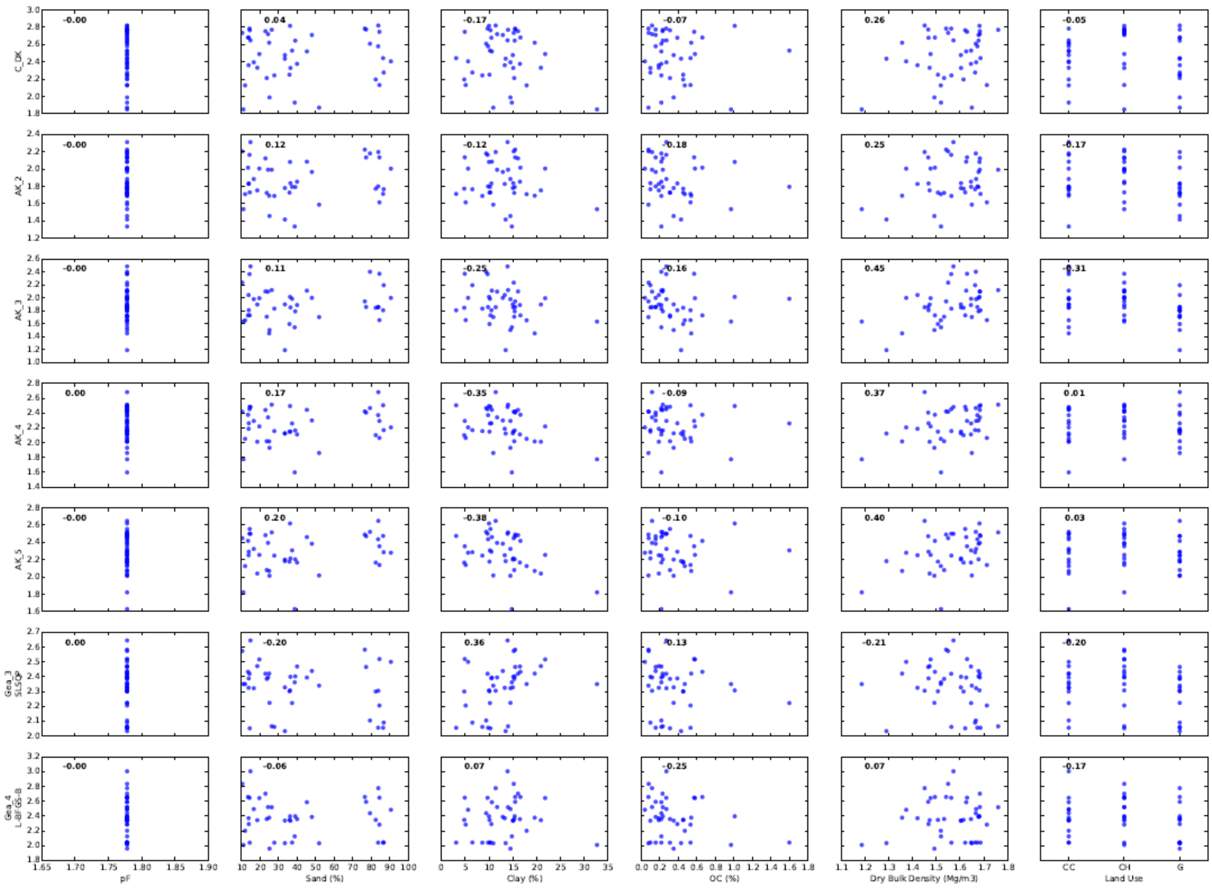

Figure 4-5. Scatter plots of PCS at -6 kPa matric potential (y axis) against basic soil information (N=126). C_DK-Gea_4 as in Fig. 4-3. Values given are Pearson correlation coefficients.

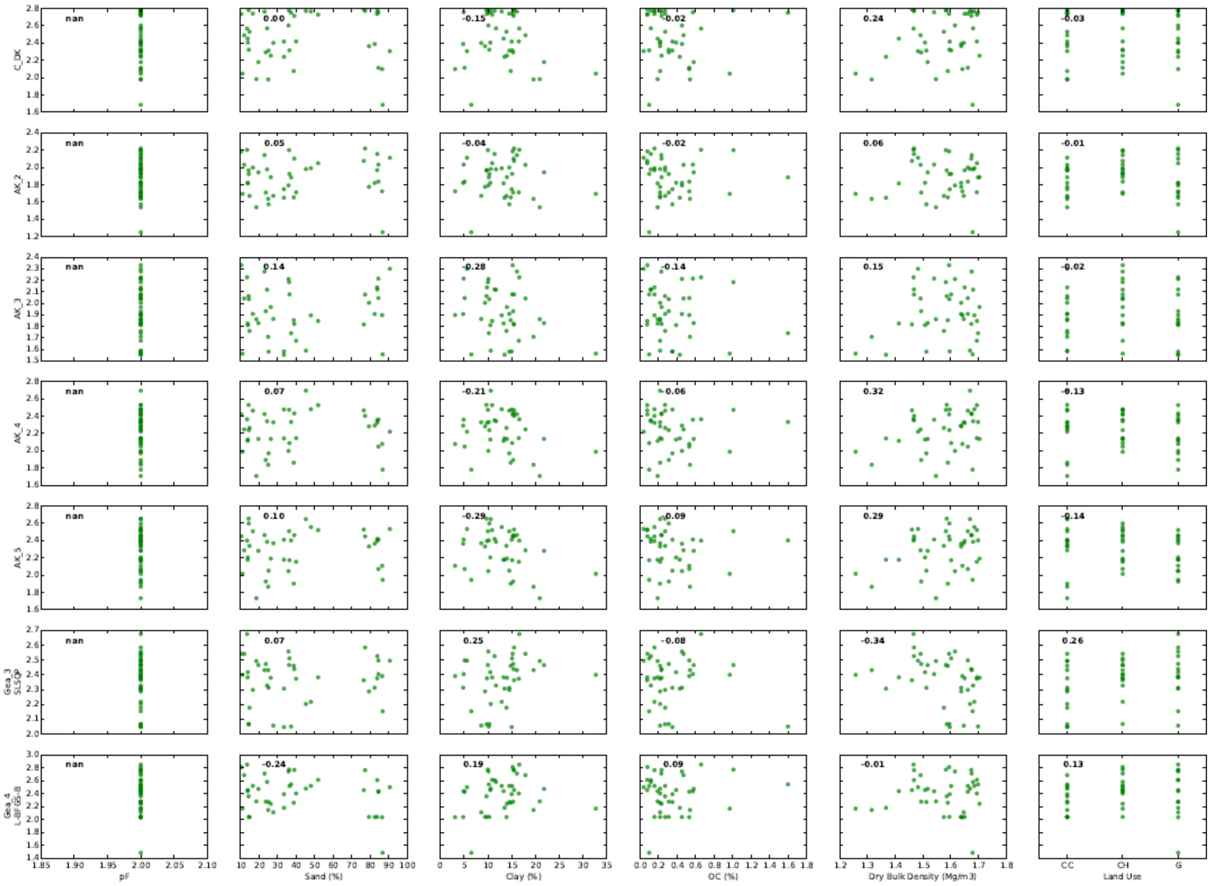

Figure 4-6. Scatter plots of PCS at -10 kPa matric potential (y axis) against basic soil information (N=126). C_DK-Gea_4 as in Fig. 4-3. Values given are Pearson correlation coefficients.

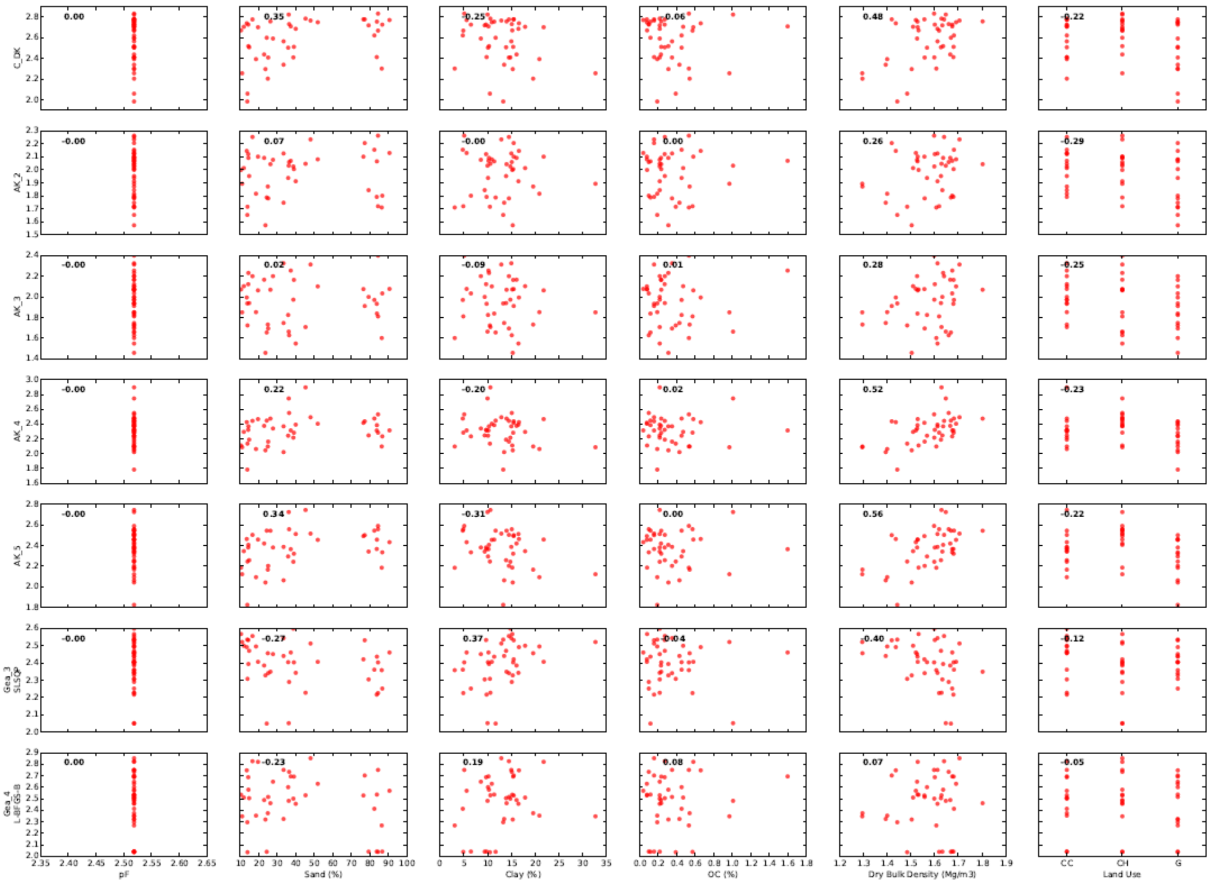

Figure 4-7. Scatter plots of PCS at -33 kPa matric potential (y axis) against basic soil information (N=126). C_DK-Gea_4 as in Fig. 4-3. Values given are Pearson correlation coefficients.

The PCS values were then ‘scaled’ to the level of soil strength observed in the field by Keller et al. (2012) as is done in Terranimo® and suggested by Schjønning (2014, personal communication). Keller et al. (2012) found that under field conditions at pF 2, soil strength was near 50 kPa, irrespective of soil texture. Since lab measured PCS values are typically higher than those observed in the field, a scaling factor of 0.215 was used so that PCS values yield 50 kPa at pF 2.

A stepwise regression showed that clay content, BD and pF were significant predictor variables, resulting in following significant PTF (with R^2 = 0.17 and RMSE of 20.0 kPa):

$$\log10(PCS) = 1.221 - 0.006 \cdot clay - 0.606 \cdot BD + 0.106 \cdot pF \quad (2)$$

with PCS from AK_5. Since BD is not available in most datasets (as it is a time-variant variable) and generally not known to potential Terranimo® users, following significant alternative was developed as well (with R^2 = 0.10 and RMSE = 20.5 kPa):

$$\log10(PCS) = 2.483 – 0.024*clay + 0.007*pF*clay \quad (3)$$

with PCS from AK_5. Both PTFs (Eqs. 2 and 3) show low accuracy and are explaining the variation in observed PCS to a limited extend only (~20%), suggesting that other factors not included in the model substantially affect PCS.

Figure 4-8 and 4-9 show scatterplots of PCS measured with Eq. (2) and (3), respectively. When evaluating Eq. (1) against our scaled PCS data, its reliability was low, with R^2 = 0.004 and RMSE = 30 kPa (Fig. 4-10). Similarly, Van De Vreken et al. (2009) found very poor matches between observed and predicted PCS. They used the same 'slow rate' procedure to establish stress-strain curves as we did, but with Casagrande's method for deriving PCS, and used the PTFs by Lebert and Horn (1991). Recently, Stettler et al. (2014) reported that PCS values of Arvidsson and Keller (2004) (for soils from Sweden) and of Rücknagel et al. (2007) (for soils from Germany) were comparable to those calculated with Eq. (1). Based on the above, it was decided to keep on working at this stage with the current PTF incorporated in Terranimo® (Eq. 1). More research on deriving PCS is, however, warranted.

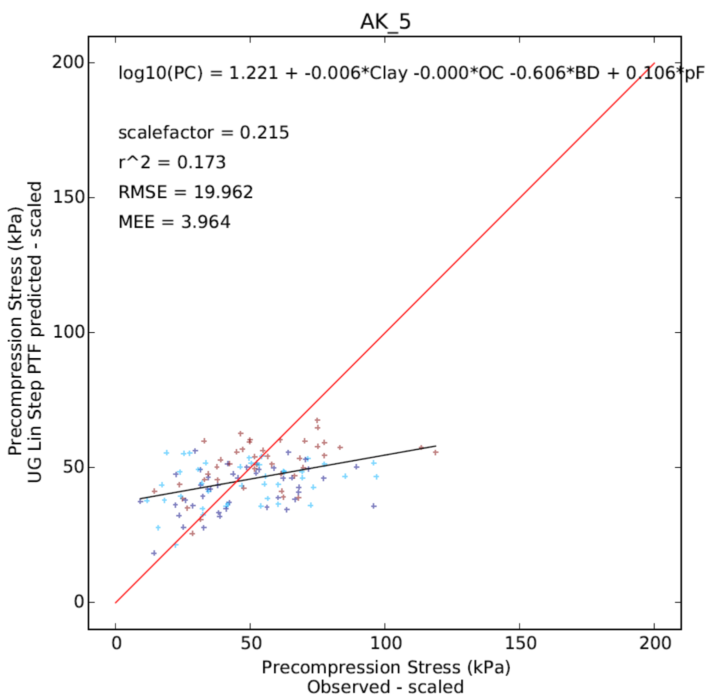

Figure 4-8 Observed vs predicted (Eq. 2) precompression stress PCS (N=126). Different colours refer to different predefined matric potentials.

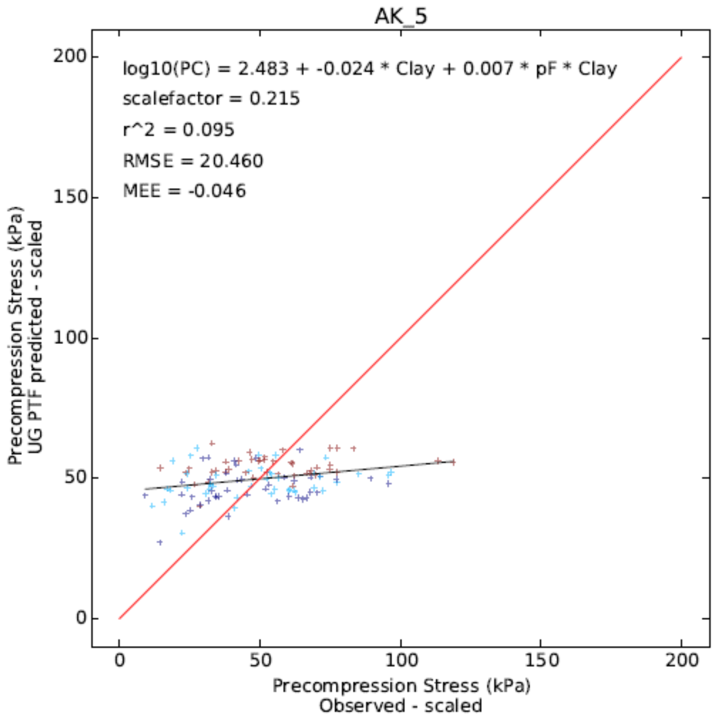

Figure 4-9. Observed vs predicted (Eq. 3) precompression stress PCS (N=126). Different colours refer to different predefined matric potentials.

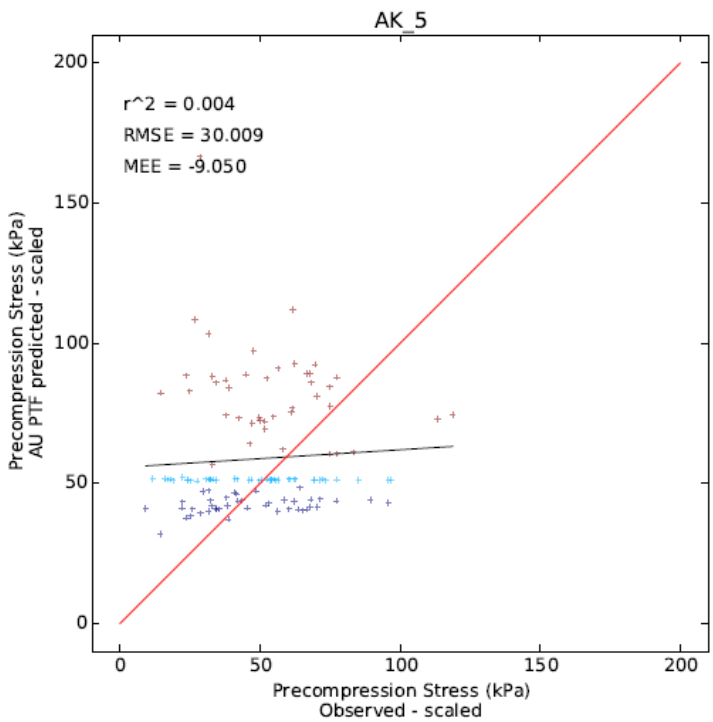

Figure 4-10. Observed vs predicted (Eq. 1) precompression stress PCS (N=126). Different colours refer to different predefined matric potentials.

Regarding, the *effect of matric potential and bulk density on PCS*, data were analysed per soil textural class. Figures 4-11 and 4-12 show that for most soil textural classes, PCS increases with increasing pF value (increasing matric suction) and with increasing BD as was also found in literature (e.g., Berli, 2001; Keller et al., 2004), although the correlations were for some classes rather poor and contra-intuitive. This might be due to the uncertainties associated with deriving PCS from stress-strain relationships as discussed earlier, and to matric potentials deviating from the predefined values during the compression tests. This in turn affects soil strength, and its effect depends on inherent soil properties.

As an outcome of this study, a master student at UGent started in the academic year 2014-2015 research to better understand the factors affecting stress-stain relationships and the PCS derived from that of unsaturated soil (compression).

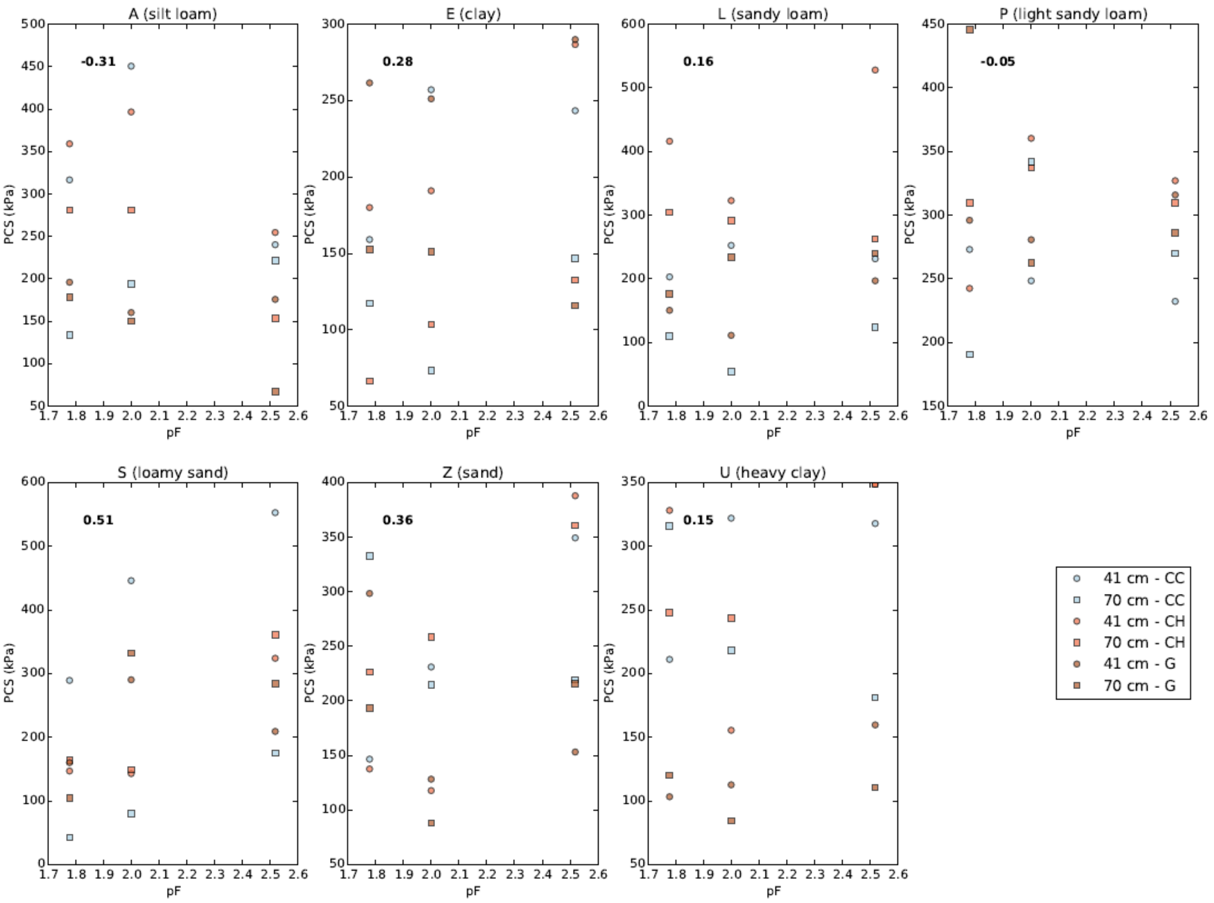

Figure 4-11. Observed PCS vs pF value (log of matric suction in cm), per major textural class according to the Belgian soil classifiication. Values given are Pearson correlation coefficients. CC is crop land central, CH is crop land headland, G is grass land.

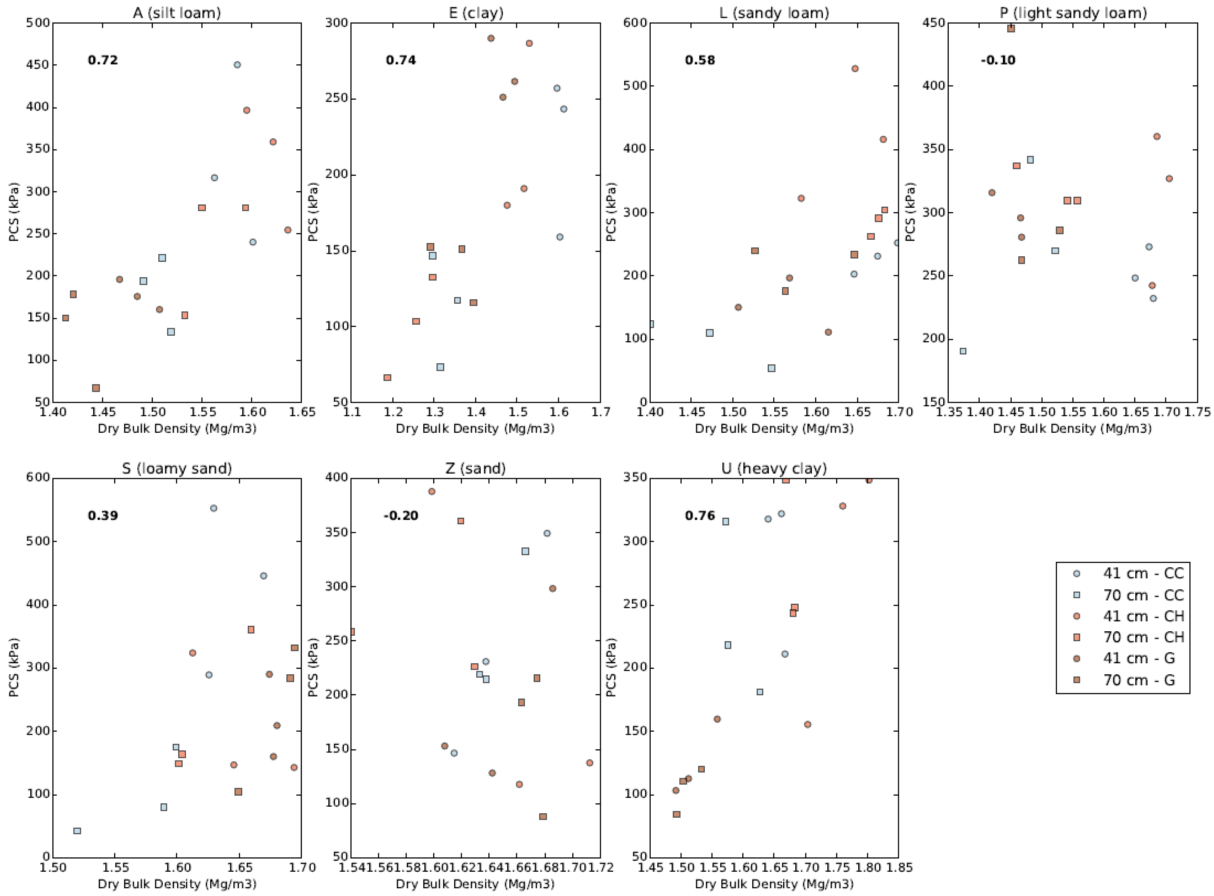

Figure 4-13. Observed PCS vs bulk density BD, per major textural class according to the Belgian soil classifiication. Values given are Pearson correlation coefficients. CC, CH, G as in Fig. 4-9.

Table 4-1 Basic soil properties per sampling depth and position/land use at the seven sampling sites in Flanders

Ring ID	Site	Text. Class	Land use	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	OM (%)	BD (g/cm^3)
85-87	Baaigem	A	CC	41	14.3	76.1	9.7	0.5	1.56
88-90		A	CC	70	11.9	70.2	17.9	0.9	1.52
91-93		A	CH	41	14.4	75.3	10.3	0.6	1.62
94-96		A	CH	70	10.4	74.4	15.2	0.2	1.55
79-81		A	G	41	13.9	75.6	10.5	0.8	1.47
82-84		A	G	70	13.8	72.8	13.3	0.4	1.42
109-111	Zevergem	E	CC	41	33.4	51.6	15.0	0.7	1.36
112-114		E	CC	70	24.9	55.4	19.6	1.1	1.11
115-116		E	CH	41	19.6	58.6	21.8	1.2	1.17
118-120		E	CH	70	11.0	56.3	32.7	1.9	0.91
7B-9B		E	G	41	13.5	69.9	16.6	1.3	1.11
10B-12B		E	G	70	33.4	53.0	13.5	0.9	0.93
55-57	Wortegem	L	CC	41	37.3	52.4	10.2	3.2	1.61
58-60		L	CC	70	18.5	60.6	20.9	0.4	1.39
97-99		L	CH	41	36.2	53.7	10.0	2.0	1.53
100-102		L	CH	70	22.9	61.0	16.1	0.5	1.47
43-45		L	G	41	35.9	54.0	10.1	0.9	1.51
46-18		L	G	70	27.7	63.7	8.6	0.4	1.56
67-69	Moortsele	P	CC	41	83.8	6.5	9.8	0.3	1.67
70-72		P	CC	70	90.7	3.7	5.6	0.1	1.50
73-75		P	CH	41	48.0	39.2	12.9	0.3	1.68
76-78		P	CH	70	76.6	8.0	15.5	0.2	1.54
49-51		P	G	41	77.3	7.1	15.5	0.3	1.47
52-54		P	G	70	83.9	4.7	11.4	0.2	1.45
25-27	Melle	S	CC	41	45.3	44.1	10.6	0.4	1.63
28-30		S	CC	70	38.7	46.5	14.8	0.4	1.52
1-3		S	CH	41	40.0	43.5	16.5	0.4	1.65
4-6		S	CH	70	36.4	48.5	15.1	0.2	1.60
31-33		S	G	41	39.0	45.5	15.4	0.5	1.68
34-36		S	G	70	51.9	37.2	10.9	0.2	1.65
13-15	Eke-Landuit	Z	CC	41	82.5	12.7	4.8	0.9	1.61
16-18		Z	CC	70	79.4	11.2	9.4	0.4	1.67
7-9		Z	CH	41	84.5	10.4	5.1	1.1	1.71
10-12		Z	CH	70	84.5	10.6	4.9	1.1	1.63
19-21		Z	G	41	86.5	10.4	3.1	1.1	1.69
22-24		Z	G	70	86.8	6.7	6.5	0.2	1.66
103-105	Zwalm	U	CC	41	16.6	68.8	14.5	0.5	1.67
107-109		U	CC	70	14.8	71.3	13.9	0.5	1.57
61-63		U	CH	41	26.3	59.7	14.0	0.5	1.76
64-66		U	CH	70	24.3	64.0	11.7	0.2	1.68
37-39		U	G	41	25.1	60.4	14.5	0.7	1.49
40-42		U	G	70	23.6	61.1	15.3	0.6	1.53

Texture class according to Belgian triangle. G is grassland, CC is cropland central, CH is cropland headland

Table 4-2. Stresses at different strains at a matric potential of -6 kPa of sampled sites in Flanders

Ring ID	Stress (mm/mm) at Strain 15 kPa	Strain 29 kPa	Strain 57 kPa	Strain 113 kPa	Strain 224 kPa	Strain 447 kPa	Strain 895 kPa	Strain 1786 kPa
85	-0.003056	-0.006312	-0.010821	-0.016633	-0.024601	-0.034631	-0.048446	-0.066963
88	-0.009031	-0.017218	-0.029216	-0.046837	-0.069673	-0.095783	-0.124146	-0.154216
91	-0.010305	-0.017408	-0.025755	-0.035067	-0.045872	-0.056178	-0.069679	-0.086843
94	-0.004337	-0.00773	-0.012449	-0.018933	-0.028865	-0.044427	-0.067419	-0.094578
79	-0.003963	-0.012701	-0.022689	-0.035574	-0.052533	-0.072553	-0.097493	-0.123733
82	-0.006545	-0.010721	-0.016698	-0.02525	-0.036873	-0.05044	-0.066811	-0.084696
109	-0.008096	-0.012756	-0.02001	-0.030392	-0.043971	-0.06139	-0.08019	-0.100785
112	-0.016108	-0.025412	-0.038869	-0.056378	-0.081308	-0.115145	-0.168844	-0.209154
115	-0.00666	-0.010721	-0.016733	-0.027004	-0.042835	-0.066583	-0.09544	-0.125801
118	-0.009884	-0.017862	-0.030155	-0.062217	-0.090617	-0.123487	-0.157195	-0.190589
7B	-0.009483	-0.016673	-0.02584	-0.035998	-0.049581	-0.071951	-0.103411	-0.136678
10B	-0.024612	-0.034117	-0.045655	-0.060192	-0.078049	-0.099199	-0.122138	-0.146073
55	-0.009437	-0.013702	-0.019176	-0.026706	-0.036591	-0.049257	-0.063905	-0.080522
58	-0.00794	-0.013126	-0.019939	-0.030561	-0.048642	-0.077307	-0.107164	-0.13407
97	-0.004942	-0.01009	-0.018162	-0.026004	-0.035381	-0.046573	-0.060843	-0.08191
100	-0.006563	-0.010821	-0.016533	-0.023486	-0.033216	-0.046993	-0.06654	-0.090731
43	-0.015883	-0.021736	-0.028978	-0.038047	-0.055384	-0.078119	-0.104367	-0.13002
46	-0.007915	-0.012374	-0.018792	-0.03016	-0.039636	-0.0503	-0.062873	-0.077855
67	-0.009131	-0.014927	-0.022127	-0.030506	-0.040642	-0.052985	-0.067486	-0.085107
70	-0.003356	-0.007717	-0.015581	-0.027079	-0.04529	-0.064779	-0.09003	-0.118637
73	-0.001959	-0.007927	-0.01653	-0.026843	-0.039317	-0.054942	-0.075561	-0.098645
76	-0.000753	-0.006729	-0.016654	-0.029721	-0.046493	-0.068682	-0.09943	-0.140612
49	-0.005752	-0.011705	-0.020857	-0.032766	-0.048826	-0.068129	-0.095047	-0.13006
52	-0.010355	-0.016858	-0.022611	-0.029714	-0.038676	-0.051133	-0.069734	-0.097548
25	-0.005861	-0.010681	-0.016177	-0.023532	-0.034994	-0.048562	-0.066222	-0.089228
28	-0.011312	-0.021274	-0.034671	-0.054247	-0.085398	-0.124347	-0.159809	-0.189563
1	-0.00651	-0.011871	-0.020105	-0.031012	-0.047895	-0.073965	-0.102955	-0.131174
4	-0.005672	-0.011897	-0.020883	-0.033584	-0.051182	-0.072138	-0.096081	-0.122003
31	-0.006478	-0.014257	-0.023827	-0.036295	-0.05332	-0.075956	-0.104317	-0.131383
34	-0.004794	-0.012594	-0.027747	-0.046826	-0.068489	-0.09227	-0.117661	-0.14362
13	-0.010225	-0.014206	-0.020682	-0.034841	-0.045632	-0.063406	-0.083195	-0.10443
16	-0.001955	-0.004977	-0.009216	-0.015311	-0.023343	-0.033032	-0.04508	-0.058785
7	-0.014355	-0.019716	-0.027747	-0.04289	-0.053286	-0.070173	-0.092523	-0.113346
10	-0.002254	-0.004205	-0.008066	-0.014471	-0.024328	-0.035771	-0.051355	-0.07029
19	-0.010536	-0.017173	-0.023605	-0.031552	-0.041575	-0.052423	-0.065027	-0.08082
22	-0.00507	-0.008293	-0.013556	nan	-0.029066	-0.0377	-0.048042	-0.06024
103	-0.008831	-0.013636	-0.019459	-0.026813	-0.038894	-0.054177	-0.072343	-0.092746
107	-0.003306	-0.005556	-0.008517	-0.012788	-0.019138	-0.032264	-0.051553	-0.075801
61	-0.007477	-0.012304	-0.017344	-0.023096	-0.03155	-0.042094	-0.055608	-0.073046
64	-0.004862	-0.009533	-0.015755	-0.023474	-0.033868	-0.047865	-0.06593	-0.086603
37	-0.013443	-0.023242	-0.036495	-0.054144	-0.076129	-0.099931	-0.124246	-0.149246
40	-0.010893	-0.016972	-0.026556	-0.041255	-0.063155	-0.090657	-0.12023	-0.149704

nan refers to unavailable data

Table 4-3. Stresses at different strains at a matric potential of -10 kPa of sampled sites in Flanders

Ring ID	Stress (mm/mm) at							
	Strain 15 kPa	Strain 29 kPa	Strain 57 kPa	Strain 113 kPa	Strain 224 kPa	Strain 447 kPa	Strain 895 kPa	Strain 1786 kPa
86	-0.006753	-0.011655	-0.018551	-0.024772	-0.031598	-0.04047	-0.052576	-0.006753
89	-0.006015	-0.010085	-0.016217	-0.025288	-0.039337	-0.06217	-0.090664	-0.006015
92	-0.003163	-0.006613	-0.016197	-0.025405	-0.033266	-0.041533	-0.052354	-0.003163
95	-0.003915	-0.007128	-0.011317	-0.016967	-0.025554	-0.039156	-0.058584	-0.003915
80	nan	nan	nan	nan	nan	nan	nan	nan
83	-0.01004	-0.01506	-0.023092	-0.03524	-0.05261	-0.075316	-0.101257	-0.01004
110	-0.01515	-0.022488	-0.028664	-0.036768	-0.048324	-0.062931	-0.08044	-0.01515
113	-0.008885	-0.016244	-0.026656	-0.049161	-0.094151	-0.131541	-0.169337	-0.008885
116	-0.005689	-0.010035	-0.021901	-0.03452	-0.052082	-0.076412	-0.106121	-0.005689
119	-0.010621	-0.020754	-0.033216	-0.058306	-0.090844	-0.12879	-0.168775	-0.010621
8B	-0.001953	-0.005561	-0.010971	-0.018436	-0.029709	-0.05005	-0.079401	-0.001953
11B	-0.010304	-0.021172	-0.033684	-0.049096	-0.070331	-0.096581	-0.124503	-0.010304
56	-0.015763	-0.019485	-0.025301	-0.033182	-0.043343	-0.056659	-0.073644	-0.015763
59	-0.006998	-0.012056	-0.019809	-0.034249	-0.062433	-0.101593	-0.137418	-0.006998
98	-0.005519	-0.009224	-0.014189	-0.020993	-0.030055	-0.0429	-0.061766	-0.005519
101	-0.00506	-0.008266	-0.01266	-0.018687	-0.027104	-0.038827	-0.05501	-0.00506
44	-0.004465	-0.007526	-0.012596	-0.019367	-0.029904	-0.043605	-0.074661	-0.004465
47	-0.011673	-0.016683	-0.022494	-0.029308	-0.041082	-0.050526	-0.062224	-0.011673
68	-0.00261	-0.007276	-0.013707	-0.021839	-0.032781	-0.044091	-0.059387	-0.00261
71	-0.0014	-0.003469	-0.016358	-0.021063	-0.035517	-0.049874	-0.069522	-0.0014
74	-0.009778	-0.014807	-0.021665	-0.028729	-0.037168	-0.048574	-0.064419	-0.009778
77	-0.006713	-0.013577	-0.022612	-0.034175	-0.047695	-0.063276	-0.084569	-0.006713
50	-0.004666	-0.00868	-0.015102	-0.024234	-0.039826	-0.059781	-0.087521	-0.004666
53	-0.002809	-0.006625	-0.013236	-0.022779	-0.037079	-0.053135	-0.075062	-0.002809
26	-0.012158	-0.02136	-0.029814	-0.038921	-0.049332	-0.063314	-0.083391	-0.012158
29	-0.007526	-0.012543	-0.020471	-0.034169	-0.059357	-0.091319	-0.122077	-0.007526
2	-0.009321	-0.018168	-0.027605	-0.039689	-0.0577	-0.082515	-0.112672	-0.009321
5	-0.004016	-0.00693	-0.013744	-0.024096	-0.039508	-0.059487	-0.083785	-0.004016
32	-0.010441	-0.016019	-0.023044	-0.03188	-0.043524	-0.061995	-0.090326	-0.010441
35	-0.007325	-0.014851	-0.022428	-0.030807	-0.041946	-0.058003	-0.081276	-0.007325
14	-0.005157	-0.011723	-0.020107	-0.029698	-0.042282	-0.056863	-0.074248	-0.005157
17	-0.004317	-0.010414	-0.017617	-0.026405	-0.038052	-0.05015	-0.065072	-0.004317
8	-0.003061	-0.007615	-0.013376	-0.02525	-0.043086	-0.065102	-0.089378	-0.003061
11	-0.002204	-0.006255	-0.01159	nan	-0.028957	-0.039428	-0.053549	-0.002204
20	-0.001354	-0.009131	-0.018063	-0.032513	-0.050752	-0.069493	-0.089917	-0.001354
23	-0.010386	-0.020574	-0.03447	nan	-0.066683	-0.084739	-0.102408	-0.010386
104	-0.008016	-0.013727	-0.020686	nan	-0.038474	-0.051102	-0.069438	-0.008016
108	-0.009811	-0.016516	-0.024861	-0.03521	-0.046987	-0.060793	-0.076506	-0.009811
62	-0.004167	-0.007975	-0.0138	-0.029445	-0.040745	-0.055143	-0.072754	-0.004167
65	-0.007803	-0.011458	-0.016358	-0.023061	-0.031765	-0.045072	-0.06088	-0.007803
38	-0.012419	-0.020331	-0.032023	-0.04523	-0.064457	-0.092467	-0.119658	-0.012419
41	-0.006262	-0.010025	-0.016042	-0.031112	-0.05015	-0.079005	-0.1067	-0.006262

nan refers to unavailable data

Table 4-4. Stresses at different strains at a matric potential of -33 kPa of sampled sites in Flanders

	Stress (mm/mm) at							
Ring ID	**Strain 15 kPa**	**Strain 29 kPa**	**Strain 57 kPa**	**Strain 113 kPa**	**Strain 224 kPa**	**Strain 447 kPa**	**Strain 895 kPa**	**Strain 1786 kPa**
87	-0.004214	-0.007651	-0.013524	-0.022227	-0.034157	-0.051166	-0.0745	-0.101505
90	-0.001503	-0.006811	-0.013927	-0.022795	-0.035936	-0.053056	-0.074699	-0.098664
93	-0.005047	-0.008046	-0.012106	-0.018809	-0.029214	-0.040075	-0.054577	-0.073686
96	-0.001643	-0.00447	-0.01154	-0.024209	-0.04238	-0.064606	-0.092925	-0.12228
81	-0.006753	-0.014722	-0.02628	-0.04017	-0.057578	-0.076638	-0.098819	-0.122861
84	-0.00462	-0.008985	-0.017377	-0.029919	-0.06004	-0.099949	-0.135949	-0.167419
111	-0.003398	-0.006809	-0.010843	-0.016566	-0.02585	-0.040763	-0.060092	-0.082013
114	-0.007629	-0.014327	-0.025958	-0.045139	-0.071843	-0.104365	-0.139921	-0.178883
117	-0.009651	-0.014234	-0.018634	-0.024799	-0.034093	-0.047991	-0.07084	-0.095933
120	-0.00648	-0.012024	-0.020243	-0.035225	-0.060556	-0.094423	-0.131733	-0.169164
9B	-0.006913	-0.011723	-0.018136	-0.026708	-0.038376	-0.05539	-0.080711	-0.110869
12B	-0.01075	-0.016658	-0.025257	-0.037858	-0.058731	-0.090845	-0.123859	-0.154777
57	-0.005271	-0.008082	-0.0125	-0.018875	-0.027974	-0.041365	-0.059575	-0.079907
60	-0.007465	-0.013798	-0.022222	-0.036264	-0.056748	-0.088359	-0.124887	-0.15797
99	-0.011905	-0.019772	-0.027413	-0.034282	-0.043921	-0.055827	-0.071303	-0.094644
102	-0.003991	-0.007425	-0.012099	-0.021776	-0.030323	-0.041394	-0.055928	-0.075514
45	-0.010975	-0.015654	-0.022679	-0.032764	-0.046763	-0.067937	-0.094578	-0.122629
48	-0.00518	-0.008481	-0.013119	-0.020015	-0.03017	-0.044226	-0.062113	-0.083483
69	-0.008324	-0.013627	-0.020135	-0.028306	-0.038917	-0.051102	-0.065603	-0.082615
72	-0.003995	-0.006773	-0.013808	-0.024184	-0.034417	-0.048118	-0.067277	-0.091931
75	-0.004647	-0.008054	-0.012256	-0.018159	-0.026028	-0.038049	-0.056825	-0.08069
78	-0.003782	-0.008584	-0.015662	-0.024347	-0.034939	-0.048649	-0.066656	-0.090261
51	-0.004618	-0.010125	-0.018875	-0.030561	-0.044688	-0.064809	-0.093674	-0.131526
54	-0.005761	-0.012297	-0.021841	-0.033216	-0.047595	-0.067434	-0.092935	-0.124498
27	-0.008734	-0.018714	-0.026237	-0.034036	-0.042304	-0.055371	-0.073704	-0.098215
30	-0.007927	-0.012192	-0.018263	-0.027496	-0.043953	-0.07456	-0.114249	-0.151402
3	-0.010497	-0.02072	-0.035467	-0.04672	-0.062418	-0.085492	-0.117358	-0.151325
6	-0.013877	-0.020831	-0.028211	-0.036455	-0.046192	-0.06146	-0.086372	-0.115531
33	-0.005902	-0.009467	-0.014342	-0.02131	-0.031244	-0.045972	-0.067383	
36	-0.006121	-0.010436	-0.016357	-0.023795	-0.033908	-0.047742	-0.066633	-0.089671
15	-0.005961	-0.010771	-0.017885	-0.027758	-0.04038	-0.05516	-0.073947	-0.095741
18	-0.005873	-0.010742	-0.017921	-0.026556	-0.037349	-0.050602	-0.066415	-0.084445
9	-0.003879	-0.006768	-0.01114	-0.016805	-0.023596	-0.032621	-0.045372	-0.065232
12	-0.004659	-0.011823	-0.023141	-0.033176	-0.043123	-0.054218	-0.070996	-0.088326
21	-0.010837	-0.019167	-0.0315	-0.044924	-0.060213	-0.092764	-0.120973	-0.150275
24	-0.00625	-0.010737	-0.017358	-0.025539	-0.035536	-0.047114	-0.060863	-0.076768
105	-0.004271	-0.007317	-0.01274	-0.02024	-0.029924	-0.043987	-0.065631	-0.093937
106	-0.005321	-0.009992	-0.017821	-0.029417	-0.045228	-0.066563	-0.092369	-0.12018
63	-0.003953	-0.009433	-0.01656	-0.024535	-0.033266	-0.044836	-0.061113	-0.081372
66	-0.012241	-0.019159	-0.028064	-0.037463	-0.047173	-0.06013	-0.076138	-0.095797
39	-0.013246	-0.019016	-0.026593	-0.036728	-0.052182	-0.074611	-0.101605	-0.127696
42	-0.016403	-0.025162	-0.034067	-0.043556	-0.062331	-0.093659	-0.12567	-0.153076

nan refers to unavailable data

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ACHIEVEMENTS WP 5: TOOL IMPROVEMENT

WP 5 was led by SLU (Johan Arvidsson and Thomas Keller)

Objectives

The objective of WP5 was to refine an existing web-based tool for calculation of soil stresses and the risk for compaction (Terranimo) by

- Including Swedish and Dutch language in Terranimo.
- Including soil data for Belgium, the Netherlands and Sweden
- Including routines for calculation of stresses under rubber tracks (presently Terranimo is only applicable for tyred verhicles).

Achievements

Task 1. Including Swedish and Dutch language in Terranimo.

The content to run the Terranimo model has been translated into both Swedish and Dutch. The new version with the two languages included can be found on the website www.soilcompaction.eu.

Task 2. Including soil data for Belgium, the Netherlands and Sweden

Data for Swedish soils have been included into Terranimo. The most common Swedish classification method for soils have been used, since this is most well known by farmers and advisors. It is based on the clay content, dividing the soil into groups with different contents: <5, 5-15, 15-25, 25-40, 40-60 and >60 % clay. Within each group, a soil with typical texture and bulk density have been chosen (Andersson and Wiklert, 1972). The pedotransfers already included in Terranimo will be used for the Swedish soils. At this stage, only the clay content is used as an input parameter, so this classification is sufficient for the model simulations.

Data for Flemish soils have been included into Terranimo. Soils are classified according to the Belgian soil classification, wherein soils series are defined based on soil texture, soil profile development and drainage. In the Belgian soil classification, designation of textural class is based on the texture of the topsoil only (<30 cm) (Van Ranst and Sys, 2001). Depending on the profile development, subsoil clay content can therefore deviated substantially from that of the topsoil and corresponding to the major textural class. In order to generate 'typical' clay content distributions (as required in Terranimo to predict how PCS varies with depth – see WP4), the 'Aardewerk' database, which contains particle size distribution data of 41789 soil samples in 6886 profiles spread over the Flemish Region, mostly to over 1.5 m depth, was used. For each profile, 'Aardewerk' provides horizon thickness with the associated clay content.
In this project, discretized 1.5-m thick soil profiles were constructed at a 0.01 m resolution, which contained clay, silt, sand, OC and BD data (the latter being derived from the class PTF

of Van Hove, 1969, which uses textural class to estimate BD). In this discretized profile, the particle size distribution data of each layer was stored. Finally, for a set of texture classes (A, E, L, P, S, U, Z) and profile development classes (a, b, B, c, d, e, f, g, h, m, p, q, s, x), the mean, median, standard deviation, minimum, maximum and 25 – 75 percentile values were calculated for every depth of the selected soil profiles. It was concluded that it is most appropriate to aggregate profile development classes into three groups: (1) soils with texture B horizon (argic horizon; Dondeyne et al., 2012): a, B, c, d; (2) soils with non-texture horizon or lacking profile development (cambic, mollic, umbric, brunic, spodic, plaggic, terric; Dondeyne et al., 2012): b, e, f, g, h, m, p, q, s; (3) soils with poorly expressed soil profile development (cambic; Dondeyne et al., 2012): x. As a result, 21 soil types (7 textural classes x 3 profile development classes) were introduced in TerranimoÒ. Users can easily find info on textural class and profile development class for their very field on https://www.dov.vlaanderen.be/portaal/?module=public-bodemverkenner#ModulePage. Per soil type, data was aggregated to 10 cm intervals, and to three major horizons, with thickness depending on the soil type. At this stage, only clay content is used as an input parameter in Terranimo.

Task 3. Including routines for calculation of stresses under rubber tracks (presently Terranimo is only applicable for tyred verhicles).

The main objective in WP5 was to develop a model to calculate stresses under tracks. The work was done in two steps. In the first step, stresses under different vehicles were measured. In the second, a model for stress distribution in the contact area was developed. The model was written in Visual Basic and implemented in an Excel file that is available on http://www.slu.se/sv/institutioner/mark-miljo/forskning/jordbearbetning-och-hydroteknik/verktyg/jordpackning/ . The model will be further validated and refined within the next few months, and then implemented in the online tool Terranimo®. Below, results from stress measurements and model development is presented.

Stress measurements - methods

Soil stresses for tracks and tyres were measured using a method presented by Arvidsson & Andersson (1997). Sensors were installed at different depths in the soil profile from an excavated pit and the soil above the sensors was then subjected to traffic by all the investigated tracks and tyres. Each installation was considered as one replicate (block).

In the autumn 2013, measurements of soil stresses were made with wheeled and tracked tractors at Valstad close to Linköping in Sweden. The tractors were: John Deere 9330 equipped with dual wheels on one side and single wheels on the other side, Case IH Steiger MX 435 with dual wheels, Case Quadtrack 485 with four tracks (Fig. 5-1), CAT Challenger 765 B with two tracks (Fig.5-2) and Valtra T191 with dual wheels. The tyres were inflated with the recommended inflation pressure for a high torque at a speed of 10 km/h. With the Valtra tractor, also a lower inflation pressure of 0.4 bar was used and compared with the recommended of 0.6 bar. Tyre and track dimensions, wheel load and inflation pressure of the tractors are presented in Table 5-1.

Fig 5-1. Tracks of the Case Quadtrack 485.

Fig 5-2. CAT Challenger 765 B.

Table 5-1. Dimensions, wheel and track load and inflation pressure for the tractors at Valstad

	Dimension	Load (kg)	Infl. pressure (bar)
JD dual wheels	650/65 R38	2550 (2000)[1]	0,6
JD single wheel	650/65 R38	4900 (4000)	1,2
Case dual wheels	710/70 R42IF	2650 (1930)	0,4
Valtra 0,4	650/65 R42	1150	0,4
Valtra 0,6	650/65 R42	1250	0,6
Case Quadtrack	185*71 cm	6400 (5430)	0,5[2]
Challenger	237*70 cm	7680	0,4

[1] Values in parenthesis show wheel load of the rear wheel. [2] Values for the tracks are calculated from the weight and the calculated track area. The length given is the distance between the wheel centers.

The CAT Challenger was driven over the sensors in two modes: without load, and pulling an implement. The implement was a 5 m wide Väderstad Top Down, working with discs and tines to a depth of approximately 20 cm, to simulate realistic working conditions in the field.

Measured soil stresses

Examples of stress measurements with the different tractors are shown in Figs. 5-3 - 5-7. For the Case Quadtrack, only the three central supporting rollers could be seen as stress peaks. At 15 cm, the peaks were very sharp, while at 30 cm the stress was more evenly distributed. The stress was evenly distributed between the front and rear of the tracks. This agrees with the study by Arvidsson et al. (2011) for a tractor with four retrofitted tracks which are allowed to rotate around a central axle.

Soil stresses at 15 cm depth for the CAT Challenger is shown in Fig. 5-4 without load and in Fig. 5-5 pulling an implement. Without load, the stress at the rear bearing wheel was very small, but increased when the tractor was pulling an implement. Compared to the study by Keller at al. (2002), soil stress in this study was relatively well distributed along the track. Soil stress for the John Deere with single wheels and the Case with dual wheels is shown in Figs. 5-6 and 5-7. The stress was similar for the front and rear tyres.

Soil stress for all tractors at the different depths is shown in Table 5-2. The maximum soil stress was clearly largest for the John Deere with single wheels. Soil stresses were generally lower for the dual wheels than for the tracks, although differences were in many cases not statistically significant. These results also agree with the previous study by Arvidsson et al. (2011) when comparing retrofitted tracks and tyres on a medium-sized tractor. It can be seen as surprising that the stresses of the Case Quadtrack was relatively low, since most of the load seems to have been concentrated to the three supporting rollers.

The lower inflation pressure of 0.4 compared to 0.6 bars in the dual wheels resulted in lower soil stress at 15 cm depth, although differences were not statistically significant. At 30 and 50 cm depth there were no differences, reflecting the decreasing effect of inflation pressure with depth in the soil profile. Soil stresses at 50 cm depth mainly reflected the difference in total weight for the different tyres and tracks.

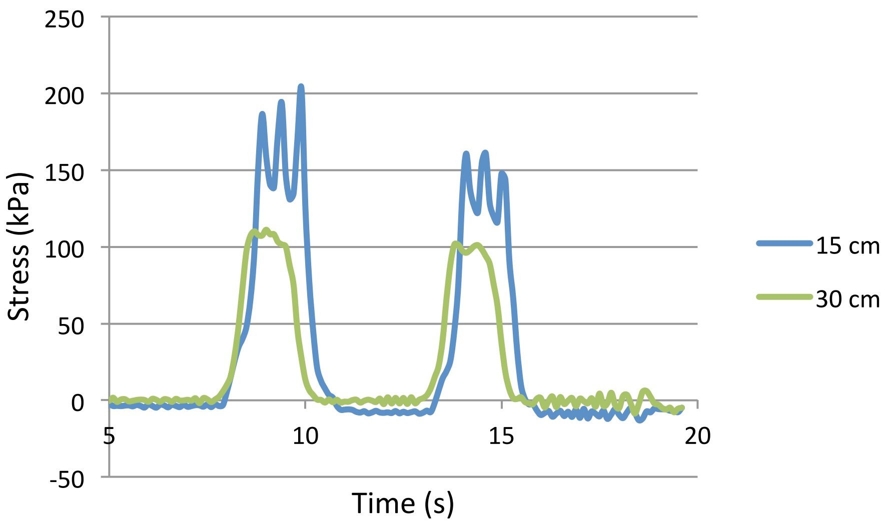

Fig. 5-3. Soil stress under Case Quadtrack.

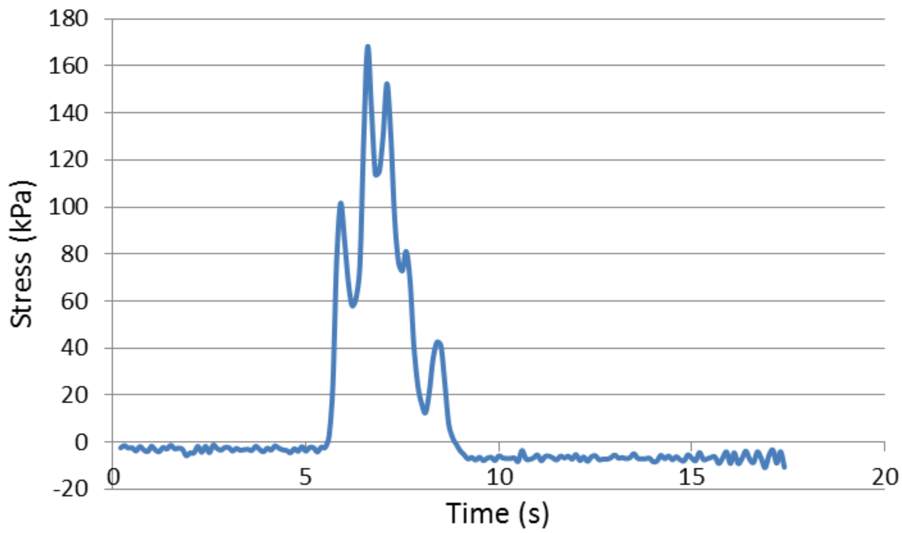

Fig 5-4. Soil stress at 15 cm depth under the CAT Challenger without load.

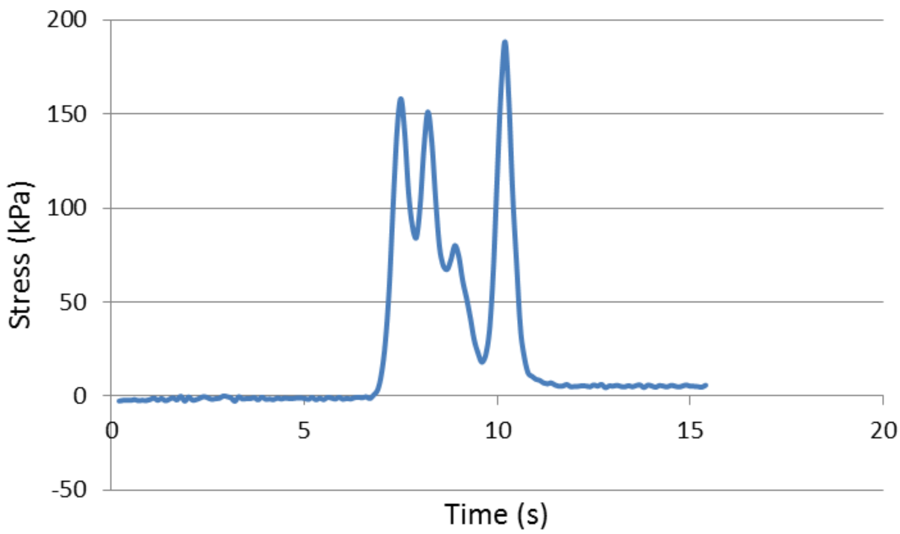

Fig 5-5. Soil stress at 15 cm depth under the CAT Challenger pulling a tillage implement.

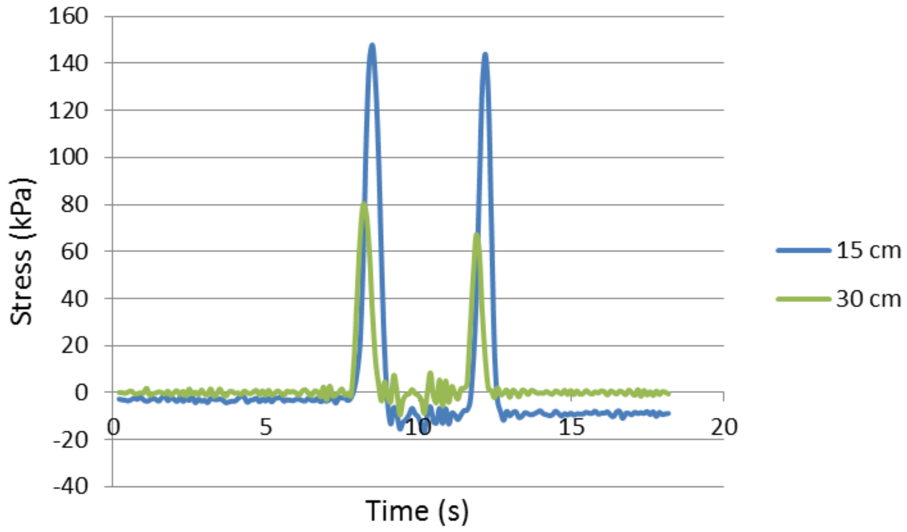

Fig 5-6. Soil stress at 15 and 30 cm depth for dual wheels of the John Deere tractor with an inflation pressure of 0.6 bar.

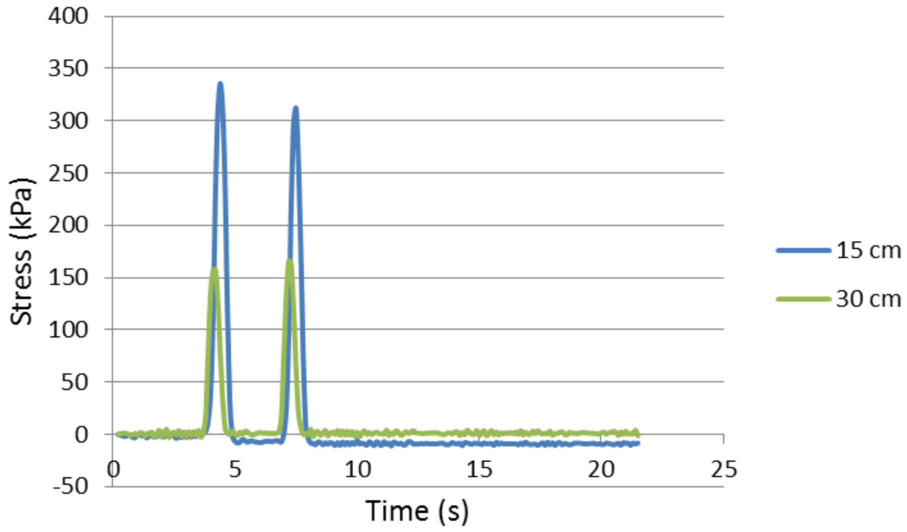

Fig 5-7. Soil stress at 15 and 30 cm depth for the single wheel of the John Deere tractor with an inflation pressure of 1.2 bar.

Table 5-2. Maximum stress at different depths. Values not sharing the same letters are significantly different ($P<0.05$)

	15 cm	30 cm	50 cm
JD dual wheels	147bc	96c	70bc
JD single wheel	296a	215a	151a
Case dual wheels	115cd	98bc	73bc
Valtra 0.4	99cd	51d	36cd
Valtra 0.6	111c	51d	35d
Quadtrack	126bcd	118bc	98b
Challenger no load	161b	117bc	94b
Challenger loaded	159b	142b	80b

A model for prediction of the distribution of vertical stress at the rubber track-soil interface

We developed a model for generation of distribution of vertical stress at the track-soil interface based on our stress measurements. The model requires the input of the track length and width, the load on the track, as well as the number of supporting rollers. The model was written in Visual Basic and implemented in an Excel file that is available on http://www.slu.se/sv/institutioner/mark-miljo/forskning/jordbearbetning-och-hydroteknik/verktyg/jordpackning/ . The model will be further validated and refined within the next few months, and then implemented in the online tool Terranimo®.
The model assumes fixed positions for the wheels (idler and sprocket) and rollers within the track undercarriage. A parabolic stress distribution is assumed over the wheels and rollers in longitudinal direction (driving direction). The 'width' of the parabola is determined by the diameters of the wheels, which are empirical functions of the track length in the current model version. In transversal direction (i.e. perpendicular to the driving direction), the vertical stress is assumed to decrease linearly from the centre of the track to the edge of the track. A decrease in vertical stress from track centre to track edge was observed for all our measurements. The reason for this is not fully clear, but might be related to the complex contact problem (flexible rubber track with stiff wheels and rollers on deformable soil) and the soil deformation below the track. A minimum vertical stress of 5 kPa is assumed at any point of the track contact area (i.e. at any position between the rollers and between the rollers and the wheels).
Figures 5-8 – 5-9 show comparisons of simulated and measured vertical stress along two rubber track undercarriages.

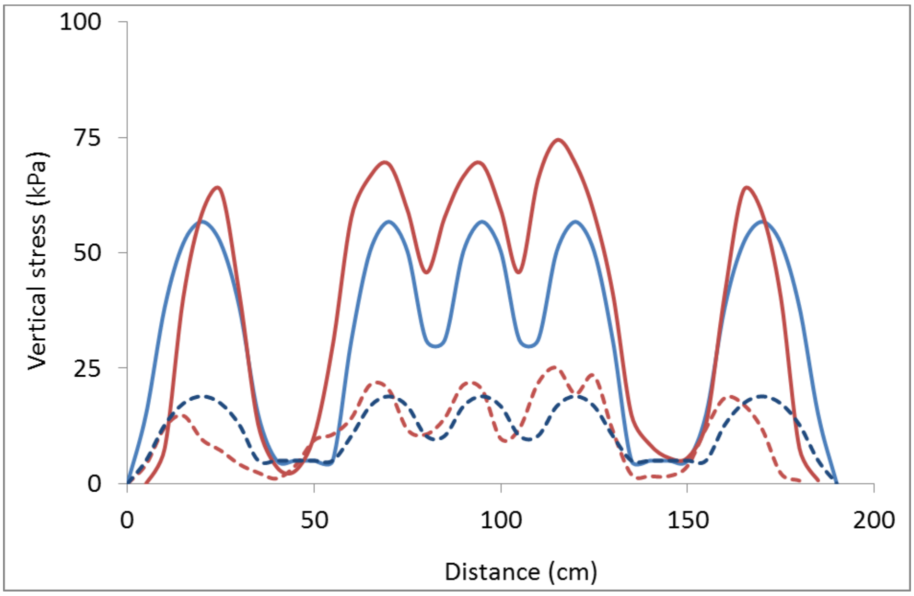

Figure 5-8. Distribution of vertical stress under a rubber quad-track undercarriage (track length: 200 cm, track width: 60 cm; track load: 2350 kg) mounted on a tractor. Red curves: measurements, blue curves: simulations; continuous curves: track centre, and dashed curves: track edge.

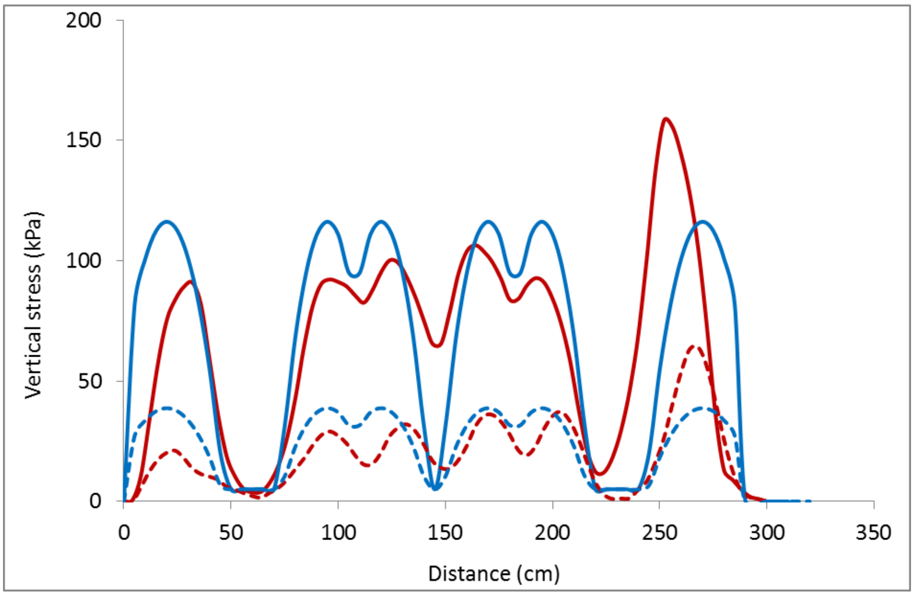

Figure 5-9. Distribution of vertical stress under a rubber track undercarriage (track length: 300 cm, track width: 75 cm; track load: 9000 kg) mounted on a tractor. Red curves: measurements, blue curves: simulations; continuous curves: track centre, and dashed curves: track edge.

It is seen from Figures 5-8 and 5-9 that the simulated stress distribution is uniform in longitudinal direction, while measured distributions are often not perfectly uniform (e.g. higher stress under the front relative to that under the rear wheel or vice versa, or higher or lower stress under the supporting rollers relative to that under the wheels). The model also slightly underestimates the stresses between the rollers and between rollers and wheels.

The generated rubber track-soil contact stresses can then be used as upper stress boundary condition to simulate stress propagation in the soil profile. For example, stress in the soil profile can be calculated using the Söhne (1953) summation procedure based on the work of Boussinesq (1885), e.g. by employing SoilFlex (Keller et al., 2007).

Comparisons of simulations with measurements show that the model for stress at the track-soil interface yields a pragmatic and satisfactory approximation of the real stress distribution, but that the approach tends to underestimate stresses in the soil (Fig 5-10). Reasons for the model underestimations are the more advantageous (i.e. more uniform) stress distribution at the track-soil interface generated by the model as compared with real stress distributions, and the slight underestimation of stress between rollers and between rollers and wheels. These issues are subject to further model refinement. We also note that the representation of a track undercarriage with wheels of unequal diameters (as e.g. found on track undercarriages on tractors) cannot be properly represented with the present model. Further work is therefore needed to refine the model.

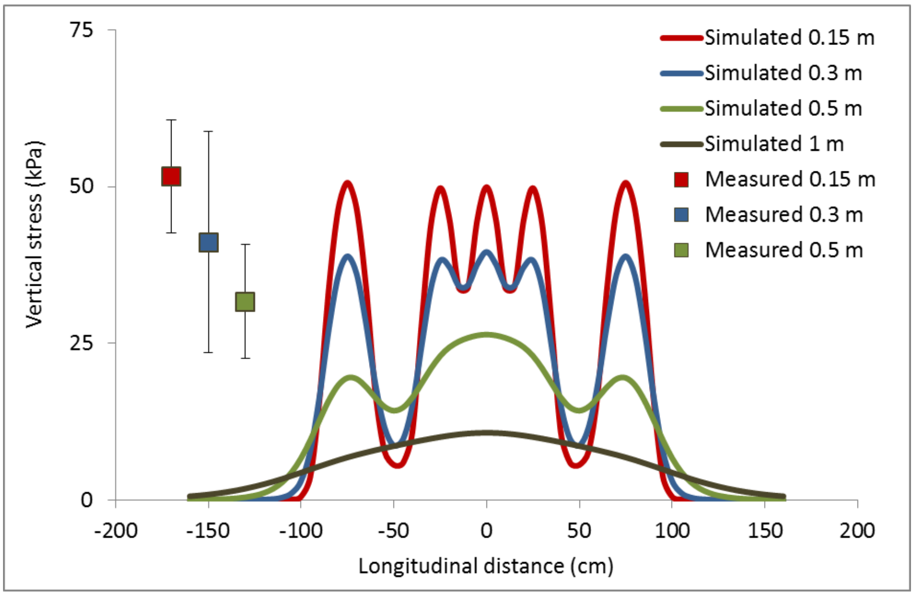

Figure 5-10. Simulated and measured vertical stress under a rubber quad-track undercarriage (track length: 200 cm, track width: 60 cm; track load: 2350 kg) mounted on a tractor. Measurements from Arvidsson et al. (2011).

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ACHIEVEMENT WP 6: AWARENESS RAISING

WP 6 was led by CLM (Anneloes Visser)

Objectives

- To raise awareness among relevant stakeholders in the Netherlands, Belgium and Sweden on the risks related to soil compaction
- To stimulate actors to take measures to reduce risk of soil compaction, through both practice and policy, using the soil compaction tool TERRANIMO

Achievements

On 11th of April results of WP2 (incentives of stakeholders) and WP3 (socio-economic aspects) were presented and discussed by the project partners. Knowledge level and incentives of the stakeholders can be different in each country. In general stakeholders do know causes of soil compaction. They can mention some risks, but do not really experience them in the field. This is one of the important results for the implementation of WP6.

Awareness raising should focus on making effects of soil compaction visible and measurable. During all activities the model Terranimo will be promoted to make soil compaction tangible. A major incentive for farmers to take action is the economic aspect of measures. Because subsoil compaction can be irreversible we will focus on measures to prevent soil compaction rather than loosening the subsoil with heavy machinery. Applicable and especially relatively low cost measures are mentioned in the factsheet and in presentations and workshops. Measures focus on adaptation of machinery (tires, tire pressure) and stabilizing the soil structure (crop rotation, drainage). Link to the factsheet:
http://www.clm.nl/uploads/nieuws-pdfs/CLM-factsheet-bodemverdichting.pdf

The factsheet and the message 'to prevent subsoil compaction' was picked up by several journals and newsletters. See list below. The workshops and presentations generated publicity on local televion as well as on national radio. At least nine events per country took place were attention was paid to subsoil compaction. With these events we reached a large part of the main group of stakeholders: farmers and contractors. In addition the events and presentations reached policy makers, constructors and machinery companies. In Belgium the Flemish government launched the website bodembewust.be where soil compaction will be one of the subjects. In The Netherlands and Sweden we perceived that policy makers come into action by developing communication material (Prisma – phase III in The Netherlands) and intend to stimulate advisors to raise awareness (Sweden). In addition water boards in The Netherlands incorporated soil quality in their action plan 'sustainable agricultural water management'. They are now more aware of the importance of soil structure for water conservation and the importance of avoiding run-off for the water quality.

List of events and publications

Sweden:

- 24/10/13: Arranged course on soil compaction for advisors within Focus on Nutrients. Uppsala.
- 21/11/13: Lecture on soil compaction for farmers. Kalmar.
- 3/12/13: Lecture on soil compaction for advisors. Regional conference, Växjö
- 11/2/14: Workshop on compaction for farmers. Vessigebro, Halland.

- 13/3/14: Arranged seminar on tillage and compaction in cooperation with Väderstadverken. Linköping.
- 25-26/6/14: Demonstration of stress measurements at Borgeby field days. Swedish outdoor exhibition with approximately 20.000 visitors.
- 30/6/14: Radio broadcast: Sveriges Radio
- 1/10/14: Article on soil compaction under tracks and tyres, 4 pages in Lantmannen, the main journal on plant production for Swedish farmers.
- 15/10/14: Lecture on soil compaction for advisors, Skövde.
- 13/11/14: Workshop on soil compaction for farmers, Gamleby
- 26/11/14: Lecture on soil compaction for advisors. Regional conference, Linköping
- 25/12/14. Article in Swiss farmers magazine. Bodenverdichtung: Sind Raupen wirklich besser? Die Grüne, Nr. 25/2014, 8-11.

Belgium:

- 10/03/2014 : information workshop soil compaction 'De Bodem Doorgrond' (Presentation Terranimo)
- 23/06/2014: information workshop organic matter 'Organische stof: Regelgeving en praktijk' (Presentation Terranimo)
- blogs on Inagro website about the subjects of the workshops
- 18/08/2014: class Nationaal Agrarisch Centrum Lichtervelde (Presentation compaction and Terranimo)
- 02/09/2014: class NAC Ieper (Presentation compaction and Terranimo)
- 04/09/2014: information workshop farming without ploughing
- 16/09/2014: information workshop cereals 'graanavond' (Presentation Terranimo)
- 16/09/2014: Class NAC Boezinge (Presentation compaction and Terranimo)
- 18/09/2014: Class NAC Tielt (Presentation compaction and Terranimo)
- 23/09/2014: Class NAC Woumen (Presentation compaction and Terranimo)
- 22/10/2014: Class NAC Ruddervoorde (Presentation compaction and Terranimo)
- 06/10/2014: information workshop green covers (Presentation Terranimo)
- 18/11/2014: Class NAC Ieper (Presentation compaction and Terranimo)
- 02/12/2014: Class NAC Oudenaarde (Presentation compaction and Terranimo)

The Netherlands:

- 5/12/13 Film 'Band versus rups': https://www.youtube.com/watch?v=FIp4inapU-s
- 10/12/13 Two key note presentations on subsoil compaction and prevention at the Congress for farmers and contractors on soil compaction 'Soil to be Farmed' organized by Boerderij, Lunteren.
- 24/12/13 Boerderij: 'Rups is milder voor de bodem dan IF-band'.
- 18/2/14: Lecture on soil compaction for members of CZAV/Covas (suger beet cooperation), Baexem.
- 25/2/14: Lecture on soil compaction for young farmers, Steenwijk.
- 24/4/14: Meeting of regional policy makers (Utrecht) on subsoil compaction.
- 1/7/14: Film 'Research Wageningen University: Track has less impact on the ground than UltraFlex tyre'
    - Dutch: https://www.youtube.com/watch?v=oPJk2ZL4OI8
    - German: https://www.youtube.com/watch?v=eKir4uDBYRE
    - English: https://www.youtube.com/watch?v=k6UJEOUb8U4

- 2/9/14: Film ‘Difference soil compaction using tracks or tyres’ https://www.youtube.com/watch?v=aRrIwOrZpmQ
- 5/9/14: CLM field day on soil (and water) quality with machinery companies and contractors, Vessem. https://www.youtube.com/watch?v=_XlHbVUKINY
- 11/9/14: Field day ‘Trees for the future’. Factsheet (with information on Terranimo) distributed.
- 22/09/14 Agriholland: nieuwsbrief
- 10/10/14 Bodemacademie voor beleid en praktijk: nieuwsbrief
- 11/10/14 Agripress Benelux: online artikel
- 11/10/14 Nieuwe Oogst, ledenblad LTO: online artikel
- 15/10/14: CZAV/ZLTO field day, Colijnsplaat on soil compaction: adjusting machinery and catch crops.
- 13/11/14: Meeting of regional policy makers (Utrecht) on subsoil compaction.
- 26/11/14: Cattle and machinery exhibition, Gorinchem: workshop for farmers, contractors, advisors, and machinery companies on soil compaction and Terranimo.
- 1/12/14: Cattle and machinery exhibition, Venray: workshop for farmers, contractors, advisors, and machinery companies on soil compaction and Terranimo.

Annex 1
WP3: Impact assessment study on soil compaction from farmers' perspective

1 Introduction

Soil compaction is a process of densification in which soil porosity and permeability are reduced due to changes in the spatial arrangement, size and shape of soil grains. As consequence, compaction increases soil strength and soil bulk density (Soane and van Ouwerkerk, 1994; Hamza and Anderson, 2005). Soil compaction can affect both the topsoil, corresponding to the normal annual cultivation depth, and the subsoil, that lies below the A horizon, see figure 1 (Jones et al., 2003). The depth of compaction depends on the cause of compaction; it ranges from 10 to 60 cm in presence of vehicle traffic, and from 5 to 20 cm in presence of livestock trampling (Hamza and Anderson, 2005). Although soil compaction effects can last for years depending on the clay content, topsoil compaction can be remediated through soil tillage and natural loosening processes such as freezing/thawing, drying/wetting and biological activity. The low resilience of the subsoil to compaction makes it difficult and expensive to alleviate. Moreover, since natural loosening processes are reduced in the deep layers and pore functions are not restored after their deterioration, subsoil compaction is considered persistent (Voorhees, 1991; Alakukku, 1996; Radford et al., 2001; Raper, 2005; van den Akker and Hoogland, 2011). Even when alleviation is necessary, attention must be paid not to make the soil more susceptible to re-compaction in the future (Spoor et al., 2003). Under the drive for greater productivity, the risk of subsoil compaction increases with increasing farm size, level of mechanization and equipment size. The increased number of passes and loads carried on agricultural vehicles further contribute to increasing the hazard of soil compaction (Stoate et al., 2001; Jones et al., 2003; Glab, 2007).

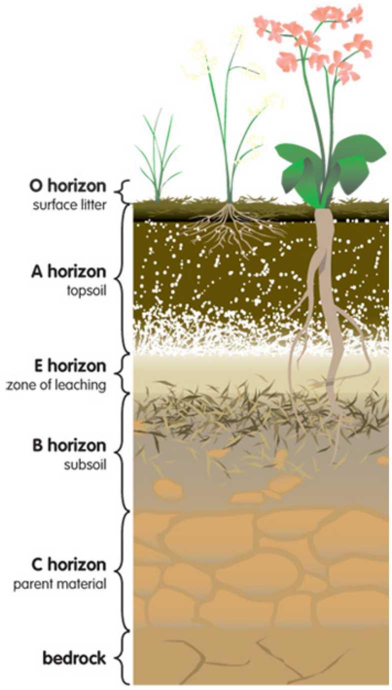


Figure 1. Soil horizons. Source SparkNotes, 2011

Since soil compaction may not show evident marks on the soil surface, it is a type of degradation difficult to identify and locate. It was estimated that 33 million hectares in Europe are affected by soil compaction problems (Stoate et al., 2001; Hamza and Anderson, 2005; Hanse et al., 2011). Although Arvidsson et al. (2000) stated that the effects of soil compaction on crop production and on the environment are difficult and complex to predict, Hamza and Anderson (2005) defined soil compaction as "the most serious environmental problem caused by conventional agriculture". Soil compaction is considered responsible for prejudicing the development of the root system, increasing surface runoff and creating a soil pan within the soil that inhibits drainage, causing water-logging (Stoate et al., 2001; Horn and Fleige, 2009). Water-logging has not only a direct detrimental effect on the crop and yield, but also on trafficability and workability and harvest conditions. Although soil compaction is blamed to lower crop yields by creating unfavourable growing conditions for roots and restricting oxygen, water and nutrients supply, its impact on crop production depends on the crop type, the farming system and the level of mechanization (Glab, 2007). Lipiec and Simota (1994) stated that root crops (especially sugar beet) are the most sensitive crops to over-compaction. Among small-grained cereals, soybeans and peas resulted to be more sensitive to soil compaction than barley and wheat (Lipiec and Simota, 1994). Perennial plants did not always show sensitiveness to soil compaction (Glab, 2007).

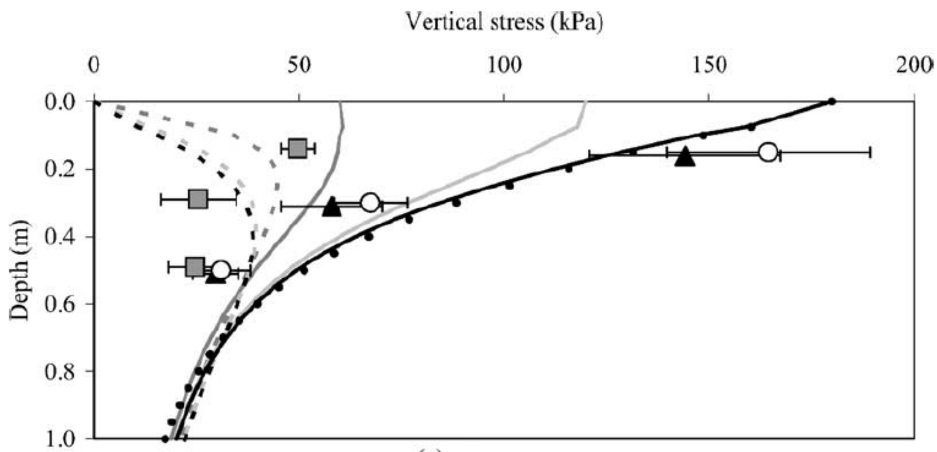
This report aims to provide an overview of farmers' awareness on soil compaction on arable land in Belgium, Holland and Sweden. After an introduction to the causes of soil compaction and the susceptibility of soil to compaction, results coming from farmers' interviews are presented. Farmers awareness on soil compaction is discussed as well as the environmental and economic impacts of soil compaction as perceived by the interviewed. Additionally, this study provides an overview of the measures against soil compaction currently taken by the interviewed as well as of the factors hindering them to take additional measures. As the concern of European policymakers on soil compaction has raised in the last two decades because of its economic, social and environmental impacts (Stoate et al., 2001; Hamza and Anderson, 2005; Hanse et al., 2011), this study may help to develop European policies for soil quality preservation.

- 1.1 Soil susceptibility to compaction

Soil is composed of water, air and mineral components. When vehicle traffic occurs, the mineral components are pressed closer together and the volume available for air and water is reduced (Raper, 2005). To know the maximum mechanical load capacity of a soil helps avoiding soil compaction especially in the subsoil (Horn and Fleige, 2009; Rucknagel et al., 2013). "The maximum major principal stress that a soil horizon (and in the sum the whole profile, respectively) can withstand against any applied external vehicle stress" is called "precompression stress" (Pc) (European Commission, 2012). Soil bulk density, cone index and saturated hydraulic conductivity (Ks) can be used as indicators of soil compaction (Raper, 2005; Hanse et al., 2011). Raper (2005) defined soil bulk density as a measure of the mass per unit volume that varies with the soil type. The bulk density value ranges from 1.20 to 1.80 Mg/m^3 in sandy and sandy loam soils, and from 1.00 to 1.60 Mg/m^3 in clay, clay loam and silty loam soils. By altering the spatial arrangement, size and shape of clods and aggregates, compaction increases soil bulk density and soil strength (Hamza and Anderson, 2005; Raper, 2005; Usaborisut and Niyamapa, 2010). Severely trafficked soils may have bulk density values near 2.00 Mg/m^3 (Raper, 2005). In some cases, a high bulk density does not represent compaction when this concerns the high density of individual soil units (Voorhees, 1991). Soil strength reflects the resistance of the soil to root penetration and it is commonly assessed by the cone index. The cone index is the force per unit basal area required to push a penetrometer cone into the soil (Herrick and Jones, 2002; Hamza and Anderson, 2005). It has two main advantages over bulk density: measurements can be 1) automated and 2) easily compared across soil types. Nonetheless cone index measurements are highly sensitive to the soil moisture content (Raper, 2005). By representing the ease with which water can move through the soil, the soil water infiltration rate can be also used to monitor soil compaction especially in the topsoil (Hamza and Anderson, 2005).

Soil susceptibility to compaction depends on:

- natural predisposition of the soil to compaction: soil texture, nature of the clay fraction and associated ions, bulk density, organic matter content and structure, type, size and degree of the ped development;
- soil moisture content (vol%) and the soil moisture potential (kPa);
- farming system;
- type of machineries used on the field (Fig. 2).



(a)

Figure 2. Measured vertical stress below the single wheel centre (white circles), the centre of a dual wheel (black triangles) and the centre of the dual wheel configuration (grey squares). Single wheel load is 22 kN; dual wheel loads are 2 x 22 kN; all tire inflation pressures are 60 kPa. Calculated vertical stress below the single wheel centre (black dotted curve), the centre of a dual wheel (black solid curve) and the centre of the dual wheel configuration (dashed curve) using uniform (dark grey), parabolic (light grey) and linear (the stress declines linearly from a maximum at the contact area centre to zero at the contact area edge) contact stress distribution (black). Note that the stress below the single wheel and below the centre of a dual wheel almost coincidences, and the dots 'disappeared'. The error bars indicate ± S.E., n = 4. (Keller and Arvidsson, 2004)

The propagation of the soil stresses varies with the soil texture. By literature (Hamza and Anderson, 2005) is known that the dominant penetration direction of the stresses is vertical in soils with coarse texture and multidirectional in soils with finer texture. While sandy soils are characterized by a gradual distribution of macro and micropores, there is a large discrepancy between the size of macropores and micropores in clay soils. As consequence, small density changes are needed to close the macropores in clay soils, which are more susceptible to soil compaction than other soil types (Botta et al., 2006; Kingwell and Fuchsbichler, 2011). Since organic matter retains soil water, stabilizes soil structure, and improves the resilience capacity of soils, it decreases the risk of soil degradation. Based on that, the lower the organic matter content, the more susceptible a soil is to persistent compaction.

Porosity, permeability and nature of the macropores are influenced by soil evolution (pedogenesis). Although the presence of a strong soil layer below the cultivation depth ("plough pan" or "hard pan") is in most cases the bottleneck for root growth and infiltration of water, it helps preventing the occurrence of deeper subsoil compaction by spreading compaction stresses. Loosened soil is very vulnerable for recompaction, resulting in a homogeneous compacted layer with strongly reduced soil physical qualities (Kooistra et al., 1984; Kooistra and Boersma, 1994). Therefore the plough pan should not be disrupted if it does not limit root development, gas exchange and drainage. Recently tilled soils and soils near to field capacity have no inherent strength and are more subjected to soil compaction than untilled and dry soils. Hamza and Anderson (2005) stated that at low soil water content high loads do not deform the soil more than 2 cm in depth. The application of too heavy loads on wet soil does not result in further soil compaction once all air is pressed out and the soil is saturated. Then the saturated soil becomes plastic and incompressible like a fluid. This results in deep ruts and complete destruction of soil structure. The use of high weight large tractors, grain carts, manure spreaders, and combines promotes soil compaction as well as the use of small tractors and other field equipment repeatedly passing in the same location (Jones et al., 2003; Spoor et al., 2003; Hamza and Anderson, 2005; Raper, 2005; Birkas et al., 2009;). According to Jones et al. (2003), "a highly susceptibility soil is one that has properties that make it likely to become compact given the appropriate compaction forces and the right moisture status".

1.2 Causes of soil compaction

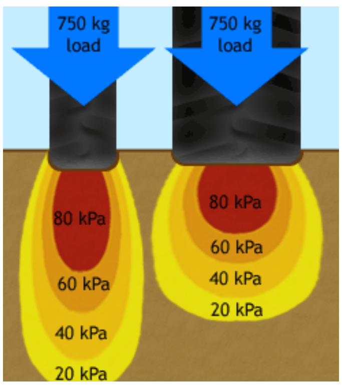
Depending on the land use, soil compaction can be caused by vehicle traffic, intensive cropping, short crop rotation plans, livestock grazing/trampling, inappropriate land management, climate change, water-logging and drought occurrence (Hamza and Anderson, 2005; Birkas et al 2009).

Vehicle traffic is the main cause of soil compaction on arable land. Its effects on soil depend on soil mechanical strength, structure of the tilled layer at wheeling and soil moisture content and loading. The latter is related to axle load, tyre dimensions and velocity, and soil-tyre interaction. The load imposed to the soil by vehicle tyres or tracks causes vertical and horizontal deformations that reduce porosity and connectivity while increasing mechanical resistance to root exploration. In highly mechanized systems, the tractors used for crop establishment have an axle load ranging from 50 kN (kiloNewton) to 100 kN. The axle load of harvesting equipment usually ranges from 150 kN upwards (Hamza and Anderson, 2005; Tullberg, 2010). By literature (Hamza and Anderson, 2005) is known that topsoil compaction is caused by the ground pressure, that corresponds to the axle load divided by the surface area of contact. The causes of subsoil compaction differ with the soil depth. While compaction of the upper subsoil is caused by the combined effect of ground pressure and axle load, compaction of the lower subsoil is considered entirely caused by the axle load. Because of the relationship existing between wheel load and tyre pressure, low tyre pressures lower the risk for soil deformation in presence of heavy loads. Soil damage increases when machineries are characterized by high tyre inflation pressures and small width (Radford et al., 2001). Harvesting and manuring equipment can have wheel loads up to 120 kN. These high wheel loads require inflation pressures around 200 kPa (2 bar), even if the widest tyres available are used. This results in compaction up to one meter depth (Arvidsson et al., 2001, 2002). Another main cause for subsoil compaction is driving in the open furrow during ploughing directly on the top of the subsoil.

According to Hamza and Anderson (2005), soil is usually over-compacted along the wheel tracks and on the turning strips at field edges. Soil compaction (especially subsoil compaction) has been proved to decrease with increasing distance from the wheel tracks. Radford et al. (2001) stated that the greatest amount of soil compaction occurs with the first pass of machinery. However, the soil compaction risk increases with increasing traffic intensity (number of passes). Hamza and Anderson (2005) claimed that the advantages to prevent topsoil compaction deriving from the use of a light tractor are lost after 10 passes. During one cropping cycle, the ground area trafficked by the tyres of heavy machineries is more than 30% under zero tillage, 60% under minimum tillage (2-3 passes) and more than 100% under conventional tillage; we thus have to notice that the trafficked field area is greater when wide tyres are used. Although soil susceptibility to compaction increases with increasing soil water content, tillage and harvest operations are usually carried out when soil moisture is not optimal for wheel traffic (Radford et al., 2001).

In order to better understand the causes of soil compaction, also in relation to economic factors, it is possible to make a distinction between tillage-induced and traffic-induced soil compaction. In this context, tillage is the main cause of soil compaction under unfavourable economic conditions as traffic (number of passes) tries to be limited because of its cost (Birkas et al 2009). Considering that it is impossible to practice agriculture without using machineries and that the impact of vehicle traffic on soil mainly depends on tyre inflation pressure, tyre width and soil moisture content at the time of the field operations, it is possible to minimize the effects of vehicle traffic on crop production by:

- reducing soil susceptibility to compaction: conduct field operations and allow grazing at the time soil has greater strength (i.e. when the soil moisture is less than 60% of field capacity), reduce tillage to minimize soil disturbance, increase the amount of organic matter into the soil, etc.;



- controlling the traffic on the field: reduce the number of passes by farm machinery, use of a controlled traffic system, reduce the intensity and frequency of grazing, etc.;
- reducing the size of the vehicles, which also means to reduce their weight and axle load;
- increasing the ground contact area: increase tyre width and decrease tyre inflation pressure, see figure 3;
- subsoiling/deep ripping the soil in presence of compacted layers.

In addition, the inclusion in the crop rotation plan of crops and pasture plants with strong tap roots able to penetrate soils characterized by high bulk densities can help preventing and alleviating soil compaction problems (Hamza and Anderson, 2005; Raper, 2005; Tullerg, 2010; Hanse et al., 2011).

Figure 2. Distribution of soil stresses within the soil at different tyre widths. Source Missouri University, 2013

- 1.3 Environmental impacts of soil compaction

The environmental impacts of soil compaction are mainly related to changes in soil structure, soil bulk density, soil strength, soil gas diffusivity and soil hydraulic conductivity. Even if in the short-term topsoil compaction has more impact than subsoil compaction, the latter is considered the most serious environmental threat. Topsoil and subsoil compaction are considered responsible for reducing the water infiltration capacity of the soil, for affecting the distribution of sources and sinks of water in the soil system by changing the surface configuration, and for leading to **soil erosion, flooding and water-logging** (Horton et al., 1994; Lipiec et al., 2003; Raper, 2005; van den Akker and Hoogland, 2011; Gasso et al., 2013). Compaction stress changes the pore space geometry leading to the creation of a tortuous soil pore system. Moreover, the presence of excessive soil water leads to the complete homogenisation of the soil structure (Horton et al., 1994; Horn and Rostek, 2000). The deterioration of the soil structure can accelerate effective runoff and increase lateral seepage of excess water over and through the soil. On one hand nutrients and agrochemicals can be washed away and pollute surface waters because of the poor development of the root system and the limited ability of soil microorganisms to decompose agrochemicals. On the other hand, the reduction in soil macropore network caused by soil compaction can reduce the risk of **nutrients and agrochemicals leaching**. The risk for **water pollution and eutrophication** is also increased by the decreased capability of the soil to act as a buffer and filter for pollutants. Moreover, soil compaction increases **greenhouse gases (GHGs) emission** because the poor soil gas diffusivity creates anaerobic conditions. The release of carbon dioxide (CO_2) in the atmosphere through soil respiration is lower in compacted soils than in others also because of reductions in root and microbial respiration. While under aerobic conditions agricultural soils function as sinks of methane (CH_4) by absorbing and oxidising it, under anaerobic conditions they function as sources of CH_4. Although the reduced soil gas diffusivity increases the retention time of nitrous oxide (N_2O) in the soil, the production of N_2O through denitrification is higher in compacted soils than in uncompacted soils. Ammonia (NH_3) coming from fertilization can acidify the ecosystem by reacting with nitrates and sulphate. In presence of soil compaction, the reduced soil hydraulic conductivity limits NH_3 infiltration into the soil and increases the emission of this GHG in the atmosphere (van den Akker and Hoogland, 2011; Gasso et al., 2013).

The influence of soil compaction on the atmosphere and on soil and water resources is shown in figure 4.

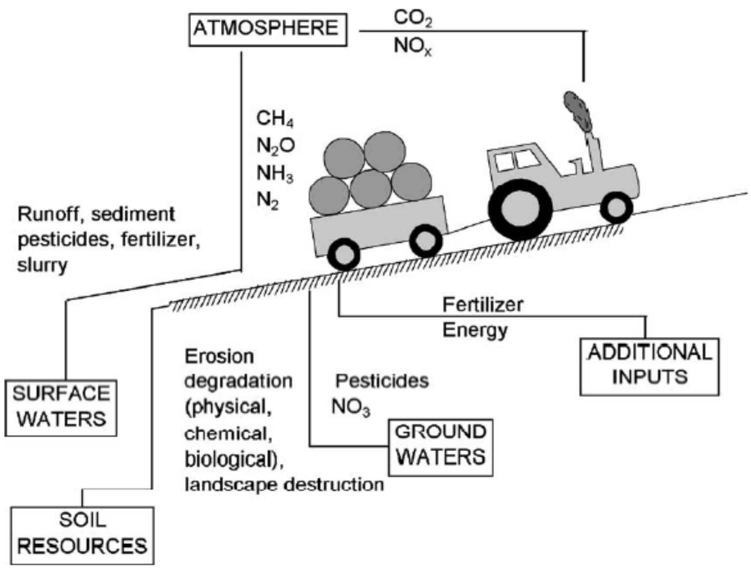


Figure 3. Influence of soil compaction on the atmosphere, and on soil and water resources (Lipiec et al., 2003)

As soil strength and soil bulk density increase, the ability of soil to hold and conduct water, nutrients and air decreases. Moreover, water flow from deeper soil layers toward the root zone is impeded and soil resistance to root penetration (mechanical impedance) is increased. As consequence, the **under and above ground plant growth and development** are affected (Raper, 2005; Birkas et al., 2009; Usaborisut and Niyamapa, 2010). According to Horton et al. (1994) and Glab (2007), the development of the root system depends on the degree of compaction of the soil. Usually, plants growing on a compact soil concentrate their root systems in the upper layer, which is supposed to have a lower bulk density. In this way, roots decrease in length and depth. In presence of strongly compacted soils, root distribution is heterogeneous because of the tendency to grow in cracks, fissures and bio-pores (macropores formed by earthworms) (Glab, 2007). According to Hamza and Anderson (2005) and Glab (2007), the shape of the root system does not necessarily affect the aboveground growth of the plant nor the yield. Botta et al. (2006) and Birkas et al. (2009) stated that plants growing on compacted soils are less resistant to pests, pathogens and weeds, and more sensitive to droughts. Although soil compaction usually does not change soil water properties below 30 cm depth, it reduces soil moisture near the soil surface (Horton et al., 1994; Raper, 2005). Some studies demonstrated that furrow compaction can be used to improve the use of irrigation water (Raper, 2005). Soil water regimes influence the movement of nutrients, fertilisers and agrochemicals into the soil (Horton et al., 1994). Nutrient uptake by plant roots depends on the degree of soil compaction and on the nutrients and water supply. Above a certain bulk density value, the increased tortuosity of soil pores and the reduced ability of roots to penetrate the soil, result in decreasing the diffusion coefficient of ions (Lipiec and Stepniewski, 1995). By literature (Lipiec and Stepniewski, 1995) is known that the mass flow is an important mechanism in the transport of N, Ca, Mg, S, B, Cu, Zn, Fe and Cl, as diffusion is in the transport of P and K. Nutrients transformation and uptake is also related to the soil aeration status. Sulphur and sulphate reduction, P availability, and redox transformations of N, Mn and Fe, depend on oxygen availability and thus on the presence of aerobic or anaerobic conditions within the soil. In most cases, soil compaction reduces nutrient uptake and has great impact especially on nitrogen balance. Nitrogen uptake showed to be strongly reduced by subsoil compaction. The high rate of nutrients lost because of soil compaction, leads to use even more artificial inputs (fertilizers) on compacted soils to overcome crop yield losses (Lipiec and Stepniewski, 1995; Alakukku 2000).

The effect of compaction on soil properties and processes, soil quality, crop yield and the environment, is shown in figure 5 (Lipiec et al., 2003).

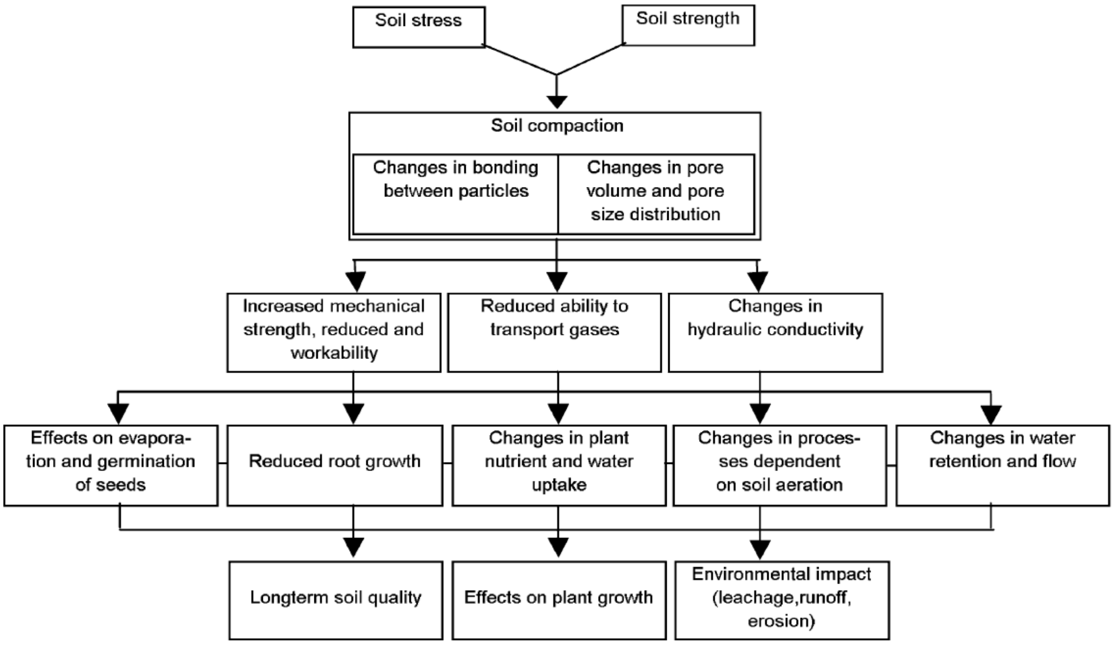


Figure 4. Effect of compaction on soil properties and processes, soil quality, crop yield and the environment (Lipiec et al., 2003)

- 1.4 Social and economic impacts of soil compaction

To estimate the economic impacts of soil compaction, information on crop yield, long-term soil productivity and environmental impacts are required (Arvidsson et al., 2000). By literature (Lipiec and Simota, 1994; Soane and van Ouwerkerk, 1994; Gasso et al., 2013) is known that soil compaction **reduces the quantity and the quality of the crop yield** by reducing soil aeration, and limiting the development of the root system and its ability to uptake nutrients and water. Soil compaction degree, soil type and soil susceptibility to compaction are not the only factors responsible for reducing crop yield. Lipiec and Simota (1994) stated that the impact of a certain degree of compactness on crop production is highly dependent on the site conditions. Weather conditions and availability of nutrients and water in soil are indeed important factors to determine the final yield of a crop. Raper (2005) stated that soil compaction may slightly increase crop yield at some location in relation to the climatic conditions. Moreover, yields lower than the potential are obtained if the length of the growing period is short compared to the crop requirements (Boone and Veen, 1994). In addition to soil-plant-climate interactions, the final crop yield is affected by the stage of growth of the plant, the crop variety, the crop rotation plan and the farming system (i.e. type of vehicle traffic) (Lipiec and Simota, 1994; Arvidsson et al., 2000; Raper, 2005; Usaborisut and Niyamapa, 2010).

Crop establishment and growth are often reduced in trafficked fields where plants' response to the inputs applied (i.e. fertilizers, agrochemicals, quantity of seeds, etc.) is lower than the expected (Soane and van Ouwerkerk, 1994). Although it is difficult to make a distinction between the effects of topsoil compaction and the effects of subsoil compaction on crop yield, Arvidsson et al. (2000) and Voorhees (2000) stated that while topsoil compaction is responsible for reducing the yield during the first year after the application of a load, subsoil compaction affects crop yield for several years. In presence of vehicle traffic, the numbers of passes influences the final crop yield (Botta et al., 2006). Referring to other studies, Raper (2005) stated that in presence of severe (1.82 Mg/m^3) and moderate compaction (1.76 Mg/m^3) maize yield was reduced by 50 and 25%, respectively. This trend can be related to the fact that wheel traffic reduces maize root growth in the upper 30 cm of the soil when compared to untrafficked areas. According to Botta et al. (2006), even though maize yield significantly changes when a machinery passes 0-10 times, its change is negligible with more than 15-20 passes. increase in bulk density. The effects of excessive compaction on yield quality are, for instance: lower sugar content in sugar beet, lower specific weight of strawberry fruit and higher proportion of shorter and deformed roots in carrots. In addition, potatoes marketability decreases as tubers dimensions are < 35 mm (Lipiec and Simota, 1994). The growth of root and bulb crops such as potatoes and sugar beet, two important crops in North-West Europe, is strongly dependent on the structural conditions of the soil. By literature (van Loon and Bouma, 1978; Stalham et al., 2007) is known that soil compaction decreases **potatoes yield** while increasing the percentage of deformed tubers. Depending on the soil compaction degree, the percentage of deformed tubers ranged from 1.5% in loose, not compacted soils with surface irrigation, to 58% in presence of strongly compacted topsoil (van Loon and Bouma, 1978). Topsoil compaction mainly affects plant growth in the first 60 days after emergence by slowing roots and foliage growth. By creating a plow-pan within the soil, subsoil compaction inhibits vertical root elongation and thus slows down foliage growth. Although a slight compression is required for the establishment of **sugar beet** plants, this crop is highly susceptible to both topsoil and subsoil compaction because of the need for high-quality seedbeds and deep soil layers in which roots can elongate. Hanse et al. (2011) established a damage threshold of 10% (v/v) for the topsoil air-filled porosity at field capacity (AP), and 0.10 m day^{-1} for the saturated hydraulic conductivity (Ks) of the subsoil. Yield depressions were found below these damage thresholds. Arvidsson et al. (2000) and Hanse et al. (2011) stated that subsoil compaction showed to have a great impact on the long-term productivity and value of arable land, and that its long lasting effects affect all the crops in rotation. Considering that different crops are differently susceptible to compaction, Hanse et al. (2011) estimated an **average yearly yield loss of 11.4%.** Nonetheless, it is important to keep into consideration that crop response to compaction is also affected by the farming technique and the tillage depth (Hanse et al., 2011). Vermeulen and Klooster (1992), stated that under low and zero ground pressure, the yield of root crops increased by 4% and 9%, respectively, when compared to the yield from high ground pressure treatments. Otherwise, the yield of wheat crop did not show significant differences under different ground pressure treatments. Andersen et al. (2013) stated that on loamy sand soils different compaction treatments result in a reduction of the yield of ca. 8-9% for wheat crop. These reductions were due the impairment of root penetration and to drought stress despite the almost sufficient precipitation. Alblas et al. (1994) showed that due to subsoil compaction the average yield of silage maize was 15% and 4% lower when an axle load of 10 Mg and 5 Mg was applied, respectively. Subsoil compaction may not result in a decrease of the yield every year because the changing climatic conditions affect the moisture content of the soil (Voorhees, 2000). Botta et al. (2013) claimed that clayey and loamy soils trafficked for five years with loads of 144 and 177.9 kN showed an increased cone index value that resulted in a reduction of the maize yield. Since the degree of compactness of a soil (cone index) is independent from the soil texture, it can be used to compare the effects of compaction on crop production in different soils (Lipiec and Simota, 1994).

In presence of yield losses caused by soil compaction, an economic assessment study should be carried out to see if the adoption of preventive and restoration measures is worth. Indeed, Voorhees (1991) claimed that changing farming system (i.e. adopting no-till or reduced tillage practices) is not always profitable and that, even when the reduction in crop yield is statistically significant to be of practical concern to the farmer, it may still not be significant when considering the total scheme of crop production and land management. More important is to understand if yield losses are effectively caused by soil compaction rather than from other causes. It would save time, energy and money to farmers, which could focus their efforts on counteracting the real cause(s) of yield depression (Voorhees, 1991). **Ploughing and subsoiling costs** should be taken into consideration when analysing the economic impacts of soil compaction, as well as the use of special machineries developed to reduce the axle load and increase the tyre-soil contact surface (Hakansson and Medvedev, 1995). Moreover, social-economic impacts result from the environmental impacts of soil compaction. Nutrients and agrochemicals leaching imply the **use of additional inputs** and thus increase farming costs. Flooding, erosion and GHGs emissions have a direct impact on the society, which has to pay for them as a whole (Hakansson and Medvedev, 1995; Arvidsson et al., 2000; Gasso et al., 2013). By providing farmers with an economic reason to prevent and counteract soil compaction, compaction problems would be most likely reduced.

Moreover, the so far slowed down development of new machineries and technologies (i.e. biotechnologies) would be fostered (Voorhees, 1991; Arvidsson et al., 2000).

The adoption of a controlled traffic system (CTF) can limit soil damage and traffic-induced compaction across the field by restricting the use of all the machineries to permanently defined traffic lanes (tramlines) ensuring field drainage. It potentially decreases soil erosion, water logging, runoff and leaching of nutrients and agrochemicals. CTF can also preserve or even improve soil structure, increase water infiltration, increase soil water moisture and result in crops less sensitive to droughts. Based on statements by growers that moved from a random traffic system (RTF) to CTF, it significantly increases the quality and the quantity of the yield by increasing the amount of plant available water and facilitating root growth (Hamza and Anderson, 2005; Tullberg, 2010; Kingwell and Fuchsbichler, 2011; Gasso et al., 2013). CTF increased yields of about 4-14% in root and bulb crop systems with sugar beet, potatoes and onions as main crop types (Gasso et al., 2013). Across different soil types, farmers practicing CTF had an average 10% increase in wheat, barley and canola yields. Moreover, the adoption of a controlled traffic system allows farmers to employ less skilled drivers at lower cost to conduct the field operations (Tullberg, 2010; Kingwell and Fuchsbichler, 2011). Kingwell and Fuchsbichler (2011) stated that spraying costs can be reduced by up to 10% because the use of aid-navigation and auto-steering systems diminishes overlaps when inputs such as fertilizers, seeds and agrochemicals are applied to the fields. Although the non-productive in-field travelled distance is 24-47% higher in CTF than in RTF, the in-field energy usage is reduced in CTF mainly because less force is required for primary tillage and there is less or no need for compaction-removal tillage. Regardless of the farming system, energy requirements depend on the tillage depth, soil type, degree of compaction, soil moisture at the time of tilling and type of machinery used. The benefits from CTF are highly dependent on the soil type and are greater in clay soils than in sandy soils (Hamza and Anderson, 2005; Kingwell and Fuchsbichler, 2011; Gasso et al., 2013). The diffusion of CTF as farming system is slowed down by the lack on the market of compatible equipment track, tyre and working width (Tullberg, 2010).

2 Impact assessment study

This report is an impact assessment study on soil compaction from the farmers' perspective. It aims to assess the environmental and socio-economic impacts of soil compaction on arable land in Belgium, Holland and Sweden as perceived by the farmers interviewed. It also provides information on farmers' awareness on soil compaction as well as on the soil compaction mitigation measures currently taken by the interviewed.

2.1 Research approach

This study focuses on arable land only. It relies on data collected by interviewing farmers online and at an agricultural fair during the months of November and December 2013. Online surveys based on closed questions were conducted by using the online program Kwiksurveys.com. The designed questionnaire was first tested on a few farmers in the Netherlands and then translated and sent to farmers in Belgium and Sweden. Among the 93 farmers interviewed, 32 were Belgian, 28 were Dutch and 33 were Swedish. Farmers were asked to answer questions on their farming system as well as on the presence of soil compaction on their fields. Additionally, they were asked to provide information on the economic and environmental impacts of soil compaction. The questionnaire also researched the soil compaction mitigation measures currently taken by the interviewees as well as the factors hindering them from adopting mitigation measures. Data were analysed with the software Excel making a distinction between answers provided by farmers declaring to have soil compaction problems and farmers declaring not to have soil compaction on their fields. Results are presented mostly considering the three countries as a whole. The analysis refers to the country level only when the difference in the answers provided by farmers in the different countries is large.

2.2 Farmers' awareness on soil compaction

To assess the presence of soil compaction from the farmers' perspectives, we first asked the farmers for the presence of soil compaction on their fields. By looking at all 93 farmers, the difference in percentage between farmers declaring to have soil compaction and farmers declaring not to have soil compaction was small (46% and 54%, respectively). Nevertheless, the percentage of farmers with and without soil compaction was considerably different at the country level. In Belgium, the Netherlands and Sweden, the percentage of farmers with soil compaction problems was 34.4%, 53.6% and 72.7%, respectively.

Because farmers' opinion on soil compaction is subjective, we asked the farmers to quantify soil compactness on a scale of 0 to 10 with 0 referring to no soil compactness and with 10 referring to high soil compactness. Farmers with soil compaction problems were expected to assess soil compactness as higher than 5 and farmers without soil compaction problems were expected to assess soil compactness as lower than 5. On average, all farmers with soil compaction problems assessed soil compactness around 4,5. With respect to farmers without soil compaction problems, Dutch and Belgium farmers assessed soil compactness at an average level of 3,5 and Swedish farmers assessed it at an average level of 1,5 (Table 1). This implies that Swedish farmers are more aware of soil compaction than farmers in the other two countries. In general, it is quite remarkable that even farmers declaring to have soil compaction problems did not give very high ratings when asked to assess soil compaction on a scale of 0 to 10. One reason could be that soil compaction occurs but only locally (not leading to significant problems); another reason could be that "scaling" soil compaction problems is difficult for farmers, and that a scale of 5-6 is already considered quite high.

Table 1. Average level (on a scale of 0 to 10) of soil compactness on the fields of the farmers interviewed in Belgium, the Netherlands and Sweden.

	Average level of soil compactness	
Country	**Farmers declaring to have soil compaction**	**Farmers declaring not to have soil compaction**
Belgium	4,5	3,3
The Netherlands	4,3	3,7
Sweden	4,5	1,5

As soil compaction can be distinguished in **topsoil and subsoil compaction**, farmers were asked to express an opinion on the importance of topsoil and subsoil compaction in agricultural production (figure 6 and 7). On a scale of 0 to 10 with 0 referring to low importance and 10 referring to high importance. Dutch farmers were the ones giving more importance to the presence of both topsoil and subsoil compaction with respect to how it affects agricultural production. Although most of the Swedish farmers declared to have soil compaction problems on the fields, the majority of them did not think that the yield is affected by topsoil and subsoil compaction. Belgium farmers mainly assigned low importance to the presence of topsoil compaction in agricultural production. Nevertheless, their opinion on the importance subsoil compaction in agricultural production did not show a clear trend.

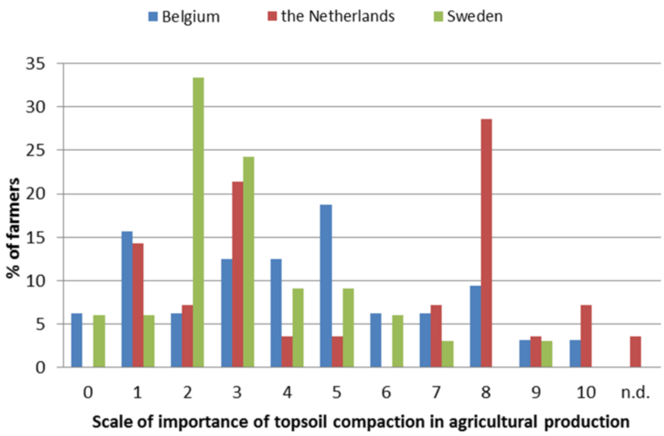


Figure 6. To what extent topsoil compaction affects agricultural production according to farmers (on a scale of 0 to 10)

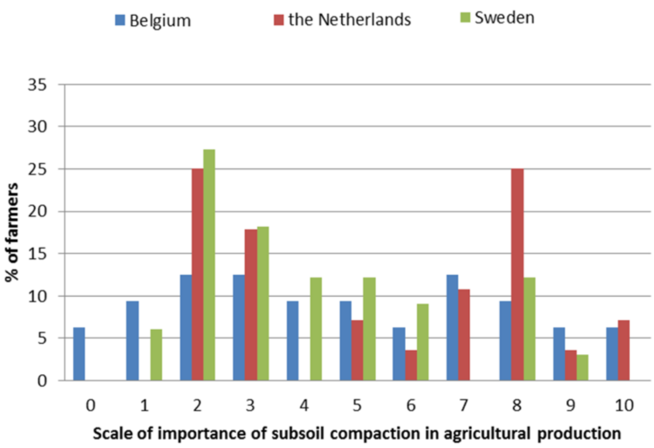


Figure 7. To what extent subsoil compaction affects agricultural production according to farmers (on a scale of 0 to 10)

In order to see if farmers were aware of the impacts of agricultural machineries on soil compactness, this study also researched on the machineries that farmers consider as the most harmful for the subsoil. Farmers were asked to choose between the following machineries: manuring, harvester, combine and harvesting cart, which are known to cause most subsoil compaction. The majority of the farmers pointed the harvester as the most harmful machinery for the subsoil. However, farmers with soil compaction problems mainly pointed to the combine as the most harmful machinery. Additionally, farmers without soil compaction problems mainly referred to the harvesting cart as the most harmful machinery. With respect to the harvesting cart, which is known to cause soil compactness, we asked the farmers if this passes on the same track of the harvester. Only 27% of the interviewed stated that the harvesting cart and the harvester pass on the same track (which is a good practice). Among this 27% were mainly farmers without soil compaction problems (see Table 2). Hence, based on this outcome, apparently soil compaction can be counteracted by adopting a controlled traffic system, especially in presence of heavily load machineries such as the harvesting cart.

Table 2. Percentage of farmers (%)stating that the harvester and the harvesting cart pass on the same track

Country	Farmers declaring to have soil compaction problems	Farmers declaring not to have soil compaction problems
Belgium	18%	33%
The Netherlands	7%	54%
Sweden	30%	11%

Farmers' awareness on soil compaction can also be related to farmers' awareness of other soil quality parameters such as soil porosity and soil's ability to retain and infiltrate water as these decrease with increasing soil compactness. Although these parameters are better discussed in the following subchapter on the environmental impacts of soil compaction, it is worth mentioning that a large percentage of the interviewed was not able to express an opinion on possible changes occurring in soil porosity and water infiltration capacity over the last 10 years.

2.3 Environmental impacts of soil compaction from farmers' perspective

To assess the environmental impacts of soil compaction as perceived by the interviewees, we asked for information on the ability of the soil to retain and infiltrate water as well as agrochemicals and fertilizers, as these can be washed away and pollute surface and ground-water. Thus, we inquired about surface runoff, soil porosity and water-logging. During the last 10 years, about 62% of the interviewed did not notice an **increase in the surface runoff**. In particular, this refers to Dutch and Swedish farmers (71% and 75%, respectively) as the percentage of Belgium farmers that did not notice an increase in the surface runoff was 37% only. The percentage of farmers that was not able to express an opinion on the surface runoff was 20%. Based on this result apparently in Belgium soil compaction is worse than in the other countries, although increase of surface runoff can also be attributed to other factors than soil compaction. However, the topography of the country significantly affects the amount of surface runoff on arable land so that in countries as flat as the Netherlands the surface runoff is difficult to see and quantify.

Concerning soil porosity (see Table 3) only in Belgium quite a high percentage of farmers declared that soil porosity has decreased. These were both farmers with and without soil compaction problems. In the other countries this percentage was remarkably lower. Only in the Netherlands a high percentage of the farmers without soil compaction problems declared that soil porosity had not decreased over the past 10 years. However, in all countries the majority of the interviewees was not able to express an opinion on **soil porosity, which is also related to soil ability to retain and infiltrate water**. This shows that this soil property is not something that really calls the attention of farmers.

With respect to the ability of the soil to retain and infiltrate water, Belgium farmers were the main ones reporting a decrease in these soil quality parameters. Otherwise, Dutch farmers and Swedish farmers without soil compaction problems were the main ones declaring that the water infiltration and retention capacity of the soil did not decrease over the last 10 years. With respect to the last 10 years, about 40% of the farmers with soil compaction problems as well as about 20% of the farmers without soil compaction problems did not have an opinion on the possible change in the water retention and infiltration capacity of the soil (see Table 4). Again, apparently these are soil characteristics that are not very much taken into account by the farmers interviewed.

Table 3. Percentage (%) of farmers thinking that soil porosity decreased over the last 10 years. The percentages refer to farmers declaring to have soil compaction (S.C.) and farmers declaring not to have soil compaction (No S.C.).

	Belgium		**The Netherlands**		**Sweden**		***On average***	
	S.C.	No S.C.	S.C.	No S.C.	S.C.	No S.C.	S.C.	No S.C.
Soil porosity decreased	45%	43%	0%	23%	13%	11%	16%	30%
No opinion about the possible change in soil porosity	55%	38%	87%	15%	54%	56%	64%	35%
Soil porosity did not decrease	0%	19%	13%	62%	33%	33%	20%	35%
	100	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Table 4. Percentage (%) of farmers thinking that soil ability to retain and infiltrate water decreased over the last 10 years. The percentages refer to farmers declaring to have soil compaction (S.C.) and farmers declaring not to have soil compaction (No S.C.)

	Belgium		The Netherlands		Sweden		*In average*	
	S.C.	No S.C.	S.C.	No S.C.	S.C.	No S.C.	S.C.	No S.C.
The water retention and infiltration capacity decreased	45%	33%	7	31%	25%	0%	24%	26%
No opinion about the possible change in the water retention and infiltration capacity of the soil	45%	24%	33%	8%	46%	22%	42%	18%
The water retention and infiltration capacity did not decrease	10%	43%	60%	61%	29%	78%	34%	56%
	100	**100**	**100**	**100**	**100**	**100**	**100**	**100**

As **water-logging** can be a symptom of soil compaction, farmers were asked to quantify the severity of water-logging problems on the fields on a scale of 0 (low severity) to 10 (high severity). The difference in answers between farmers with and without soil compaction on the fields was not large. Additionally, the majority of the farmers assessed the severity of water-logging problems as 1 and 2. When researching on the causes of water-logging, about 70% of the farmers with soil compaction problems blamed this to be the cause of water-logging on the fields. Soil compaction was blamed to cause water-logging also by 30% of the farmers without soil compaction problems. Figure 8 provides an overview of the causes of water-logging for all the farmers interviewed. Additionally, the causes of water-logging for farmers with soil compaction on the fields are shown at country-level. Although soil compaction remains the main cause of water-logging for all three countries under study, soil topography and subsoil infiltration capacity were also considered as main causes of water-logging by the farmers interviewed. **Soil texture** resulted to be an important cause of water-logging for Swedish farmers especially.

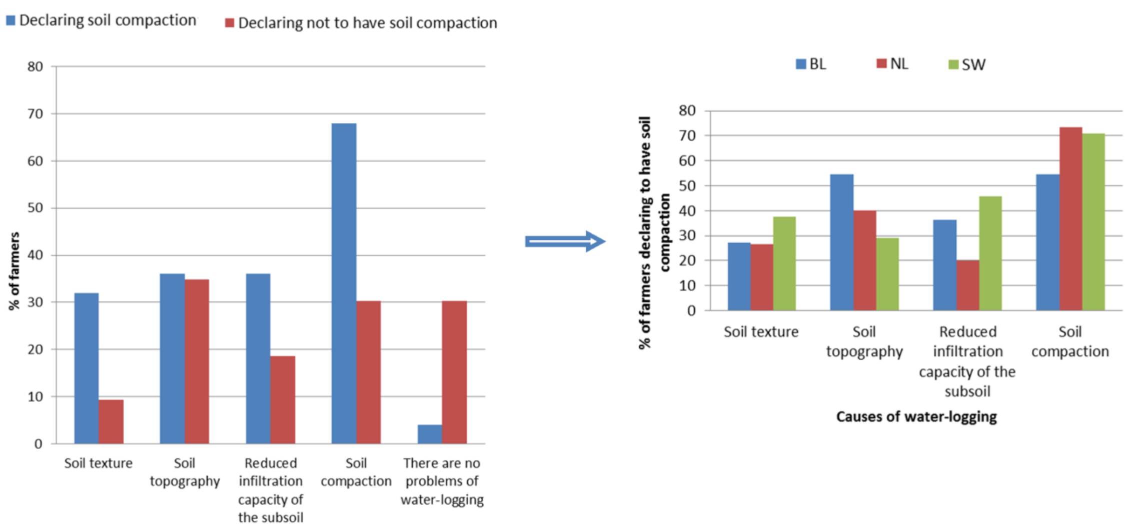


Figure 8. Causes of water-logging for farmers declaring to have whether or not soil compaction on the fields.

While sandy soils were mainly cultivated by farmers without soil compaction problems, clay soils were mainly farmed by farmers with soil compaction (figure 9).

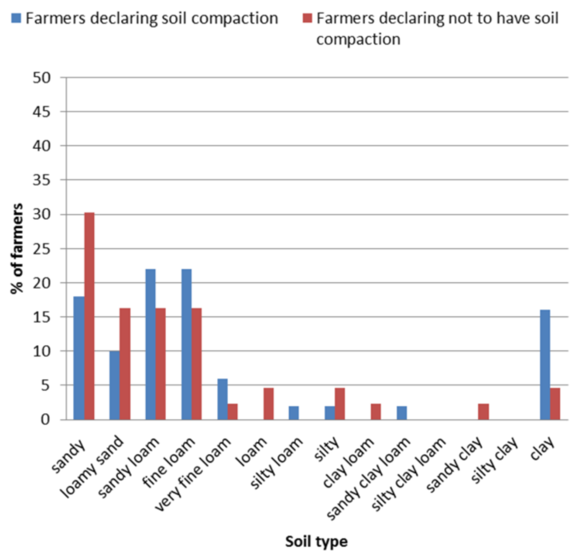


Figure 9. Opinion of the farmers on the soil type characterizing the majority of the fields they farm

Farmers were also asked for the **amount of agrochemicals and fertilizers** applied to the crops in the last 10 years as these can be washed away because of the increased compactness of the soil. With respect to the agrochemicals applied, 18% of the farmers without soil compaction and 8% of those with soil compaction, perceived an increase in the ease of the agrochemicals applied to be washed away in the last 10 years. Furthermore, of the same groups, 60% and 40% respectively did not perceive such a trend. Again, a high percentage of the farmers (about 40%) did not have an opinion on this trend.

With respect to the amount of fertilizers applied on a same crop in the last 10 years, a high percentage of the farmers (about 80%) did not increase the amount of fertilizers applied to their fields; this was quite similar for farmers with and without soil compaction problems. Hence, the use of fertilizers seems not to be influenced by soil compaction; this counts for all three countries.

2.4 Economic impacts of soil compaction

Soil compaction was recognized to **affect farmers' income** by more than 80% of the interviewed with soil compaction problems. There was not a large difference between the answers provided by farmers at the country level. Nevertheless, about 4% of the Swedish farmers with soil compaction problems stated that this does not affect their final income. To assess the economic impact of soil compaction, we asked for the amount of fertilizers applied, the cost of ploughing and subsoiling, the quantity and quality of the yield and the shape of the roots of both deep rooting and root/bulb crops. Because of the decreased capacity of the soil to retain fertilizers and the increased surface runoff, soil compaction can increase the **amount of fertilizers** required by the crops and reduce the yield. In this study, the majority of the farmers (about 80%) declared not to have increased the amount of fertilizers on a same crop in the last 10 years. Thus, soil compaction did not affect farmers income with respect to the cost of fertilizer applications. With respect to **ploughing and subsoiling practices** to counteract soil compaction, those were conducted by about 20% of the farmers with soil compaction problems and by about 5% of those without soil compaction. Additionally, about 25% of the farmers with soil compaction and about 15% of the farmers without soil compaction, ploughed the fields to improve soil quality. Considering the cost of increasing the use of the subsoiler to counteract soil compaction, there were similarities in the answers provided by farmers with and without soil compaction. Even though about 10% of the interviewed stated that the cost of subsoiling is significant, 20% of them stated that this is not significant and that it does not affect their final income. Looking at the single countries, the percentage of farmers declaring that the cost of increasing subsoiling practices is significant was 18%, 14% and 6% in Belgium, the Netherlands and Sweden, respectively. The percentage of farmers declaring that the cost of increasing subsoiling practices is not significant and does not affect their final income was 21%, 32% and 9% in Belgium, the Netherlands and Sweden, respectively.

As more than 90% of the farmers with soil compaction and about 70% of the farmers without soil compaction stated that this hampers root development, the shape of the roots of deep rooting crops as well as of bulb and root crops was researched. With respect to deep rooting crops, more than 50% of the farmers without soil compaction and about 20% of those with soil compaction problems reported a homogeneous distribution of the roots in width and depth. A heterogeneous distribution of the roots in width and depth was reported by about 10% of the farmers with soil compaction as well as by about 3% of the farmers without soil compaction. About 15% of the farmers with soil compaction and about 5% of those without soil compaction stated that the roots of deep rooting crops mainly develop in the shallow rooting depth. It is worth to mention that about 22% of the farmers did not know the shape of the roots of deep rooting crops. The same ignorance on the shape of the roots was noticed in bulb and root crops, for which about 36% of the interviewed was not able to express an opinion. In both the cases, the majority of the farmers ignoring the shape of the roots were farmers with soil compaction in Sweden and farmers without soil compaction in Belgium and the Netherlands. Looking at bulb and root crops, about 50% of the farmers without soil compaction and about 35% of the farmers with soil compaction stated that (in general) root and bulb crops are in good shape and are well marketable. Additionally, 10% of the farmers with soil compaction and about 15% of those without soil compaction, reported a low percentage of small and deformed root/bulbs on the final yield. None of the interviewed reported a high percentage of small and deformed roots/bulbs on the total yield. These results need to be related to the crops planted in each of the countries under study. About 100% of the interviewed in Sweden never planted potatoes nor onions or sowed maize. Additionally, about 75% of them never sowed sugar beet. In the Netherlands, 39% of the interviewed never planted potatoes, 60% never sowed sugar beet, 67% never planted onions and 50% never sowed maize. In Belgium, 28% of the interviewed never planted potatoes, 62% never sowed sugar beet, 96% never planted onions and 15% never sowed maize.

2.5 Mitigation measures

The majority of the farmers interviewed (90%) declared to be currently taking **mitigation measures** against soil compaction. In Belgium, mitigation measures against soil compaction are taken by about 53% of the farmers without soil compaction as well as by about 28% of those with soil compaction. In Sweden, mitigation measures against soil compaction are taken by about 27% of the farmers without soil compaction as well as by about 66% of those with soil compaction. In the Netherlands about 50% of the interviewed is taking mitigation measures against soil compaction. As the **traffic system** (random or controlled) affects the level of soil compactness, we researched the traffic system adopted by the farmers in the different countries and we then related it to the presence of soil compaction. A controlled traffic system was mainly adopted by Belgium farmers (46%) followed by Dutch (21%) and Swedish farmers (15%), the majority of which declared not to have soil compaction. Only four Belgium farmers declared to adopt a controlled traffic system for all the machineries used on the fields, all the other farmers adopting a controlled traffic system claimed that this is only partly controlled depending on the crop type and the field operation under consideration. A random traffic system was mainly adopted by Swedish farmers (84%) followed by Dutch (78%) and Belgium farmers (53%), the majority of which declared to have soil compaction problems. The practice of random traffic can be related to soil compaction occurrence as in Sweden about 72% of the interviewed declared to have soil compaction on the fields. Otherwise, the percentage of farmers without soil compaction problems is about 34% in Belgium, where controlled traffic is mainly adopted.

When asking the farmers for **changes in the farming system (ploughing depth, mouldboard ploughing, no-tillage, reduced tillage, controlled/random traffic) with respect to the last 10 years**, the difference in the answer was not large for farmers with and without soil compaction. Farmers declaring to have decreased the ploughing depth in the last 10 years were mainly Swedish farmers with soil compaction problems and Dutch and Belgium farmers without soil compaction problems. The use of a reduced tillage system increased especially in Sweden and Belgium. This increase mainly refers to Swedish farmers with soil compaction problems and to Belgium farmers without soil compaction problems. In order to prevent soil compaction, even farmers without soil compaction problems (mainly Belgium farmers) started or are about to start to **include more crops** in the crop rotation plan. The improvement of the crop rotation plan as soil compaction mitigation measure, is also taken into account by farmers with soil compaction on the fields, many of which are Swedish. It has to be mentioned that although many farmers with soil compaction are willing to expend the number of crops planted to counteract soil compaction, the low value of those crops on the market hinders them from changing their actual crop rotation plan.

The soil compaction **mitigation measures that farmers would like to take in addition to those already adopted** are shown in figure 10. A large percentage of farmers with soil compaction problems (mainly from Sweden) would like to improve the drainage on the field, reduce the inflation pressure of the machineries, use tracks instead of tyres and change the crop rotation plan. Belgium farmers without soil compaction problems were mainly willing to prevent soil compaction by increasing the ploughing depth.

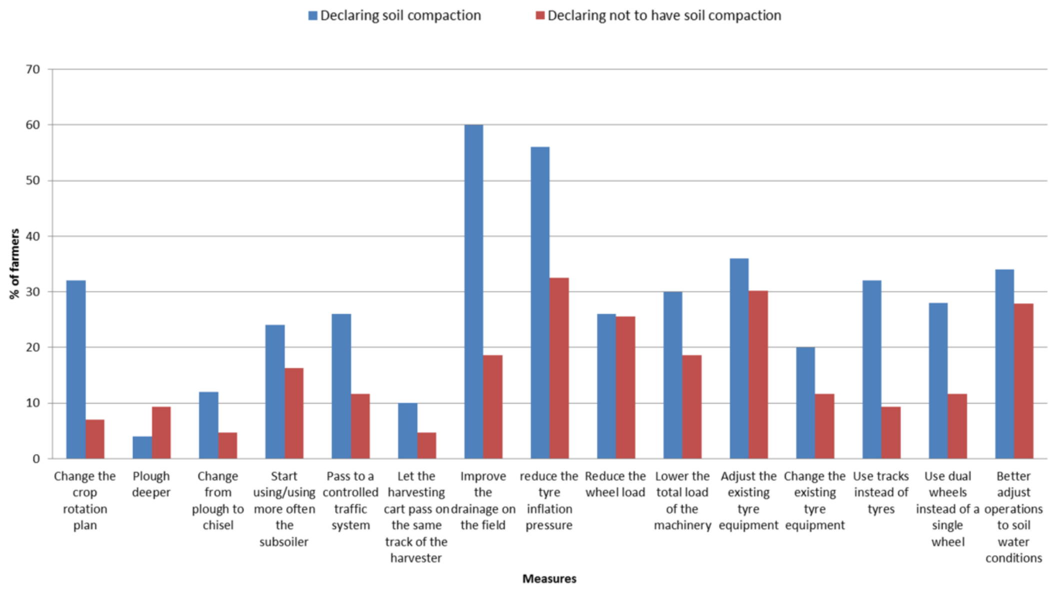


Figure 10. Measures that farmers would like to take against soil compaction

Although farmers with soil compaction problems would like to take additional mitigation measures, 50% of them claimed that it is expensive. Additionally, about 15% of them consider the measures available nowadays not effective in counteracting soil compaction. About 30% of the interviewed declared not to know which measures to take and a low percentage of them (about 20%) is not willing to take any measures as soil compaction is limited to a restricted area. With respect to farmers without soil compaction problems, the majority of them is not willing to take any additional mitigation measure against soil compaction. Even though a small percentage of those farmers would like to take additional mitigation measures, they consider them too expensive (20%) or they do not know which measures to take (10%). Looking at the main factors hindering farmers from taking measures against soil compaction, farmers are generally hindered by taking mitigation measures mainly because of economic reasons such as the cost of the implements and the low economic benefits of counteracting soil compaction. Additionally, farmers stated that the adoption of soil compaction mitigation measures requires too many changes to the actual farming system. At the country level, the mitigation measures available nowadays were considered too expensive by Swedish farmers especially. Swedish farmers were also the main ones claiming that the adoption of the currently available mitigation measures requires too many changes to the farming system and that they would wait until they buy new machineries to take additional measures against soil compaction. Dutch farmers were the main ones mistrusting the efficiency of the soil compaction mitigation measures available nowadays. Additionally, they were the main ones claiming to have already done everything possible to counteract soil compaction.

Conclusions

Based on the results of this study, it was possible to conclude that:

- The percentage (%) of arable farmers declaring perceiving to have soil compaction considerably differs between the countries. The lowest percentage of farmers perceiving soil compaction problems is in Belgium, the highest is in Sweden;

- Dutch farmers consider topsoil and subsoil compaction negative or less important as it decreases agricultural production. Otherwise, Swedish farmers are the ones giving less importance to those. Belgian farmers do not have a clear opinion on the importance of compaction on agricultural production;

- Although the majority of the farmers recognized the harvester and the harvesting cart as the most harmful machineries for the subsoil, only 27% of them stated that these pass on the same track. As those farmers were mainly the ones declaring not to have soil compaction problems, soil compaction can be counteracted by adopting a controlled traffic system especially in presence of heavily load machineries such as the harvesting cart;

- The majority of the farmers did not have an opinion on soil quality parameters related to the presence of soil compaction such as soil porosity and soil water infiltration capacity. The presence of soil compaction did not affect the amount of surface runoff in The Netherlands and Sweden especially;

- The majority of the interviewed blamed soil compaction to cause water-logging;

- The majority of the interviewed stated that the amount of agrochemicals and fertilizers applied on the crops did not change over the last 10 years;

- Although the majority of the interviewed blamed soil compaction to affect their income, it was not easy to assess the economic impacts of soil compaction. Most of the farmers do not pay attention to the shape of the roots of deep rooting and bulb/root crops. Nevertheless, the interviewed had a better idea on the cost of increasing subsoiling activities, which was considered significant by Belgium farmers especially;

- Swedish farmers with soil compaction problems were mainly using a random traffic system. The same group of Swedish farmers is however the most willing to take soil compaction mitigation measures, much more than the Belgium and Dutch farmers;

- Farmers are generally hindered by taking mitigation measures mainly because of economic reasons such as the cost of the implements and the low economic benefits of counteracting soil compaction. Additionally, several farmers declared not to know which measures to take against soil compaction;

- While Swedish farmers were mainly hindered by taking mitigation measures because of economic reasons (the mitigation measures available nowadays are too expensive or require too many changes to the current farming system), Dutch farmers were the main ones mistrusting the efficiency of the mitigation measures available nowadays and thinking to have already done everything possible to counteract soil compaction.

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Annex 2
Description of Terranimo (pdf)