Experiences with the impact and prevention of subsoil compaction in the European Community

Proceedings of the 3rd workshop of the Concerted Action "Experiences with the impact of subsoil compaction on soil, crop growth and environment and ways to prevent subsoil compaction", 14-16 June 2000, Uppsala, Sweden

J. Arvidsson, J.J.H. Van den Akker and R. Horn (Eds.)

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Abstract

The Concerted Action " Experiences with the impact of subsoil compaction on soil, crop growth and environment and ways to prevent subsoil compaction", was started in 1998, to collect and combine experiences and data on subsoil compaction in Western Europe. One of the objectives was also to construct a database including soil mechanical properties and the impact of subsoil compaction on soil and crop properties. Within the concerted action, six working groups were formed: WG1. Modeling impact of subsoil compaction on crop growth, water availability to plants and environmental aspects. WG2. Modeling the compaction process. WG3. Interactions in the tyre-soil interface. WG4. Soil mechanical measurements and measurement techniques. WG5. Setup of field experiments, measurement of soil physical properties, crop growth and environmental aspects. WG6. Equipment selection and field practices for control of subsoil compaction.

These proceedings include presentations made at the 3rd workshop of the Concerted Action 14-16 June 2000, Uppsala, Sweden, mainly divided into sections based on the working group subjects. The papers are later intended to be published in a special issue of Soil and Tillage Research.

Contents

Concerted Actions on Subsoil Compaction in Western European Countries and on Subsoil Compaction in Central and Eastern European Countries

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Abstract

Soil compaction is estimated to be responsible for the degradation of an area of 33 million ha in Europe. Wheel loads still increase and compaction expands more and more into the subsoil. This deserves special attention because subsoil compaction is very persistent and possibilities of natural or artificial loosening are disappointing. Subsoil compaction has been acknowledged by the EU as a serious form of soil degradation and therefore the EU finances two concerted actions on subsoil compaction. The concerted actions involve in total 49 institutes in 14 EC-member-countries, Switzerland, Norway, and 11 countries in Central and Eastern Europe. The general objective of the concerted actions is to make an inventory of existing knowledge and experiences with the distribution and impact of subsoil compaction in Europe, formulation of recommended methods and field experiments, and development of ways and guidelines to prevent subsoil compaction. The two concerted actions collaborate in the construction of two databases: (1) on literature on subsoil compaction; (2) on soil mechanical properties and impact of subsoil compaction on soil nutrients, physical properties, crop production and environment. In each concerted action working groups are erected to study and recommend on specific topics. Results are published in proceedings, a book, national and international papers and an Internet site: http://www.alterra.wageningen-ur.nl/subsoil-compaction/.

Keywords: subsoil, compaction, degradation, nutrients, crop growth, environment, soil quality, soil strength, database, modeling, soil physical properties, soil mechanical properties

1. Introduction

In the Concerted Actions the subsoil is defined as the soil layers underneath the topsoil or ploughed layer. In this definition the so-called plough pan is the upper part of the subsoil. In most cases problems by subsoil compaction are caused by an overcompacted upper part of the subsoil.

It has been estimated that in Europe, 72000 km^2 (25%) of all agricultural land, 54000 km^2 (35%) of all pasture land and 26000 km^2 (92%) of all forest and woodland is affected by some kind of soil degradation (Van Lynden, 1995). Soil compaction is estimated to be responsible for the degradation of an area of 33 million ha in Europe (Soane and Van Ouwerkerk, 1995). About 32 % of the subsoils in Europe are highly vulnerable to subsoil compaction and another 18 % is moderately vulnerable to subsoil compaction (Fraters, 1996). Due to the ever increasing wheel loads in agriculture, compaction is increasingly expanding into the subsoil. This deserves special attention because subsoil compaction is very persistent (Håkansson et al., 1987, Håkansson, 1994 and Alakukku, 1996) and results of natural loosening or artificial loosening

techniques have been disappointing (Kooistra et al., 1984). Deep ripping of compact subsoil of pedogenic origin has been successfully used in Germany (Schulte-Karing, 1970), and expanded under specific soil and climate conditions in many East-European countries (Stanga et al., 1973; Zaidelman, 1992). Compacted subsoil is economically and environmentally sub-optimal. It results in decreased crop production and crop quality and requires an increased input of energy, nutrients and water. At the moment, it is common practice to compensate the detrimental effects of soil or subsoil compaction on crop production by improving drainage and supplying more nutrients and water (irrigation). These "solutions" lead to excessive use of water and nutrients and pollution of the environment. Healthy subsoil, which is a habitat for soil fauna and flora, is an environmental aim in itself and a precondition for organic farming. Subsoil with good soil physical qualities allows plants to make optimal use of nutrients and water and permits reduction of inputs. Severely compacted subsoil has a decreased infiltration and storage capacity, resulting in an increased surface runoff promoting erosion and pollution of surface water with soil, nutrients and chemicals used in agriculture.

The costs of subsoil compaction in Europe are not precisely known, but Arvidsson and Håkansson (1991) estimated the effect of 38 ton sugarbeet harvesters on yield losses to be 0.5% per year. Assuming that such harvesters are used on at least 500.000 ha in the EC this results in an annual loss of sugarbeet yield of 100.000 kEURO. It is expected that these heavy harvesters will be increasingly used. Alblas et al. (1994) estimated that traffic-induced subsoil compaction has reduced the total production of silage maize in the Netherlands by 7%. This results in an annual loss in the Netherlands of 21.000 kEURO. For the USA, where much higher wheel loads are used than in the EC, long-term average maize yield reductions of 6% have been estimated (Voorhees, 1992). A report of the European Environment Agency, 'Europe's Environment, The Dobris Assessment' (Stanners and Bourdeau, 1995) reported yield losses of 5 - 35%, with an average of 12% on severe compacted subsoils. In the countries of the former USSR heavy equipment is used even on wet soils, and yield losses up to 50% by soil compaction were reported in former Soviet agriculture (Libert, 1995). Total yield losses caused by soil compaction in the former USSR countries are estimated at 13 - 15 million tons of grain (7 - 8% total yield), two million tons of sugarbeet (3%), and half a million tons of maize (4%). During ploughing, annual fuel consumption is claimed to be one million tons higher than necessary because of soil compaction. It is not possible to calculate what part of these losses can be attributed to subsoil compaction, but very persistent subsoil compaction, going deeper than 80 cm, has been registered in large areas of the former USSR. In Romania it is estimated (Canarache et al., 1984b) that 55 percent of the arable area is subject to topsoil and upper subsoil compaction of man-made origin, and 11 percent to subsoil compaction of pedogenic origin, with some 5 percent decrease in the total country crop yield, and also some 5 percent increase in fuel consumption for tillage operations. One of the impacts of subsoil compaction is that the nutrient usage efficiency decreases which means that the loss of nutrients in the environment increases. Allakuku and Elonen (1995) found that the decrease of nitrogen yield can be many times the decrease in grain yield.

Prevention of subsoil compaction is essential for an economically and environmentally sustainable agriculture. Knowledge of the susceptibility of subsoils to compaction and the load-bearing capacity of subsoils would enable manufactures to design subsoil-friendly equipment and would help farmers decide whether, where and when they should use this kind of equipment. Scenario and land evaluation studies frequently neglect the aspect of subsoil compaction, due to a lack of knowledge of the impact of subsoil compaction on the soil physical quality and the diminished rooting possibilities and crop growth resulting from this compaction.

Improved knowledge of these aspects would improve the analysis of the impact of political decisions and agricultural practices on environment, crop production and the use of natural resources. Knowledge of the susceptibility of subsoils to compaction and the bearing capacity of subsoils makes the design of subsoil friendly equipment by manufactures possible and helps farmers in deciding whether, where and when he must use this kind of equipment. Therefore one of the goals of the concerted actions is to construct a database with soil mechanical data needed to calculate the bearing capacity of the subsoil, and soil physical data needed in crop growth models and results of field experiments to verify modeling and for analyzing the susceptibility to compaction of subsoils.

Research on compaction has been widely performed in various European countries: in Romania in greenhouse pots since 1959 (Canarache and Thaler, 1963; Dumitru et al., 1992) and under field conditions since 1965 (Canarache et al., 1984a); in Bulgaria since 1963 (Stoynev and Ivanov, 1970), in Ukraine since 1976 (Medvedev et al., 1987), in Russia since 1983 (Bondarev, 1990), in Poland since 1987 (Lipiec and Stepniewski, 1985), and in the humid regions of Western Europe and North America (Håkansson et al., 1987 and Håkansson 1994). Overviews on soil compaction and subsoil compaction can among others be found in Soane and Van Ouwerkerk, 1994, Van den Akker et al., 1999, Birkas et al,. 2000, and Horn et al., 2000.

2. Description of the Concerted Actions

The EU finances the two Concerted Actions on subsoil compaction. One concerning the EU countries by the FAIR program and one concerning the Countries of Central Europe and the New Independent States by the INCO-Copernicus program. The FAIR CA started the first of January 1998 and the INCO-Copernicus CA started the first of December 1998. Both are 3-year projects. The complete titles of the concerted actions are:
FAIR CA: Experiences with the impact of subsoil compaction on soil crop growth and environment and ways to prevent subsoil compaction
INCO-Copernicus CA: Experiences with the impact of subsoil compaction on soil nutrition crop growth and environment and ways to prevent subsoil compaction

The concerted actions are very similar. However, the INCO-Copernicus CA is stressing on several additional objectives, as impact of subsoil compaction on the soil nutrient status and on the environment. It will also focus on peculiarities frequently met in that part of the world, as droughty and cold climates, heavy textured soils, soils with a clay-alluvial horizon, and specific copping pattern and farm equipment. The FAIR Concerted Action has 34 participating institutes and universities and includes all EU countries except Luxembourg, and also includes Norway, Switzerland and Poland. The coordinator is Jan van den Akker (Netherlands); subcoordinators are Johan Arvidsson (Sweden) and Rainer Horn (Germany). The INCO-Copernicus Concerted Action includes the 3 coordinating participants of the FAIR CA and 15 institutes and universities from Countries of Central and Eastern Europe: Belarus, Bulgaria, Czech Republic, Estonia, Hungary, Moldova, Poland, Romania, Russia, Slovakia and Ukraine. The coordinator is Jan van den Akker (Netherlands), scientific coordinator Andrei Canarache (Romania), subcoordinators are Elisabeta Dumitru (Romania), Marta Birkas (Hungary), Vitaly Medvedev (Ukraine). The concerted actions are not combined, however, are strongly linked.

Subsoil Compaction
Task 1: Organization

Literature

Experiences of participants

Databases European Soil Bureau

Harmonization of data and methods
Data and information transfer
(C+ S + W + All)

Task 2
Construction Database on Literature
(C + S + All)

Task 3
Construction data-base on soil proper-ties and impact
(S + C + All)

Task 4
Inventory methods and setup field-experiments
(C + S + W + All)

Task 4 Determination of gaps in data and knowledge
Selection recommended methods; setup experiments
(C + S + W + All)

Tasks 4,2,3
Embedding of databases in European Soil Bureau
(C + S)

Task 4
Publication and dissemination results

(C + S + W)

Task 4
Recommendation methods; set-up field experiments

(C + S + W)

Task 5
Initiation collaborative research

(C + S + W + All)

C = Coordinator or Scientific Coordinator
S = Subcoordinators
W = Working groups
Initiative and responsibility for the action decreases from left to right

Fig. 1. Implementation of the concerted actions

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The general objectives of the concerted actions are:
- bring experts together in order to create representative working groups on subsoil compaction, involving all European countries;
- make a contribution to an economically viable and environmentally friendly agriculture, based on an exchange and dissemination of scientific knowledge and practical experience concerning subsoil compaction and ways to prevent it;
- creation of databases with information and data of effects of subsoil compaction on soil physical and mechanical properties, plant nutrition, crop growth, erosion and environment;
- identification of soils and farming systems with a risk of subsoil compaction and determination of effective ways to prevent subsoil compaction;
- identify gaps in current knowledge on subsoil compaction and determine the need for further research;
- promotion of mutual research projects.

In figure 1 an overview of the methodology for implementing the concerted actions is presented. Five tasks can be distinguished:
1. organization of the concerted action;
2. construction of the database "Literature on subsoil compaction and soil mechanical properties";
3. construction of the database "Soil mechanical properties and impact of subsoil compaction on soil physical properties, crop production and environment";
4. identification of gaps in data and knowledge; inventory and selection of methods and design of field experiments resulting in recommendations; provision and dissemination of conclusions and results;
5. determination of required research; initiation of collaborative research.

The coordinator, scientific coordinator and subcoordinators are responsible for the organization of the concerted actions including the organization of workshops. In both concerted actions three Workshops are planned. The first workshop of the FAIR CA took place in Wageningen, 28-30 May 1998 (Van den Akker et al, 1999). The first workshop of the INCO-Copernicus CA and the second workshop of the FAIR-CA were joined to an International Conference on subsoil compaction organized by the CA-s and the IUSS working group Soil Physics, in March 1999, Kiel. A selection of papers of the three combined workshops are presented in Advances in GeoEcology 32 "Subsoil Compaction" edited by R. Horn et al. (2000). The last workshop of the FAIR CA is in Uppsala, Sweden, 14-16 June 2000, is reported in these proceedings. The second workshop of the INCO-Copernicus CA was in Gödöllö, Hungary, May 28-31, 2000. (Birkas et al., 2000). The third workshop of the INCO-Copernicus CA will be in Romania, 2001.

3. Databases

The first priority of the database "Literature on subsoil compaction and soil mechanical properties" is to include all literature on subsoil compaction of the participating countries. However also literature of other countries and literature on topsoil compaction, effects of subsoil loosening and recompaction and soil mechanical and soil physical properties of topsoils are welcome. A difference with regular literature databases is that this database has a very structured keyword index. The keywords include country; texture class (FAO), structure type; climate; drainage condition/water management; land use/crop; soil management system; nature of paper/research; what is measured or modeled; how is it measured; and treatment. If the

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research described in the paper is included in the database on soil properties and impact of subsoil compaction, then the literature database refers to relevant addresses in this database. It is also the other way around: the database on soil properties and impact of subsoil compaction refers to relevant addresses in the literature database.

Table 1. Structure of the Excel workbook for collection of data

General information (sheets 1-7)
sheet 1.   general information about participant and site; index of filled out sheets; treatment description
sheet 2.   Proforma I
sheet 3.   Proforma II
sheet 4.   Information about traffic treatments
sheet 5.   Soil conditions during traffic
sheet 6.   Tillage management and crop rotation
sheet 7.   Weather conditions
Physical parameters (sheets 8-16)
sheet 8.   Bulk density
sheet 9.   Water retention
sheet 10.   Saturated hydraulic conductivity (1)
sheet 11.   Saturated hydraulic conductivity (2)
sheet 12.   Unsaturated hydraulic conductivity (1)
sheet 13.   Unsaturated hydraulic conductivity (2)
sheet 14.   Air permeability (1)
sheet 15.   Air permeability (2)
sheet 16.   Air diffusion
Mechanical parameters (sheets 17-22)
sheet 17.   Penetration resistance
sheet 18.   Stress dependent changes of physical properties
sheet 19.   Laboratory shear test; triaxial test
sheet 20.   Vane shear measurements
sheet 21.   Stress and strain measurements (laboratory)
sheet 22.   Stress and strain measurements (field)
Chemical parameters (sheet 23)
sheet 23.   Chemical parameters
Crop parameters (sheets 24-29)
sheet 24.   Crop yield
sheet 25.   Root density
sheet 26.   Root depth
sheet 27.   Root/shoot ratio
sheet 28.   Leaf area index
sheet 29.   Nutrient uptake
Added sheets (sheets 30- ...)
sheet 30.   Porosity soil thin sections
sheet 31.   Contact area, hard surface
sheet 32.   etc.

The participants of the concerted actions deliver the data for the database "Soil mechanical properties and impact of subsoil compaction on soil physical properties, crop production and environment" in Excel workbooks. In a later stage, the Excel workbooks are to be reshaped in an ACCESS datafile, more convenient for processing and interpretation. Per experiment and per experimental year one workbook must be filled in. The structure of the workbooks is presented in Table 1.

The spreadsheet can be divided into six categories: (1) general information; (2) physical parameters; (3) mechanical parameters; (4) chemical parameters; (5) crop parameters; (6) added sheets. The last category is for special parameters proposed by the participants. This category will continue to grow. The general information sheets provide key information for the search engine of the database. The first and second sheet must be filled in completely. All other sheets are filled in as far as possible, however, often just a limited amount of sheets are filled in. The second and third sheet are copies of the forms Proforma's I and II used for collecting input data for the EC Soil Profile Analytic Database (SPADE) of the European Soil Bureau (ESB) (Montanarella, 1997). They are filled in according to the guidelines drawn up by the Scientific Committee of the ESB (Madsen and Jones, 1995). In this way the database will be in a format compatible with the European Soil Database. Proforma I (sheet 2) must be completed in full by transforming measured data according to the methodology in the guidelines as well as by estimation. Proforma I includes among others the soil name, parent material, country, groundwater level, landuse, texture, structure, organic matter content, $CaCO_3$ and $CaSO_4 .2H_2O$, pH, EC, CEC, BS, soil water retention, porosity and bulk density and root depth. Proforma II has about he same structure as Proforma I, however, only measured data is recorded and it is accepted that data will be missing. The compatibility of the database constructed in the concerted actions with the European Soil Database will make it easier to include the impact of subsoil compaction in GIS applications on European scale. It makes it better possible to translate and use experience and knowledge gained in one country in an another country. This is not only restricted to Europe, but holds true world wide because the European Soil Database is compatible to FAO soil information and standards.

4. Working Groups

In both concerted actions working groups on specific subjects are established. The working groups are a way to structure several tasks of the concerted actions. These tasks are:
- presentation and inventory of experiences, methods, experiments, data available and harmonization of data delivery;
- inventory of gaps in knowledge and data, measurement methods and design of field experiments;
- harmonization and recommendation of analytical methods and design of field experiments;
- recommendation of ways and guidelines for the farmers how to prevent subsoil compaction;
- dissemination of results in proceedings, joint publications and presentations in local, European and international conferences;
- formulation and initiation of required future mutual research.

In the third workshop of the FAIR Concerted Action on Subsoil Compaction emphasis is laid on the databases and the presentation of the results of the working groups. These proceedings include several papers of the working groups. In the FAIR CA six working groups were erected. A short description of the objectives and work of the working groups before the third workshop

of the FAIR Concerted Action follows:

WG1. Modeling impact of subsoil compaction on crop growth, water availability to plants and environmental aspects. Chairman: Jerzy Lipiec. The objective of the working group is to determine the best models which can calculate the effect of subsoil compaction on crop growth, water use, nitrogen use and leaching, etc., to determine the required input for these models, to recommend and propagate the use of these models. The working group evaluated existing models on their suitability to model the impact of subsoil compaction. Two simulation models (SIMWASSER and SIBIL) will be validated using data from Austria, Poland and Spain.

WG2. Modeling the compaction process. Chairman: Jan van den Akker. The objective of the working group is to determine the best way to model the soil mechanical compaction process, to determine the required input for these models, to recommend and propagate the use of the best models. The emphasis in the assessment is laid on the performance of the models in predicting stresses, deformations and compactions in the subsoil. The user-friendliness of models based on the Finite Element Method (FEM) proved to be increased to such extent that it has become a suitable instrument to model and study the soil compaction process. One of the problems of the use of FEM models is the required input of sophisticated soil mechanical properties. Lebert a. Horn (1991) developed procedures for estimation of some of these soil mechanical properties, which were then extended (DVWK, 1995). Koolen and Van den Akker (2000) showed that several of these soil mechanical properties can be estimated or neglected.

WG3. Interactions in the tyre-soil interface. Chairman: Pierluigi Febo. The attention will be focused on the tyre ground pressure, as this is a basic parameter for characterizing the interaction between tyre and soil and moreover important input in soil mechanical models. The following parameters must also be considered: wheel load, tyre inflation pressure, average contact pressure, wheel load distribution over the contact area, and number of passes. A study of contact area prediction models has been performed (Febo et al., 2000). One of the goals will be to define and set up a simplified method for carrying out quick tyre contact area measurements. The method will then be explained to all the participants of the Concerted Action, so that it may be adopted as a guideline.

WG4. Soil mechanical measurements and measurement techniques. Chairman: Mike O'Sullivan. The objective is to make recommendations about the measurement of soil mechanical properties relevant to subsoil compaction problems and processes. These properties are not measured as an end in themselves but the results are needed to predict how the soil will behave. Knowledge of the soil response to stress will also enable the development of guidelines about maximum permissible loads. It was considered what minimum information would be required as input to pedotransfer functions and what additional information would increase the precision of predictions. This resulted in recommended measurements at four levels of increasing detail: (1) texture, bulk density, water potential (and content), description of aggregation in the field and a measurement of soil strength, preferably vane shear strength; (2) as 1 plus pore size distribution, saturated hydraulic conductivity (k_{sat}), cohesion (c), angle of friction (f), precompression stress (p_c), organic matter content, tyre designation, inflation pressure and contact area; (3) as 2 plus changes in c, f and p_c with water potential, k_{sat} ~ stress relationship, field stress measurements and maximum intensity of drying; (4) a complete characterization of soil mechanical, physical and chemical properties.

WG5. Setup of field experiments, measurement of soil physical properties, crop growth and environmental aspects. Chairman: Inge Håkansson. The goal of the working group is to formulate recommendations of ways to set up field experiments to study the impact of subsoil

compaction on crop production and environment. After a first inventory of what has been done concerning field experiments on subsoil compaction in the EU, the need for and setup of new experiments was considered. It is concluded that the consequences of subsoil compaction by heavy traffic for environment (biodiversity, erosion, nitrogen cyclus, leaching of nutrients, use and leaching of agro chemicals) are hardly known. These aspects should be studied in conjunction with the impact on crop growth on three soils in three climatic zones in the EU as defined by the working group: a northern (Baltic), a southern (Mediterranean) and an intermediate (Central) region. To exclude topsoil compaction in the experiments it is considered to remove temporally the topsoil or to apply the wheel load in the bottom of an open furrow made by a special one-furrow moldboard plow with a widened plough body. The working group presented an extensive list of parameters to be measured in field experiments.

WG6. Equipment selection and field practices for control of subsoil compaction. Chairman: Tim Chamen. The objective of the working group is to provide a best practice framework within which growers, farmers, manufacturers and advisors can work to achieve control over subsoil compaction. Necessarily, this will also provide some degree of control of topsoil compaction. The objective requires close interaction with the other working groups and the database managers. Moreover a Questionnaire for National Experts was formulated and send to these national experts to make an inventory of crops, critical operations, existing national guidelines, area of irrigated land, area of well drained land, dominant cultivation systems, recommendations for minimizing compaction, and what do the experts consider should be the way forward in terms forward in terms of dealing with compaction. The working group identified five levels of susceptibility for subsoil compaction. However, on European (1 : 1,000,000) scale this must be reduced to three or even two classes (vulnerable and not vulnerable) because of lack of good data. An inventory of the existing damage by subsoil compaction requires opening of soil pits across the European Union in the growing season on soils that represent the dominant soil types in Europe. The working group agreed that following papers would be prepared: (1) Assessing the vulnerability of subsoils to compaction; (2) Management of the arable layer to avoid subsoil compaction; (3) Soil/machinery interactions to avoid subsoil compaction; (4) Equipment and field practices to avoid subsoil compaction; (5) Working group methodologies - how the workgroup worked to provide an outcome.

In the first workshop of the INCO-Copernicus CA, Kiel, Germany, March 1999, four working groups were erected:

Working Group 1. Impact of subsoil compaction on nutrient status, soil physical properties and environment including simulation modeling. Chairman: V. Medvedev. This working group is concentrating on putting together experimental data from all partners on changes in soil properties, crop yields and environment under the effects of subsoil compaction. A survey of indices used in various partner countries for identification of compaction is in progress. The final output of this working group will refer to conclusions concerning the effects of various factors, as soil, climate, and machinery characteristics, on changes in soils, decrease in crop development, environment degradation etc, as well as on identification of gaps in knowledge on these relationships and on suggestion for future research projects. The specific of soils and climates in CEE and NIS countries, often quite different from those in the EU countries, are taken into account. Special attention is paid to the effects of compaction on the nutrient state in soils. Various simulation models, mainly the SIBIL model developed in Romania (Simota and Canarache, 1988) and the models used in the FAIR Project, are foreseen to be checked and compared with the experimental data, which will be stored in the database to be constructed within the Project.

Working Group 2. Analytical methods and pedotransfer functions for determination and evaluation of soil strength. Chairman: B. Dawidowski. A special database form on details of soil mechanical properties has been prepared. It was developed in the Excel software, and consists of nine sheets including information on methods used in various countries for uniaxial and triaxial tests, for determination of shear, compression, penetration, stress distribution, and for bulk density and texture as basic soil physical properties needed to discuss these mechanical properties. Most of this database has already been completed, and is now being processed. Existing pedotransfer functions for soil mechanical properties, not too many found up to now in literature, are being examined. A set of more than 400 samples with complete soil mechanical and other soil physical properties have been collected in Romania, and they are now being processed with a view of developing such pedotransfer functions. As soon as these pedotransfer functions will prove to be feasible, extension using analytical data from other partners will be considered.

Working group 3. Design of field experiments related to studying the impact of subsoil compaction on nutrients, crop production and environment. Chairman: E. Nugis. This working group is concentrating its activity on examination and comparison of field experiments methodology used in studies on subsoil compaction by various Project partners. The specificity of this kind of research, not completely corresponding to the classical field experimental design and statistical processing of the results used in other fields of agronomy and soil science, are being taken into account. A special attention is to be given to the determination of the characteristics of the machinery used to produce various compaction treatments.

Working group 4. Ways to prevent subsoil compaction and to alleviate its negative effects on nutrients and water regime and on environment. Chairman: M. Iancu. This working group will focus its attention on identification of procedures developed by various Project partners for reduction of subsoil compaction (use of adequate machinery, correlation of farming operations with the soil moisture content, use of traffic lanes, sodded lanes in fruit orchards, etc.) and for restoring the pre-compaction soil properties (mechanical soil loosening, effects of freezing/thawing and wetting/drying cycles, effects of earthworms, use of specific crops, etc.). Local soil, climate, machinery and farming systems specific to the CEE and NIS countries will be taken into account.

Activities of the working groups in the INCO-Copernicus CA is still in its initial state, as most of their work will be possible only after completion of at least part of the databases, but some of their tasks are already quite advanced, as e.g. those referring to analytical methods, pedotransfer functions, and simulation modeling.

5. Results and conclusions

The FAIR CA is now in its third and last year and the INCO-Copernicus CA in its second year, with one year to go. Concrete results at this moment are the proceedings of the first workshop of the FAIR CA (Van den Akker et al., 1999) and a book "Subsoil Compaction: Distribution, Processes and Consequences" edited by Horn et al. (2000), comprising a selection of papers presented during the combined workshops of the second workshop of the FAIR CA, the first workshop of the INCO-Copernicus CA and an International Conference of the IUSS working group Soil Physics in March 1999, Kiel, Germany. Of course proceedings of the remaining workshops of the concerted actions will be produced. News about the progress of the concerted actions, reports and guidelines how to fill in the database workbooks are available on an Internet site: http://www.alterra.wageningen-ur.nl/subsoil-compaction/ . The production of national and international papers on subsoil is promoted. A Special Issue of Soil and Tillage Research

about the results of the FAIR CA on Subsoil Compaction is planned. It is the intention that also the results of the INCO-Copernicus CA will be presented in a Special Issue. The database on literature on subsoil compaction will be available on the Internet site. The database on soil mechanical properties and impact of subsoil compaction on soil nutrients, physical properties, crop production and environment, will be available via the European Soil Bureau.

This kind of concerted actions prove to be a good way to promote collaborative research and to collect, exchange and disseminate experience, knowledge, results of research and data. However a considerable effort is asked of the participants by the concerted actions. The start of the INCO-Copernicus CA in the second year of the FAIR CA and their close cooperation is very fruitful. The experiences with the set up of the FAIR CA, the database and the guidelines for collection of data were a basis for a flying start of the INCO-Copernicus CA. On the other hand not only the more than redoubling of the quantity of data, but also the extra year and extra labour will improve the quality and user friendliness, availability and usability of the databases to a great extent. The addition of the experience and knowledge of the INCO-Copernicus participants with their own specific soils, climate and agriculture to the experience of the FAIR CA participants will increase the insight and knowledge on subsoil compaction processes and their impact on soil properties, crop growth and environment considerably.

6. Acknowledgements

7. References

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Structure, development and use of a database about soil physical and mechanical properties and crop response as related to subsoil compaction

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Abstract

A database which considers results of field and laboratory experiments on the impact of subsoil compaction on physical, mechanical and crop parameters is being developed within the concerted action (CA) project "Experiences with the impact of subsoil compaction on soil, crop growth and environment and ways to prevent subsoil compaction". The database accumulates and provides all available data from the participants of the European Union and later from the Eastern European countries. It is expected to be highly useful for modelling and can act as a basis for the set-up of future field and laboratory experiments on subsoil compaction.
The database at the moment accumulates 274 Excel workbooks. An analysis of the filled out sheets shows amongst others that especially measurements about bulk density, water retention and penetration resistance but also some stress and strain measurements in the laboratory and in the field were carried out.

Keywords: Concerted action, database, subsoil compaction, crop response, soil physical and mechanical properties, future use

1. Introduction

In January 1998, the concerted action (CA) "Experiences with the impact of subsoil compaction on soil, crop growth and environment and ways to prevent subsoil compaction" was initiated. Bringing in experts from all EU-member-countries created a representative working group on subsoil compaction. Their task was to exchange scientific knowledge and practical experience with subsoil compaction, recognising "high-risk" farming systems and possible ways to prevent subsoil compaction. The working group also discusses ways to harmonise the various methods of research within the EU-member-countries. Any gaps in knowledge on subsoil compaction were to be determined and further research on subsoil compaction should be planned if possible. A major task within the CA was the construction of databases. Originally, three databases were planned: (1) a database on literature concerning subsoil compaction (2) a database concerning impact of subsoil compaction on soil physical properties and crop yield (3) a database on soil mechanical properties. However, it was decided that (2) and (3) would function as one database. In December 1998, a second similar concerted action including most Eastern European countries was initiated. The two concerted actions are working together and the collected data will be combined in one database. This paper gives information about the structure and development as well as the future use of the

database on soil physical and mechanical properties and crop response, as related to subsoil compaction.

2. Structure of the database

Each of 50 participants from 14 western European countries, and later additional participants from the Eastern European countries, are contributing to the database with one or more workbooks. One workbook concerns one experimental site one year, and consists of more than 50 spreadsheets.

The sheets can be divided into five categories: (1) general information, (2) soil physical parameters, (3) soil mechanical parameters, (4) crop parameters and (5) added parameters.

3. The database search routines

After receiving the workbooks, and having incorporated them into the database, the construction of the database operator routines can begin. It was decided that database operator routines should be constructed so data could be searched by *table, workbook number, country, year of the experiment, and by duration of the experiment.* Furthermore, it was decided that the following soil properties should be used as search criteria: *Texture, dry bulk density and parent material.*

New database operator routines will be added if any such wishes should occur from the participants. It is a main goal that the database is easy to use, so comments and ideas from the participants are important. The presentation of the database in the 3rd Workshop of the Concerted Action on Subsoil Compaction in Uppsala 14-16 June 2000, will include a session where it is possible for the participants to work with the database. Following this session, there will be a general discussion of the database.

3.1. Availability of the database

The availability of the database is an important issue that has been discussed. It has been decided that the database should be available to all the participants at as little cost as possible. There are several ways to achieve this. It is now decided that the database should be distributed on CD-ROM to all the participants when the work of the Concerted Action of the participants from the EU members is completed in 2000. This procedure requires that the participants have installed the relevant software (ACCESS 97) on their personal computers. The capacity of a CD-ROM is more than sufficient since it is estimated that the database with 300 workbooks from the FAIR CA will occupy about 12 Mb. Since it is expected that the INCO-Copernicus CA will deliver approximately 300 workbooks thus bringing the total amount of workbooks up to about 600, the database will occupy an estimated 30 Mb by the end of 2001.

For participants who do not have the ACCESS-program, the tables of the database will also be included in several EXCEL-formats on the CD-ROM. Cells with large amount of text, such "Remarks" as well as sheets as the "Description"-sheet will be given as a text-document (.TXT). This will allow for search of data using the EXCEL in combination with a word-processor.

The database will also be made available on the Internet. According to the contract with the EU, the database will be available on the Internet up to two years after the finishing of the concerted actions. The great advantage with making the database available on the Internet is that it may be improved very easily, and new workbooks can easily be added. The database will also require very little maintenance.

The third way to make sure that the databases will also be available on the long term to the participants of both concerted actions, fellow researchers and commercial advisers and institutes, will be achieved by making the databases available to the European Soils Bureau (ESB). The ESB will take care of the maintenance of the database and regulate the distribution of the database. The database will then be available to the participants for marginal costs, to fellow researchers for non-commercial activities for a very low price and for commercial activities for a moderate price.

4. Data now in the database

4.1. Delivered workbooks

As can be seen in Table 1 274 Excel workbooks have been delivered till now. However, due to the number of participants further workbooks can be expected.

4.2. Filled out sheets

Further informations about the state of the database is given in Table 2, where the filled out sheets about physical, mechanical and crop parameters of the workbooks are shown. As can be seen, some parameters have been carried out more intensively: bulk density and water retention as well as penetration resistance. In order to understand how the soil reacts on stress further information is required. Following the recommendations of workinggroup 4 "Soil mechanical measurements and measurements techniques four levels of increasing detail must be carried out in order to increase the precision of predictions about the soil response to stress, among them are stress and strain measurements in lab. and field " (van den Akker and Canarache 2000).

Links to the European Soil Database.

The possibility to link the database to the European Soil database have been contemplated. Since the Proforma data-sheets are the same supplied by the Participants are the same as those used in the soil profile analytic database of the European Soils Bureau (Madsen and Jones, 1995a, 1995b) the databases are therefore compatible. By establishing links with the European Soil database, several features will be available: For example, it will be possible to construct maps showing the location of the experiments in order to determine where additional experiments should be performed.

Table 1. Delivered workbooks (Ca subsoil compaction)

Northern (Baltic) region		
Participants	country	Workbooks/no.
Arvidsson	Sweden	ARVI 01-106
Alakukku	Finland	ALAK 01-09
Borresen	Norway	BORR 01-09
Schjonning	Denmark	SCHJ 01
total		*125*
Intermediate (Central) region		
Participants	country	Workbooks
Horn	Germany	HORN 01-104
Chamen	United Kingdom	CHAM 01
Koolen	Netherlands	KOOL 01
van den Akker	Netherlands	AKKE 01-04
Guerif	France	BOIZ 01
Schulin	Switzerland	BERL 01
Murer	Austria	MURE 01
Lipiec	Poland	LIPI 01-09
total		*122*
Southern (Mediterranean) region		
Participants	country	Workbooks
Hernanz	Spain	HERN 01-07
Moreno	Spain	MORE 01-03
Pagliai	Italy	PAGL 01-05
Panayiotopoulos	Greece	PANA 01-09
Aggelides	Greece	AGGE 01-03
total		*27*
total		274

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Table 2: Filled out sheets (Ca subsoil compaction)

Sheet-no.	Physical Parameters									Mechanical Parameters						Crop Parameters					
	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	24	25	26	27	28	29
Northern region																					
Arvidsson	x	x		x						x		x	x	x	x	x					
Allakuku		x	x	x						x						x	x	x			x
Borensen	x	x	x										x	x		x	x	x			x
Schjonning												x	x	x							
Central region																					
Horn	x	x	x	x			x	x		x		x		x	x	x	x				
Chamen	x	x								x			x			x					
Koolen	x	x												x							
Van den Akker	x	x	x							x						x		x			
Guerif	x	x	x	x						x											
Schulin	x	x												x							
Murer	x	x	x	x						x						x	x				
Lipiec	x	x								x					x	x	x	x		x	
Southern region																					
Hermanz	x	x								x						x					
Moreno	x	x	x		x					x						x	x			x	
Pagliai	x	x	x	x						x				x		x	x				
Panayiotopoulos	x	x									x										
Aggelides	x																				

Sheet-no. 8 = bulk density, 9 = water retention, 10, 11 = saturated hydraulic conductivity, 12, 13 = unsaturated hydraulic conductivity. 14, 15 = air permeability, 16 = air diffusity, 17 = penetration resistance, 18 = stress dependent changes of soil physical properties, 19 = laboratory shear test, triaxial test, 20 = vane shear measurements, 21 = stress and strain measurements (lab.), 22 = stress and strain measurements (field), 24 = crop yield, 25 = root density, 26 = root depth, 27 = root/shoot ratio, 28 = leaf area index, 29 = nutrient uptake

Modeling of crop growth, water and chemical movement in relation to topsoil and subsoil compaction: a review

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Abstract

Soil compaction influence in numerous ways soil physical properties, crop growth and the environment. Mathematical modeling contributes to better understanding of the complex and variable interrelationships. This paper reviews models for simulating topsoil and subsoil compaction effects. To characterise soil compactness most models available use bulk density and/or penetration resistance and water content data. The models allow assess the effects of soil compaction on crop yield, vertical root distribution, chemical movement and soil erosion. Potential for enhancing performance of the models by considering macroporosity and strength discontinuity (spatial and temporal variability of material parameters) is indicated.

1. Introduction

Soil compaction occurs when an applied soil stress exceeds the strength of the soil. It means by definition a reduction in porosity, and generally causes an increase in soil strength. Thereby, it changes many properties and processes in the soil, for example saturated and unsaturated hydraulic conductivity, air content and transport of gases, root growth and function, nutrient transport and uptake, mineralization of nitrogen and soil workability. Ultimately, this will effect for example crop yield, leachage, erosion and runoff, as shown schematically in Fig. 1.

Relating the highly variable effects of soil compaction to crop growth and environmental responses are difficult. Mathematical modeling can contribute to understand the complex interrelationships. Simulation models also allow us to integrate existing experimental data and to extrapolate to other site conditions. Numerous models have been constructed that deals with different parts of this scheme. Soil compactness is represented in the models available mostly by bulk density and/or penetration resistance and water content data.

In this paper, we review models of the effects of soil compaction on crop growth, water and chemical movement, present opportunities for improving capabilities of the models and suggest future research needs.

2. Modeling crop growth

Over the past several years, a number of crop growth models have been developed. Modeling effects of soil structure parameters on crop growth and water balance of soil – crop systems were reviewed thoroughly (Walczak et al., 1997; Conolly, 1998). In sixty different crop growth models (Walczak et al., 1997) bulk density or porosity as soil compaction characteristics are represented in 32%. Most frequently represented soil characteristics were water retention
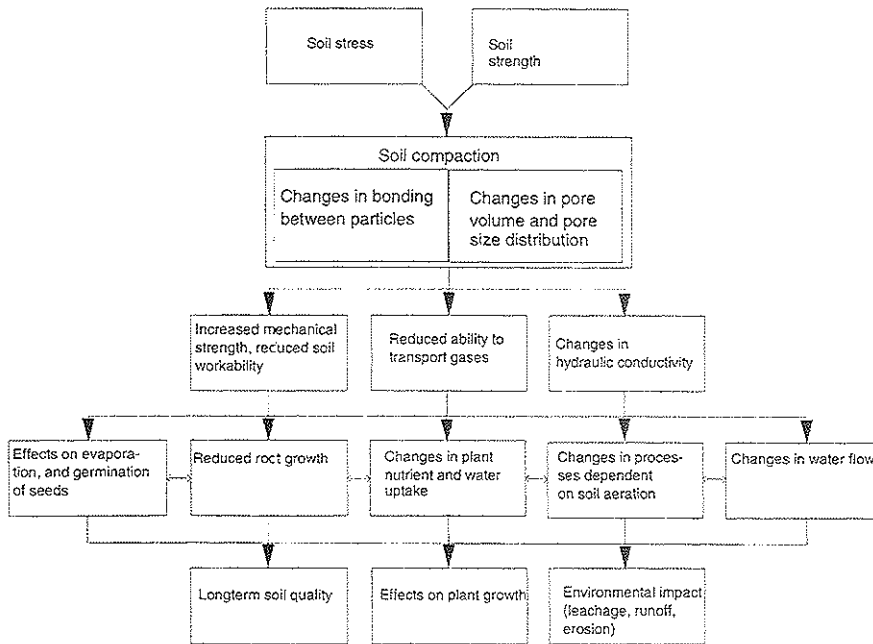
Fig. 1. Schematic diagram showing the effect of soil stress on soil properties and processes, and ultimately on long-term soil quality, crop yield and the environment. After Arvidsson, 1997.

(93%), unsaturated hydraulic conductivity (40%) and saturated hydraulic conductivity (33%) which are highly influenced by compaction.

The models available for predicting the effect of topsoil and subsoil compaction on crop growth vary widely in their conceptual approach, degree of complexity, output presentation and input parameter requirements. Summary of the models is presented in Table 1.

2.1 Root growth

Crop yields in compacted soil are mostly associated with the extent and function of the root system. In most models root growth is considered as a function of soil strength and water status. This effect can be estimated by an impedance function that is unity at zero soil strength and decreases linearly to zero at a critical soil strength value at which root growth stops (Dexter, 1987; Diggle, 1988; Bengough and Mullins, 1990). Root growth as affected by soil water matric potential and resistance can be simulated by the SIBIL model (Simota et al., 1999) in which the theory of root growth mechanics developed by Dexter (1987) is used. Soil resistance is quantified in the model using a semi-empirical model (Canarache, 1990) with clay content, bulk density and gravimetric water content as input parameters. The model SIBIL well predicted vertical distribution of root mass in variously compacted soil (Fig. 2)

Ability of roots to penetrate strong soil can increase with increasing their density (hardness) (Panayiotopoulos et al., 1994). Stenitzer (1988) assumed in SIMWASER model (Table 1) that depending on root density the values of penetrometer resistance causing beginning reduction of root growth vary from 1 MPa (low root density) to 1.7 MPa (high root density) and those stopping root growth - from 3 to 4 MPa. The critical strengths may vary depending on soil texture, macroporosity, depth and crop type (Gliński and Lipiec, 1990; Pabin et al., 1998). It

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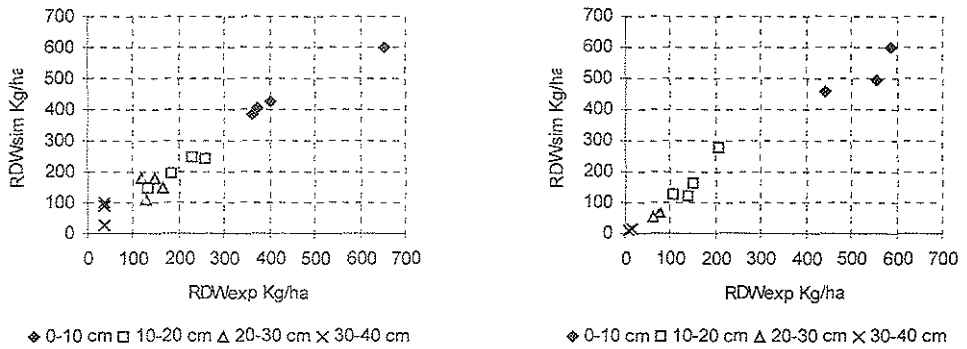
Fig. 2. Simulated vs. observed root dry weight of spring barley (at heading) for non-compacted (left) and compacted (right) soil (after Simota et al., 1999).

was shown that the values of critical soil strength and bulk density for pea root growth in the subsoil decreased with increasing content of fraction <60 μm and with decreasing soil water content (Fig. 3). However, in plough layers an increase in the fraction content resulted in greater critical soil strength for root growth due to favourable effect of organic carbon content. The presence of pores greater than roots in a dense layers will move the critical soil strength to a higher value (Ehlers et al., 1983). Setting appropriate values is thus of great importance for good simulation (Stenitzer and Murer, 1999). Scarcity of the experimental data on the 'realistic penetration resistance' is the major constraints of predictive capacity of the models(Simota et al., 1999; Stenitzer and Murer, 1999).

Soil aeration compared to soil strength was much less frequently represented in crop growth models (Walczak et al., 1997). Review of Gupta and Raper (1994) indicates that approach assuming optimum root growth in the range of soil wetness between 0 and 85% of saturation and decreasing linearly from 85 to 100% saturation is often used. Thus a negative effect of
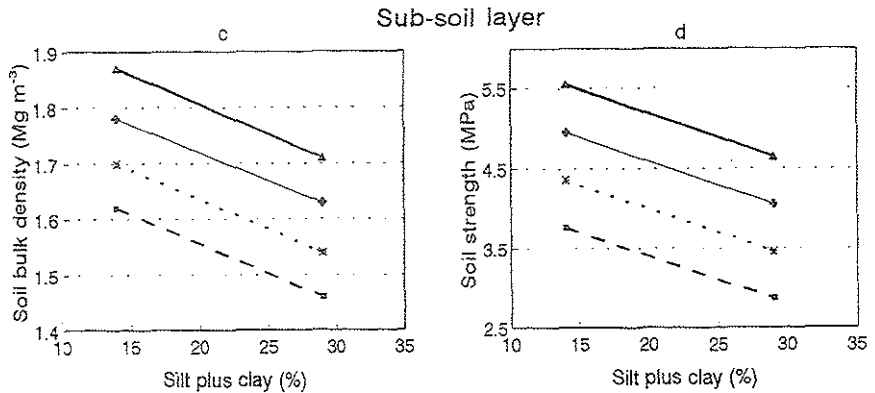
Fig. 3. Critical soil bulk density for root growth in relation to silt plus clay content, organic carbon and water level in the sub-soil layer ■ - 30; ✳ - 40; ✚ - 50 ; ▲ - 60% field water capacity (after Pabin et al., 1998)

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insufficient aeration in compacted soil will increase in soils prone to wetness (Boone et al., 1986). Insufficient aeration is often short lasting and difficult to relate to crop yield response due to soil compaction (Stępniewski et al., 1994; Håkansson and Lipiec, 2000). As indicated by Van Huyssteen and Ellis (1997) average duration of free water saturation was 1.3% for red apedal B horizons, 18.8% for yellow-brown apedal B horizons, 42.4% for yellow E and 54.2% for grey E horizons.

2.1.1 Effects of soil structural discontinuities

An important factor influencing predictability of root profile distribution is strength discontinuity. It may occur between aggregated seedbed and soil below after seedbed preparation, tilled layer and untilled subsoil, across soil horizons and various soil structural units (Dexter, 1986; Smucker and Aiken, 1992, Lipiec et al., 1993.). Table 1 presents some of the models for simulating root growth in structurally discontinuous soils. Several models performed well in predicting higher concentration of roots in the top layer of compacted soil and the decreased rooting depth in field experiments (Simota, 1993; Simota et al., 1999) or in a soil column (Grant, 1993b). Using discretized representation of a finite soil domain and local soil strength gradient in a study of Clausnitzer and Hopmans (1994) allowed calculating root growth direction vector and predict increased root density in a single-plant scale immediately above impeding layer. The presence of the structural discontinuities (dense layers) in soil profile limits application of root growth models assuming exponential declining root growth with depth (Gerwitz and Page, 1974, Feddes et al., 1988) and those using elastic modulus as a soil strength parameter controlling root growth (Rickman et al., 1992; Grant, 1993 a,b).

The discontinuities have a significant effect on root absorption. Subsoil layers are usually wetter and provide greater root-soil contact and consequently can be more effective medium for transmitting and uptake of water by roots. It was shown in growth chamber experiment that root size of maize in subsoil horizons relative to total roots was from 1 to 38 % while water use - from 54 to 74% depending on soil type (Lipiec et al., 1993). As a consequence root uptake is not always linearly correlated with greater root size. Some models allow for a preferential uptake from wet compared to dry sites (de Willligen and Noordwijk van, 1987) and anoxic sites (Schmidhalter et al., 1994).

The profile discontinuities make it difficult to separate the effect of topsoil and subsoil compaction (Lindstrom and Voorhees, 1994). Smucker and Aiken (1992) in their review indicated that to describe root functions successfully we need to move away from the simplistic approach that water is absorbed uniformly in soil profile and to include enhancements of the Darcy/Richard's equation to predict the movement of water across the structural discontinuities. In addition incorporating to models compensatory root growth and uptake in favourable local environments and short time intervals (diurnal or hourly) of the dynamic root and soil interface may increase performance of the models (de Willigen, 1990; Smucker and Aiken, 1992). Clothier and Green (1997) indicate that Time Domain Reflectometry for measuring dynamic soil water content close to roots and near the soil surface provides means by which we can better view the root zone fluxes of water and chemicals.

Another structural discontinuity is the presence of macro-pores of a diameter greater than the roots. The significant importance of continuous and stable macro-pores such as inter-pedal voids, bio-pores or dessication cracks for root growth as well as for gas, water and solute transport has been reported by several authors (Hatano and Sakuma,1990; Whalley and Dexter, 1994; Lipiec and Stępniewski, 1995). The continuous bio-pores may be particularly advantageous in strong subsoil horizons because they frequently provide the only possible pathways for root growth and are resistant to vertical compression (Ehlers et al., 1983; Whalley and Dexter, 1994).

The relationship between the distribution of macropores and roots can be described

numerically using fractal analysis (Hatano and Sakuma, 1990; Lipiec et al., 1998). The studies showed relation between fractal dimensions of distribution patterns of macro-pores and plant roots in strong soil. Macro-pores significantly influenced crop growth in modeling work of Jakobsen and Dexter (1988).

2.2 Crop yield

There are several models available for predicting the effects of topsoil and subsoil compaction on crop growth and yield (Feddes et al., 1984; Simota et al., 1999; Stenitzer, 1988) (Table 1). They are mostly designed for simulating water flow and dynamics using Darcy/Richard's one-dimensional flow equation or water and heat flow based on Fourier's law (Jansson, 1988). Unsaturated hydraulic conductivity is calculated from the water retention curve. Water balance and plant growth can be linked together by physiological interactions. The actual plant growth is calculated by the potential production rate as the proportion of actual transpiration to potential transpiration. Soil compaction effects can be simulated directly by considering bulk density or porosity (Walczak et al., 1997) or indirectly by changing inputs for saturated hydraulic conductivity, soil water retention, unsaturated hydraulic conductivity, root depth and root distribution (Rajkai et al., 1997; Eckersten et al., 1998). The lower measured saturated hydraulic conductivity improved crop yield predictions from the Erosion-Productivity Impact Calculator (EPIC) model but created too many water stress days resulting in under-estimated yields (Warner et al., 1997a).

Arvidsson and Håkansson (1991) constructed an empirical model to predict effects of compaction on crop yield based on results from a large number of experiments, mainly carried out in Sweden. To adjust the model to other regions, local yield data is of great value.

Jakobsen and Dexter (1988) constructed one of the few models that simulates soil water flow and crop growth, and where root growth is calculated from the strength of the soil.

3. Modeling of water and chemical movement

Most models for simulating water and chemical movement are based on Darcy/Richard's one-dimensional flow equation (Walczak et al., 1997; Connolly, 1998). Effect of soil compaction on water movement and redistribution in the soil profile is mostly through changes in hydraulic properties (Walczak et al. 1997) and indirectly through influences on soil mechanical resistance and aeration status and related root growth and uptake (Horton et al., 1994). Numerical models for prediction field compaction effects on soil water and thermal regimes were reviewed by Horton et al. (1994). The authors indicate that simulated water and heat flow were sensitive to traffic compaction and ridge configuration. An appropriate prediction of soil water movement is required to accurate modeling solute transport (Jarvis, 1991; Feyen et al., 1998). Chemical leaching from agricultural fields is a major source of contamination for water resources in many regions. The effects of soil compaction on components of the environment are illustrated in Figure 2. (Soane and Ouwerkerk, 1995).
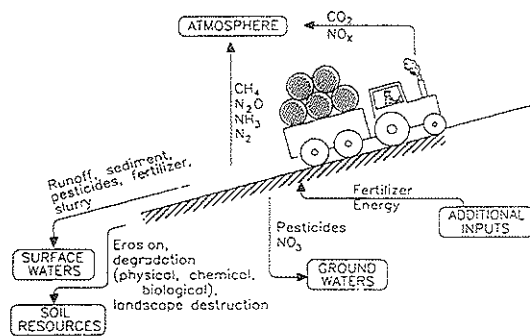
Fig. 2. A conceptual diagram showing the influence of soil compaction on components of the environment (after Soane and Ouwerkerk, 1995)

Effect of soil compaction on soil nitrogen dynamics can be simulated by STOTRASIM model (Feichtinger, 1996) (Table 1). The main attention is directed to the environment aspect of groundwater pollution by nitrate. STOTRASIM calculates also soil moisture regime and plant growth and the nitrogen cycle for agriculturally used soils. For that precipitation, irrigation, fertilisation, evaporation and interception, plant uptake, volatilisation, denitrification, mineralization, immobilization and the storage and transport in the soil are considered. Castle et al. (1999) showed that the potential for denitrification in glacial till subsoil layers is sufficient to reduce NO_3^- leaching to ground- or surface-waters to levels unlikely to result in pollution hazard. The major product of NO_3^- reduction in these subsoil layers was N_2, rather than the greenhouse gas and catalyst of stratospheric O_3 removal, N_2O. Warner et al. (1997a) reported that nitrate concentrations in a fine sand loam underlain by a compact glacial till can be predicted by EPIC model. The predictions were better for fallow than maize and for deeper than shallow soil depths.

Many soil nitrogen models were designed for advising farmers and their suitability for estimating environmental impacts is limited (O'Sullivan and Simota, 1995). Models for simulating agricultural chemical transport in lysimeter conditions were reviewed by Borah and Kalita (1999).

3.1 Effects of macro-pores

A soil matrix with macro-pores such as inter-pedal voids, bio-pores or dessication cracks offer greater potential for undisturbed growth of roots and have a significant effect on the water flow and solute transport processes. Compaction has a great influense on macro-pore flow, but there have been few attempts to model these effects. Under a flow at 0-cm tension, macro-pores >0.5mm and meso-pores 0.06 to 0.5 mm (radius for cylindrical pores or width for planar pores) contributed about 89% and 10% of the total water flux, respectively (Lin et al. 1996). The presence of macro-pores is distinguished as soil micro-heterogeneity (at the pore scale) (Feyen et al., 1998). It was shown that incorporating the flow macro-pore component into models that assume a horizontally homogenous soil profile improve their performance (Jarvis, 1991; Ludwig et al., 1999; Kumar et al., 1999; Borah and Kalita, 1999). Change in the macro-pore rate is (also) used as a measure of soil compaction (Diserens et al., 1998; Kumar et al., 1999). Kumar et al. (1999) assumed it to be inversely proportional to that of bulk density.

Sławinski et al. (1996) developed the CRACK sub-model of bypass flow through cracks or macro-pores and water redistribution in the soil matrix following infiltration to the horizontal soil layers (using the Green-Ampt approach). The sub-model enhanced performance of the ACCESS-II hydrological model (based on Richard's one-dimensional flow) in predicting water distribution in plough and subsoil layers in two sites in Poland (Walczak et al., 1996). By replacing the air-filled porosity in the Green-Ampt model with the active macro-plus

mesopores, calculated wetting front depths were close to observed maximum dye depth (Lin et al. 1996). Simultaneous ground and macro-pore flow occur in all except very coarse soils (Hatano et al., 1992; Horton et al., 1994; Feyen et al., 1998).

Macro-pore flow significantly influences pesticide movement in soil. Sadeghi and Isensee (1992) reported that atrazine movement in the subsoil, was more affected by the presence of macro-pores in the no-till than in conventionally tilled plots. Atrazine residues in the topsoil residues were higher in tilled conventionally than in no-till soil due to the presence of a ploughpan at about 30-cm depth. The movement of atrazine through macropores is greatest when high-intensity rainfall occurs shortly after atrazine application (Edwards et al., 1993). It was shown that prediction of pesticide leaching by the deterministic model MACRO (Jarvis, 1991) is highly sensitive to soil hydraulic properties defining the macropore region (e.g. hydraulic conductivity at the boundary water content). The model successfully described the leaching pattern of chlorsulforun (pesticide) with the minimum calibration related to evapotranspiration, water uptake by roots and degradation rates in the subsoil (Bergstrom, 1996).

Several studies have revealed that incorporating the macropore flow subroutine improved prediction of atrazine concentration by one-dimensional Richard's flow models LEACHM (Leaching Estimation and Chemistry Model) (Borah and Kalita, 1999) and RZQWM (Root Zone Water Quantity Model) (Kumar et al., 1998; Kumar et al., 1999). Hatano et al. (1992) using fractal analysis found that macro-pore flow contributes significantly to patterns of miscible displacement and is different depending on the type of macro-pores and the smoothness of their walls. This analysis also showed that the flow regime is almost two-dimensional and occurs through both macro-pores and ground mass.

The effect of macro-pore on transport of nutrients increases with their initial concentrations in soil. These were considered in prediction of phosphate (Hansen et al. (1999) and nitrate leaching (Jarvis, 1991).

Chemical movement in macro-pores depends on sorption capacity of the soil. Several authors (Cox et al., 1998; Levanon et al., 1993; Hansen et al., 1999) reported that lower leaching of agro-chemicals in macro-porous soil can be attributed to enhanced sorption (in no-till due to greater organic matter and lower pH).

An empirical model study on four macropore soil materials in the Eg and Btg horizons showed that the risk of phosphate leaching through subsoil macropores is significantly affected by P sorption capacity of the soil materials closest to the lumen of macropore (Hansen et al., 1999). Macropore walls in fractures (but not in earthworm burrows) in the Albic material (poor in iron oxide and bleached) with the smallest P adsorption capacity does not minimise the risk of phosphate leaching. However, usually greater adsorption is predicted when an average bulk sample is considered. Therefore, sorption properties of macropore materials need to be included in models describing transport of reactive substances in macro-porous subsoil layers. Because of fast water flow in macropores sorption reactions are far from equilibrium and the modeling studies should consider a fast initial reaction (timescale of miliseconds to seconds). Preferential transport of phosphate is of great importance in the clayey pseudogleys with low adsorptive subsoil layers and phosphate rich plough layers. Lower leaching of agrochemicals in macroporous can also be reduced by degradation.

Inclusion of measured compared to estimated macro-porosity (assumed to be reduced proportionally to an increase in bulk density) enhanced model performance in chemical movement and concentration (Borah and Kalita, 1999; Kumar et al., 1999). In cracked clay soils the shrinkage characteristic is used in modeling to determine crack volume, area and depth (Kroes et al., 1998).

Recently developed numerical model SWAP (Soil-Water-Atmosphere-Plant) (Kroes et al., 1998) is the successor of the agro-hydrological model SWATR (Soil Water-Actual

Transpiration) (Feddes et al., 1978) and some of its numerous derivatives. Main improvements are accurate numerical solution of the Richard's flow equation and incorporation of solute transport, heat flow and soil heterogeneity. It integrates water flow, solute transport and crop growth according to current modeling concepts and simulation techniques. The model can be useful to predict effects of soil compaction.

4. Soil erosion

Effects of soil compaction on erosion may be a serious environmental impact. The process may occur due to a decrease in the infiltration rate of the soil, for example in wheel ruts, or due to layers with low hydraulic conductivity, such as plough pans. Fleige and Horn (2000) measured a great increase in erosion in wheel ruts compared to untrafficked land. Bazoffi and Pellegrini (2000) found that wide low-pressure tyres caused a significant increase in erosion compared to normal tyres, possibly because the wheel tracks of the wider tyres covered a larger part of the field.

Numerous models exist to simulate erosion under various conditions. One of the most widely used is RUSLE (Revised Universal Soil Loss Equation) (Renard et al., 1991), which is mainly an empirical model based on properties of the soil surface and the crop canopy. Therefore, it is not really suitable for simulating effects of subsoil compaction on erosion. For this purpose, more physically-based models like WEPP (Laflen et al., 1997) and LISEM (de Roo and Wesseling, 1996) are more suitable. LISEM is a physically-based single-event hydrological and soil erosion model. For example, it can take into account the hydraulic conductivity of different soil layers, and the effect of wheel tracks on the soil surface. WEPP is also a physically-based model to simulate runoff and erosion. It makes daily simulations based on soil and crop properties, driven by meteorological data and should be suitable for simulating effects of subsoil compaction on erosion.

5. Spatial variability in modeling of soil parameters

Spatial variations involved with the input parameters may reduce certainty of the model output data (Horton et al., 1994; Verma et al., 1995). The spatial distribution within the field is closely related to the distribution of wheel tracks (Arvidsson and Håkansson, 1991; Walczyk, 1995). The knowledge of the spatial dependence of penetration resistance may reduce the number of penetrations and sampling positions for accurate evaluation of the effectiveness of tillage practices and mechanical impedance for root growth. Geostatical analysis showed that the range of influence (the distance over which the semi-variance increases) was greater in compacted than loose soil (Lipiec and Usowicz, 1997). In non-compaced soil the range was greater in stronger subsoil compared to the plough layer. The results imply that sampling interval for representative results should be smaller in loose soil. Chan and Hodgson (s.sci. 1995) reported that strength of the subsoil of a Vertisol was significantly higher and less spatially variable in a cropped soil compared with a pasture soil, indicating loss in the heterogeneity and changes in structural organisation as a result of cropping. Greater variability of pore distribution patterns in loose than compacted soil was shown by fractal analysis (Lipiec et al., 1998).

Koszinski et al. (1995) reported that clay and total C contents, dry bulk density and rootability in the subsoil (55 cm) were autocorrelated over a distance of about 25 to 50 m, whereas soil structural parameters, such as numbers and area of macropores as well as permeabillity properties, varied randomly even over the shortest distance (10 cm). Both in the topsoil (15 cm) and plough pan (30 cm) most parameters show random variation over short sampling distances of 10 cm. This information is of significant importance for spatial interpolation of soil properties.

Spatial variability in soil hydraulic properties and water significantly influence model predictions of main water budget components as evaporation and drainage storage (Maraux et al., 1998). Simulation agreement with measured data was the highest in the less variable subsoil layer 60-100 cm. Also nitrate concentration was better predicted in deep compared to than shallow depths using the EPIC model in a fine sandy loam underlined by compact glacial till (Warner et al., 1997a,b). Spatial variability of the hydraulic functions in models can be described with the scaling concept. In the SWAP model (Kroes et al., 1998) the reference hydraulic functions and the corresponding water and solute balance and relative crop yield are generated by a number of scaling factors (Kroes et al., 1998). Pachepsky et al. (1995) showed that scaling of soil water retention can be described by a fractal model. The scaling is an important issue in dealing with a quantitative prediction at field or regional scales (Feyen et al., 1998). Soane and Ouwerkerk (1995) stress that the spatial variability of soil properties, both vertically and horizontally, should be taken into account in studies of soil compaction effects.

6. Conclusion

Soil compaction effects on crop growth and water and chemical movement can be predicted by deterministic, mechanistic, empirical and finite-element models depending on the aim of simulation and applicability. Soil compactness is mostly represented in the models directly by bulk density (or total porosity), penetration resistance and water content or indirectly by water retention and hydraulic conductivity. The model parameter values vary depending on soil texture, depth, crop and root type. There is a considerable potential to improve model performances by incorporating the relationships between macropores and root growth, water and solute flow and sorption characteristics. The model prediction is sensitive to spatial and temporal variability in input parameters that are largely influenced by compaction. Several model parameters exhibited lower spatial variability in the subsoil than in the topsoil. Scarcity of the data considering spatial variability limits modeling of soil compaction effects.

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Table 1. Selected models for crop growth and water and chemical movement.

Model	Scale	Type	Description	Performance
Sibil Simota and Canarache, 1988, Simota et al, 1999	Point	Mechanistic	Evaluates soil water dynamics and crop growth as affected by solar net radiation/air temperature/soil resistance to penetration.	Performance was found to be satisfactory for simulating root growth and crop yield in compacted soil. Validated under different site conditions in Romania (..) and Poland (Simota et al., 1999).
SIMWASER Stenitzer, 1988	Field	Mechanistic	Simulates water flow and plant growth from interactions of assimilation and transpiration. Soil compaction effect is represented by penetration resistance, aeration and water content.	Fairly good simulation maize yield reduction was found in a field studies in Austria (Stenitzer and Murer, 1999) and Spain (Moreno..Murer?).
Jakobsen and Dexter, 1987	Point	Deterministic, Mechanistic	Simulates wheat root growth, water uptake and grain yield as affected by soil strength.	Suitable for root growth simulation in crop growth models (e.g. Simota and Canarache, 1988; Simota et al. 1999)
Arvidsson and Hakansson, 1991	Field	Mechanistic, Deterministic	Compaction effects are simulated by changing soil physical, chemical, biological and/or crop parameters. Estimates crop yield losses as affected by traffic intensity and soil water content. Effects of topsoil and subsoil compaction are treated separately.	The model is based on results from northern Europe and nothern America and it is not restricted to Sweden where developed.
SWACRO Feddes et al., 1984 Feddes et al., 1988	field	Mechanistic	Simulates soil water movement and crop growth.	Performed well in predicting subsoil compaction effects on root growth and yield of potatoes in the Netherlands.
Jakobsen and Dexter, 1988	Point	Deterministic, Mechanistic	Simulates effect of biopores on root growth, water uptake and grain yield of wheat	Simulated grain yield was significantly improved by relatively low biopore density.

Reference	Scale	Type	Description	Evaluation
Grant, 1993a,b	Soil column	Integrated	Simulates root growth from several existing algorithms between root growth and soil strength, oxygen transport, temperature, and root turgor.	Capable of simulating vertical root distribution as functions of layered soil compaction. Satisfactory evaluation was found in soil column experiment. Large computer memory required.
Clausnitzer and Hopmans, 1994	Point	Mechanistic, Finite-element grid	Simulates water movement and root growth direction as a function of local soil strength, temperature and texture. .	Permits account for the influence of soil properties on root growth and function in a single-plant scale. Good prediction of increased root density immediately above impeding layer.
SOIL Jansson, 1988	Point	Mechanistic	Simulates water and heat flows in a layered soil with vegetation.	Performed well in predicting bulk density and saturated hydraulic conductivity effects on soil water dynamics in under wheat and maize in Hungary (Rajkai et al., 1997). Not satisfactory crop yield simulation in the same study
DAISY Hansen et al., 1990	Point	Empirical	Simulates soil water and heat flows and nitrogen dynamics.	No data
CRACK Slawinski et al., 1996	Field	Deterministic	Simulates bypass flow through cracks or biopores and water redistribution in the soil matrix (Green and Ampt approach) to the horizontal soil layers.	Added to hydrological model ACCESS-II (Richard's one dimensional flow) improved significantly water distribution in topsoil and subsoil (Walczak et al., 1996)
SOIL-N Eckersten et al., 1996; Eckersten et al., 1998	Point	Mechanistic, Deterministic	Simulates nitrogen transformation and crop yield based on the availability of nitrogen. The effects of topsoil and subsoil compaction on crops can be simulated changing saturated and unsaturated hydraulic conductivity, soil water retention, root depth and distribution as input	Performed well limited N supply and maize growth in compacted soil under dry season in Hungary (Rajkai et al., 1997).

Model	Scale	Type	Description	Performance/Comments
STOTRASIM Feichtinger, 1996	Point	Deterministic, Mechanistic	Combination of SIMWASER model (Stenitzer, 1988) and a submodel to calculate nitrogen cycle dynamics. Simulates groundwater pollution by nitrate, nitrogen cycle, soil moisture regime and plant growth.	
LEACHM (Wagenet and Huston, 1992, cited by Borah and Kalita, 1999)	Point	Deterministic, Mechanistic	Simulates water (Richard's eq.) and solute movement (convection-diffusion eq.) as a function of evapotranspiration and root distribution.	Performed satisfactory nitrate and pesticide movement in several studies (e.g. Borah and Kalita, 1999)
RZQWM USDA-ARS, 1992	Point	Deterministic, Mechanistic	Estimates movement of nutrients and agrochemicals in soil profile of a unit area related to soil management, bulk density and micro- and macroporosity (Green-Ampt approach).	Capable of predicting atrazine movement and NO_3–N average concentration in soil profile. Including measured (not assumed) and preferential flow component improves significantly predictive capability of the model (Kumar et al., 1998; 1999).
MACRO (Jarvis, 1997)	Field	Deterministic	Simulates impact of dual porosity (micropores and macropores) on water movement, solute transport in macroporous soils.	Performed well leaching pattern of chlorsulfuron (pesticide) with the minimum calibration related to evapotranspiration, root water uptake and degradation rates in the subsoil (Bergstrom, 1996 –internet)
EPIC (Williams et al., 1989)	Field	Deterministic, Functional	Estimates effects of soil erosion losses and cropping systems on crop growth.	Incorporating a submodel of root growth as a function of bulk density affected simulation of root growth of a dryland cotton (Bland and Jones, 1992).

Simulation of the soil water balance of irrigated maize on a moderately compacted sandy loam soil in SW Spain

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Abstract

The simulation model SIMWASER was tested on data from an irrigation experiment on a sandy loam soil with a somewhat compacted subsoil in the Guadalquivir river valley in SW Spain. The differences between simulated and the measured components of the soil water balance agreed within 10% of the respective values.

1. Introduction:

The increase of process modelling of water balance in tillage experiments has imposed a demand of accurate measurements of soil physical properties, crop development and crop yield (Moreno et al., 1997). For given climatic conditions, and a particular soil-plant system, both the method of tillage and the system of irrigation can, however, alter the soil structure (Messing and Jarvis, 1993). For cultivated soils, the transport properties of the soil top layer can change during the growing season and thus to affect the water balance. Simulation models may be valuable tools in agricultural water management, if they are able to describe the processes, which are the most relevant for a given problem. In case of subsoil compaction for example the influence of soil strength upon effective rooting depth is very important for the amount of soil water storage which is available for crop water use. In the present work the simulation model SIMWASER (Stenitzer & Murer, 2000), by which this effect is accounted for, is tested on extensive data from irrigation experiments with maize in SW Spain (Moreno et al., 1996).

2. Materials and Methods:

2.1. Experimental site

The experiments were conducted at the experimental farm of the Instituto de Recursos Naturales y Agrobiología de Sevilla (IRNAS, CSIC) located at Coria del Río close to Seville city in SW Spain (37° 17' N, 6° 3' W). The climate is typically Mediterranean, with mild rainy winters and very hot, dry summers. The average annual rainfall (average 1971-1992) is 550 mm and most falls between October and May.

An experimental plot of 0.1 ha was used. Spatial variability of some physical and chemical soil properties was analyzed by kriging (unpublished data), after taking samples at the nodes of a 5 x 5 m grid. The soil is a sandy loam (Xerochrept), developed on limey sandstone of the Aljarafe Miocene, with a depth of more than 3 m. The spatial variability of some soil properties was studied after taking samples at the 45 grid nodes of a 5 x 5 m cell mesh, at two

depths, 0-0.5 m and 0.5-1 m. Mean textural values are, at 0-0.5 m and 0.5-1 m respectively: coarse sand 60.7%±4.9 and 57.3%±4.6; fine sand 16.8%±2.8 and 17.8%±3.0; silt 9.0%±1.8 and 8.3%±2.1; clay 13.1%±2.2 and 16.4%±1.9. Organic matter contents are 0.88%±0.15 and 0.55%±0.09 at depths of 0-0.5 m and 0.5-1 m respectively.

2.2. Crop management, treatments and tillage operations

The experimental plot was divided into two subplots, A and B, each of 450 m^2, with the aim of establishing two nitrogen fertilization treatments. Both subplots were cropped with maize (cv. Prisma) during three consecutive years from 1991 to 1993. Planting was carried out on the 5th of April 1991, 24th of March 1992, and 24th of March 1993. The rows were 0.8 m apart, and with a plant density of 75,000 plants ha^{-1}. Subplot A had 510 kg N ha^{-1} yr^{-1}, a rate widely used in the area. Subplot B at 170 kg N ha^{-1} yr^{-1}, was one third of this. Fertilization was applied at three times: one deep fertilization of 1000 kg ha^{-1} (15-15-15 complex fertilizer) some 10 days before planting, and two top dressings at about 45 and 75 days after planting. Each top dressing consisted of 400 kg urea ha^{-1} (46% N) in subplot A and one third of this amount in subplot B. Standard management practices, typical for the Guadalquivir river valley, the main area for irrigated maize in the region, were used. The crop was irrigated by furrow in both subplots, but some sprinkler irrigations were applied between planting and the establishment of the furrows. Dates and quantity of irrigation are given in Fig. 1. Irrigation stopped at about the end of July, or the beginning of August, some 20 days before harvest. The crop was kept healthy and free of weeds. The land surrounding the experimental plot was cropped every year with furrow or sprinkler irrigated crops (maize or cotton). This minimized the advection. Rainfalls during the experimental period are given in Fig. 1.
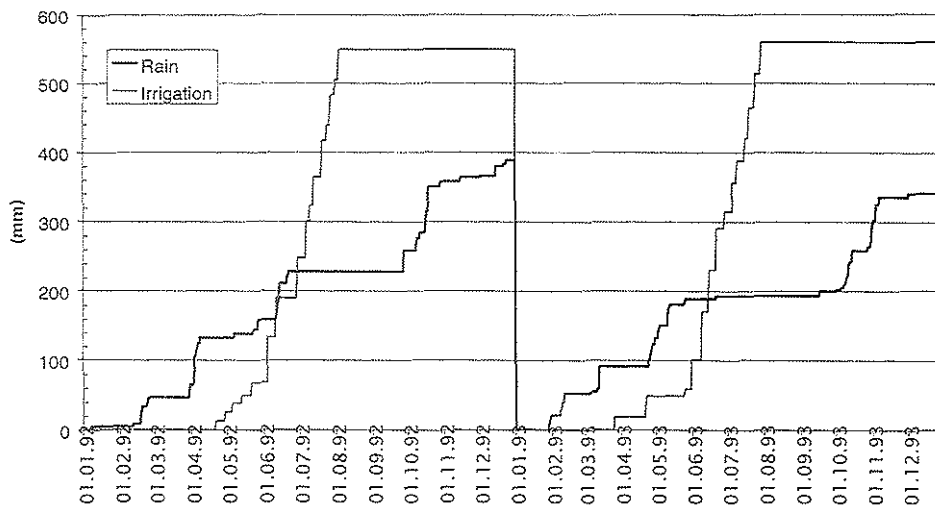

Figure 1: Cumulative Rainfall and irrigation during the experimental period.

Tillage operations consisted: mouldboard ploughing 25-30 cm depth after harvesting of maize crop, disc harrowing 15 cm depth (twice crossing the field) before sowing and cultivator application (15-20 cm depth) between crop row as secondary tillage.

The soil of the plot was kept bare during the period between the harvest and the beginning of the next crop season.

2.3. Measurements

Several measurement sites were installed in every subplot (three in subplot A and three in subplot B, named A1, A2, A3 and B1, B2, B3, respectively), each one equipped with the following equipment:

- One access tube for the neutron probe to measure soil water content every 0.1 m down to 2.3 m.
- Five mercury tensiometers at 0.3, 0.5, 0.7, 0.9 and 1.1 m depth.
- Soil water content was monitored every five or seven days during the crop period. During the bare soil period these measurements were carried out every two weeks, and always after a rainfall. Tensiometer readings were recorded daily during the crop season, and one or two times per week during the bare soil period.
- Rainfall and micrometeorological data were obtained from a meteorological station situated in the experimental farm, 200 m away from the plot.
- Some crop development parameters (crop height, leaf area index and root density), nitrogen uptake by the crop and yield were determined.

These measurement sites were located where the study of spatial variability indicated representative locations of the main soil parameters. Thus, rather than replicate the subplots, detailed measurements were taken within them to determine the water balance components accurately.

2.4. Determination of water balance

The water balance was calculated from the mass conservation equation:

$$\Delta S = R + I - D - AET \tag{1}$$

where ΔS is the change in water storage (mm) in the soil profile exploited by the roots, R the rainfall (mm), I the depth of irrigation applied (mm), D the drainage (mm) at a depth (z_r) below the root zone, AET the actual evapotranspiration (mm). Water runoff was neglected because it was practically nil on this field site.

The drainage component D was estimated using Darcy's law

$$D = q \, \Delta t = -K(\theta) \, \text{grad} \, H \, \Delta t \tag{2}$$

where q is the mean volumetric flux density (mm d^{-1}) during Δt, Δt is the period of time (d), $K(\theta)$ is the hydraulic conductivity (mm d^{-1}) corresponding to the water content θ at a depth z_r, and grad H is the hydraulic head gradient at the same depth. For the application of this method $K(\theta)$ must be known. The $K(\theta)$ relationship was determined by the internal drainage method (Hillel et. al., 1972) at a selected site of the plot, and by the application of the "zero flux plane" method (Vachaud et. al., 1978) at every measurement site. From these determinations the following $K(\theta)$ was deduced:

$$K = 7.49 \ 10^{-6} \exp(63.5\theta) \tag{3}$$

$$(r^2 = 0.84)$$

2.5. *The Simulation model SIMWASER*

The model SIMWASER (Stenitzer, 1988) is designed to describe one-dimensional, vertical flow of water in a soil profile; inter-flow and preferential flow are neglected. Water balance and plant growth are linked together by the physiological interaction of assimilation and transpiration. The increase of dry matter production depends on taking carbon dioxide from the air in exchange for water vapour via the stomata. As long as the delivery of water to the stomata can satisfy potential transpiration, potential assimilation and potential plant growth take place. The actual plant growth is calculated from the potential production rate as the proportion of actual transpiration to potential transpiration (Equation 4).

$$P_{act} = P_{pot} * T_{act} / T_{pot} \tag{4}$$

P_{act}, P_{pot} actual and potential plant production
T_{act}, T_{pot} actual and potential transpiration

Potential evapotranspiration PET, is calculated according to the well known "Penman-Monteith- formula"; potential evaporation and potential transpiration are derived from PET in dependence on the development stage of the plants. Actual transpiration is equivalent to the root water uptake, which is the result of balanced forces at the root surface and is calculated according to equation (5).

$$WUR = (\Psi p - \Psi s)/(Rp - Rs) * RLD * H \tag{5}$$

WUR water uptake by roots within a soil layer
Ψp plant water potential
Ψs soil water potential
Rp plant resistance
Rs soil resistance
RLD root length density within the soil layer
H thickness of the soil layer

The water balance on daily base is made at the soil surface with precipitation and irrigation as input and evaporation and transpiration as output. Interception is also taken into account. The water movement within the soil is calculated by Darcy's Law and the "continuity equation". Taking into account the soil physical parameters of each soil layer either capillary rise or seepage will be the result at the lower boundary of the soil profile.

Impact of soil compaction upon root growth is expressed by a so called "root growth factor RF", which represents the relation of actual current root growth to its potential value under ideal growing conditions. In the present version of the model RF is influenced by mechanical soil resistance against root growth only (Figure 2), poor aeration is supposed to influence root growth also and is represented by a "water logging factor WLOGF" (Equation. 6). Possible chemical or toxic influences are not taken into consideration.
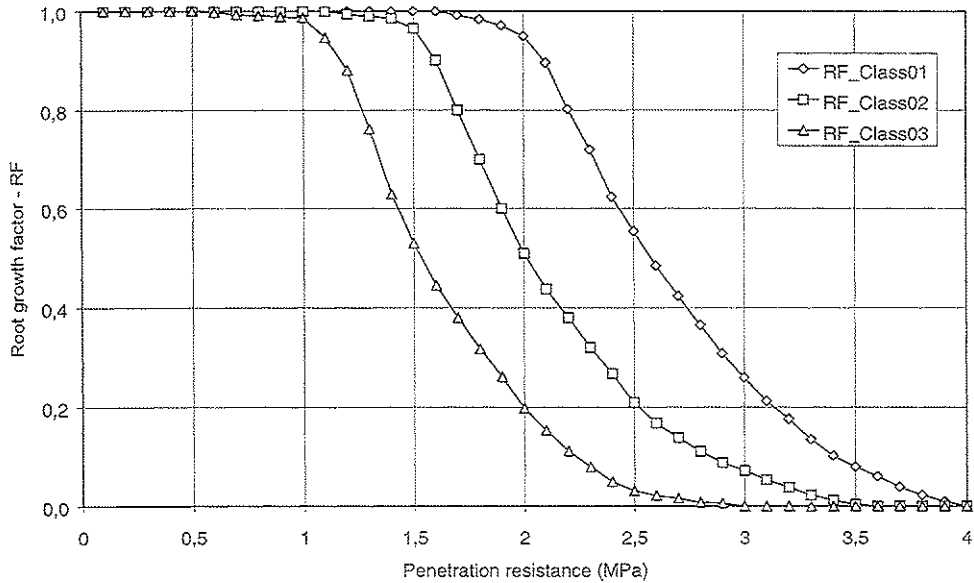
Figure 2: Theoretical Root Growth Factor RF for different root types (Class 01: very dense; Class 02: medium; Class 03: weak)

As long as the (vertically growing) root tips are growing within a soil layer (i), WLOGF of this layer is calculated as (Equation 6):

$$WLOGF(i) = \text{function of } ((WSAT(i)-W(i))/AIRMIN) \qquad (6)$$

WLOGF(i)	reduction factor due to poor aeration in soil layer (i)
WSAT(i)	water content at saturation (Vol.-%) of soil layer (i)
W(i)	soil water content (Vol.-%) within soil layer (i)
AIRMIN	minimum air volume necessary for good plant growth

Daily assimilation is influenced by the weighted mean value of all WLOGF(i) throughout the current rooting depth (Equation 7):

$$WLOGMEAN = SUM(WLOGF(i)*RDM(i))/SUMRDM \qquad (7)$$

WLOGMEAN	mean "Water logging" - factor
WLOGF(i)	reduction factor (s. equation 3)
RDM(i)	root dry matter within soil layer (i)
SUMRDM	total root dry matter

Soil resistance against root growth is represented by penetrometer resistance PE, which is supposed to be a soil physical parameter depending on soil texture, bulk density and water content (Borchert, 1987). For running the model SIMWASER the soil physical parameters "pore size distribution" (Figure 3) and "capillary conductivity" (Figure 4) of each typical soil layer as well as its "penetrometer resistance" (Figure 5) must be available in a tabulated format as functions of the matric potential!

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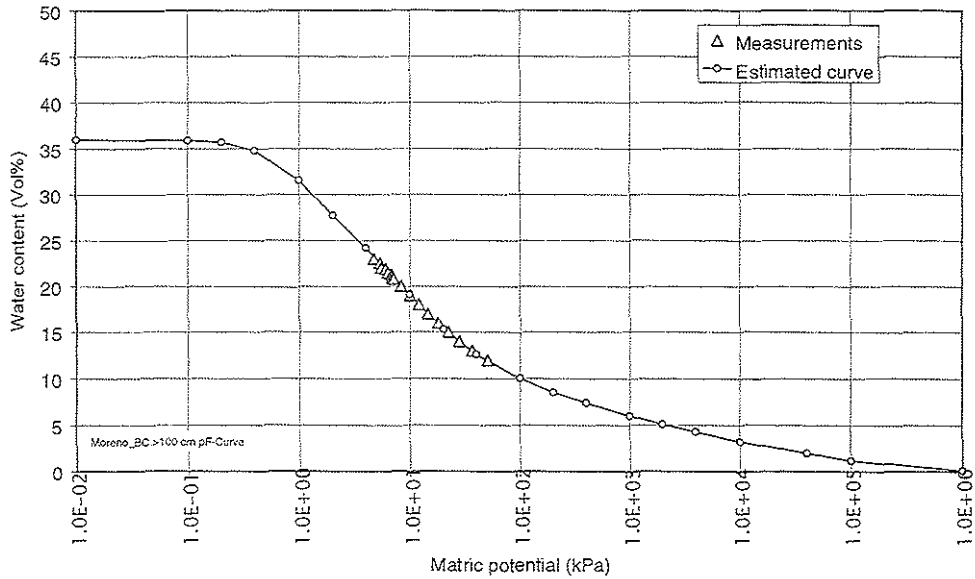
Figure 3: Pore size distribution in 100 cm depth at the experimental field
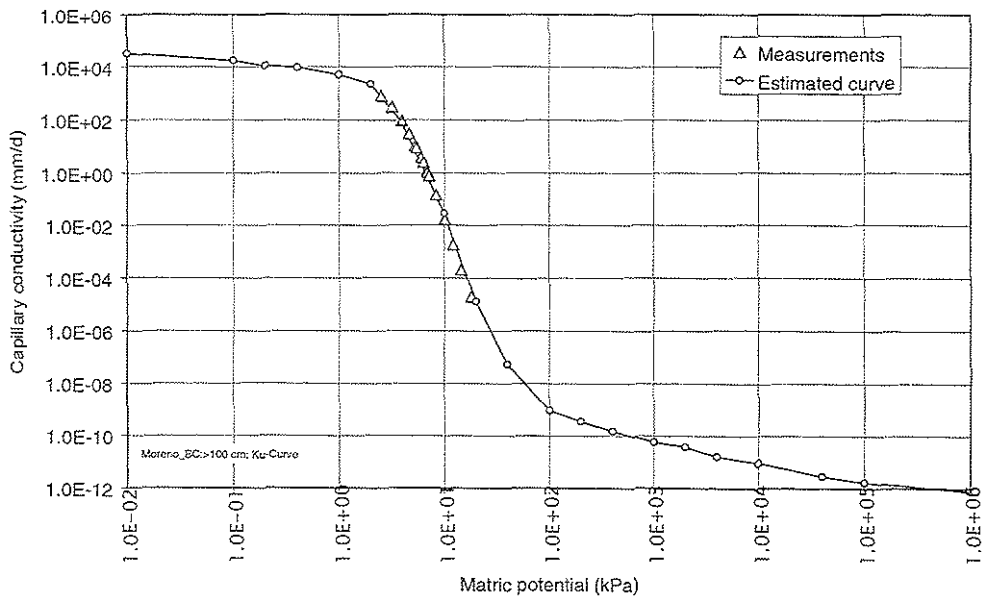
Figure 4: Capillary conductivity in 100 cm depth at the experimental field
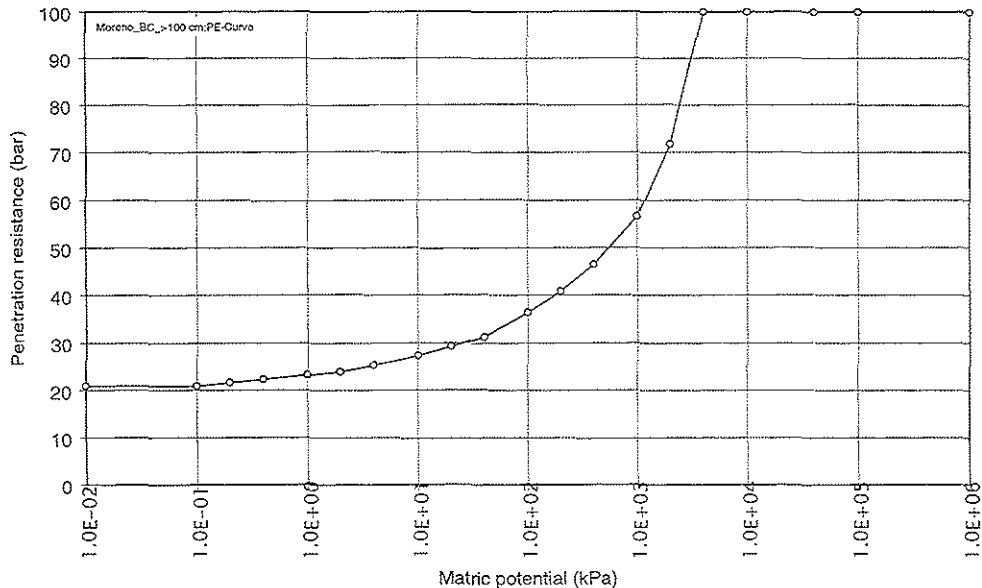
Figure 5: Penetration resistance in 100 cm depth at the experimental field

3. Results

The Fig. 6 shows results of simulated and measured soil water content in different soil layers of the profile during the maize crop seasons in 1992 and 1993. In general, the values simulated by the model agree fairly good with the measured values, particularly for the crop season of 1992. In contrast, some discrepancy was observed between simulated and measured soil water content at the depths of 30 and 50 cm during the last part of the crop season in 1993. At this time, the model tended to underestimate the soil water content in the mentioned soil depths. This could be related with the root distribution in the profile. When the crop was fully developed, the highest root length density was observed between 10 and 50 cm depth (Cayuela, 1996). It seems that some differences can occur between the observed root distribution and that estimated by the model for the crop season of 1993.

The water storage in the soil profile (0-100 cm) is shown in Fig. 7. The agreement between simulated and measured values is also good. The Fig. 8 shows the cumulative actual evapotranspiration by the crop and the drainage (D) below the root zone. During the crop season in 1992 both components of the water balance AET and D simulated by the model were in good agreement with those determined experimentally. In the crop season of 1993, the values of AET simulated by the model were lower than the experimental values for the period between 80 and 110 days after planting. The model tended to overestimate the drainage from the day 80 after planting. This is related with the underestimation of the soil water content at the depths of 30 and 50 cm (Fig. 6) as has been mentioned above.

The higher drainage observed during the crop season in 1992 than in 1993 may be due to the rainfall distribution. In 1992 about 90 mm of rain fell during the early growth period, concentrated mainly in a few days, when the soil was wet from previous irrigations, and while water consumption by the crop was still low. This situation was well simulated by the model.

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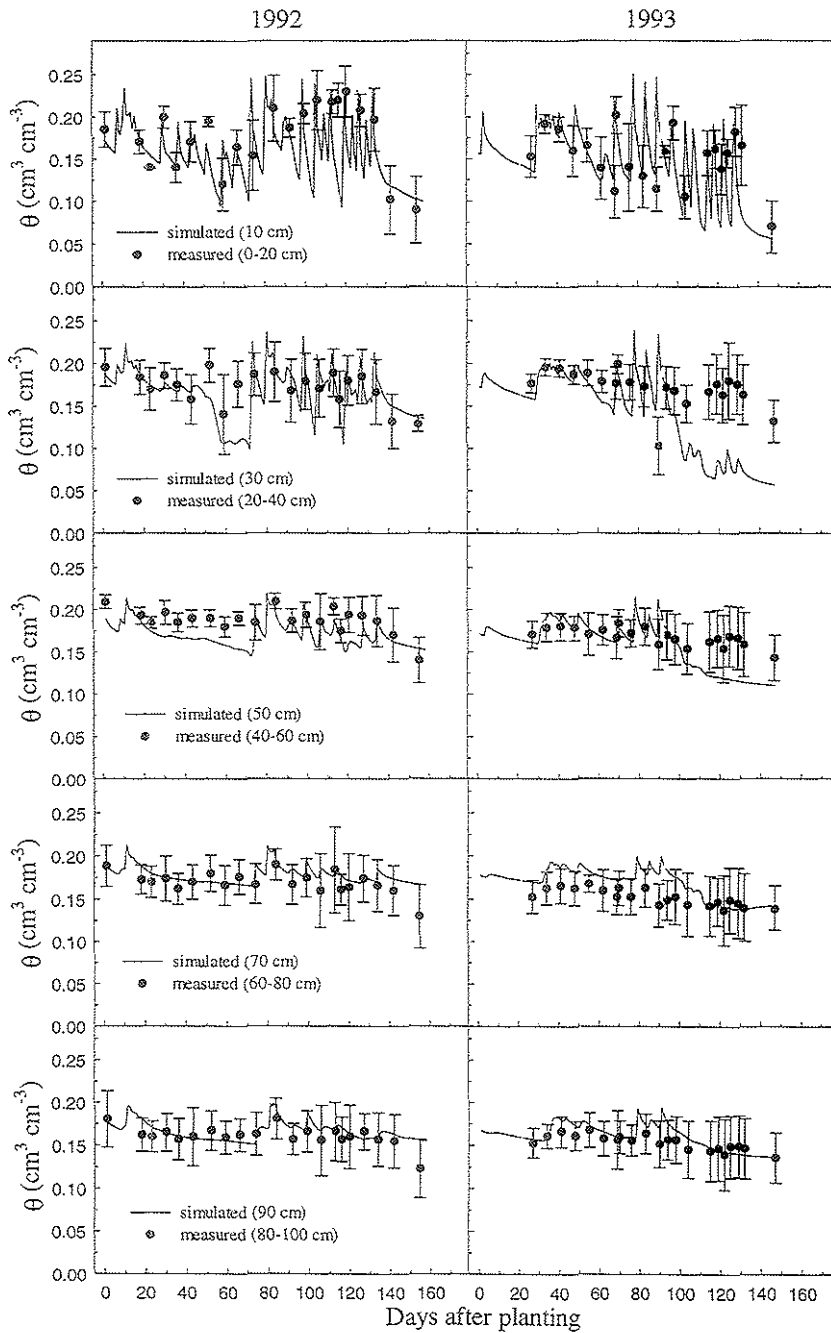
Figure 6: Simulated and measured soil water content in different soil layers of the profile during the crop seasons in 1992 and 1993 (vertical bars are the limits of confidence at 95%).
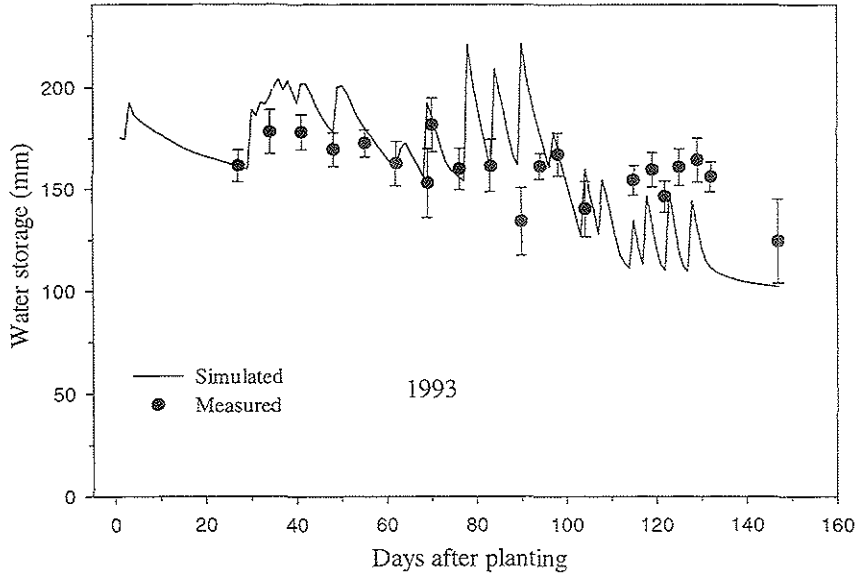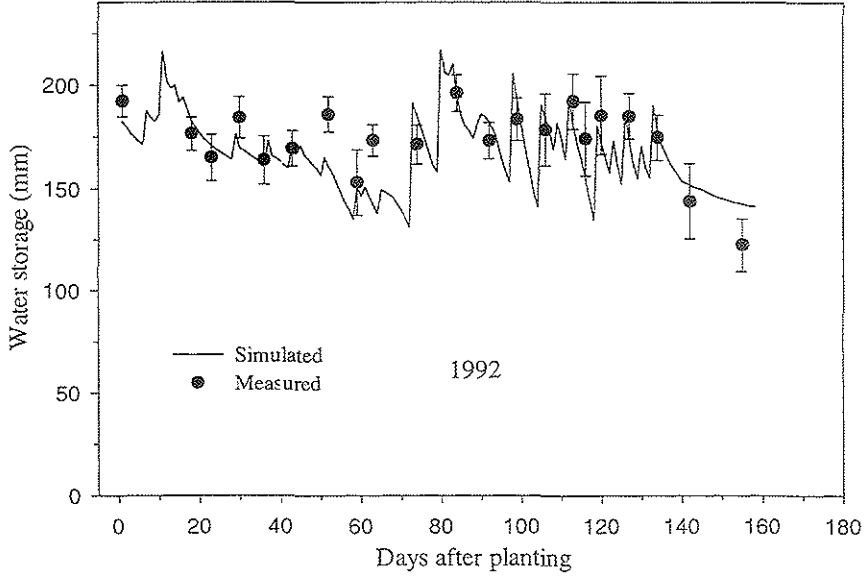
Figure 7: Soil water storage (0-100 cm) during the crop seasons in 1992 and 1993 (vertical bars are the limits of confidence at 95%).
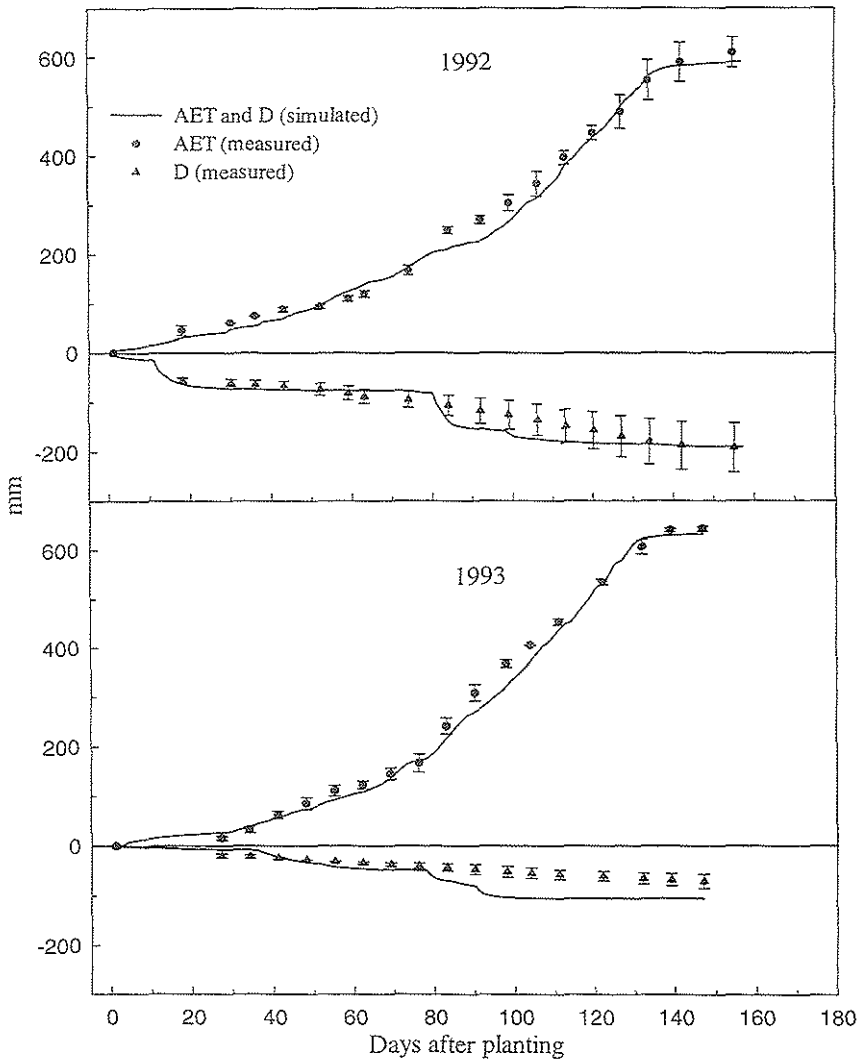
Figure 8: Cumulative actual evapotranspiration (AET) and drainage (D) during the crop seasons in 1992 and 1993 (vertical bars are the limits of confidence at 95%).

4. Conclusions

The SIMWASER model has been successfully validated by comparing model predictions with field measurements of the soil water balance under irrigated maize crop in southern Spain. The performance of the model under the conditions of southern Spain seems to be of

high level. The differences between simulated and measured components of the soil water balance were, in general not higher than 10%.

5. Acknowledgements

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Impact of soil compaction upon crop yield estimated by SIMWASER

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Abstract

The features of the simulation model SIMWASER relevant for estimating the effects of soil compaction upon plant growth are shortly described and the results of a simulation run with input data from a field experiment are compared with experimental findings.

Keywords: Soil compaction; Field experiment; Maize yield; Root length density; Soil water model

1. Introduction

The Institute for Land and Water Management Research is taking part in the FAIR 5 project "Concerted Action on Subsoil Compaction: Experiences with impact and prevention of subsoil compaction in the European Community". According to the goals of Working Group 1: „Modeling impact of subsoil compaction on crop growth, water availability to plants and environmental aspects" the simulation model SIMWASER (STENITZER 1988) will be presented and evaluated on its suitability to model the impact of soil compaction on crop growth, using some experimental results from a field test on the influence of wheel traffic upon soil structure, water regime and plant growth (MURER 1998).

2. Material and Methods

2.1. Field experiment

Influence of soil compaction by wheel pressure upon soil structure, water regime and plant growth was investigated on an Eutric Cambisol, with loamy silt soil texture (Table 1) near Wieselburg (Austria) at an elevation of 260 m in the semihumid sub alpine zone. Mean air temperature is 8.6 °C and mean annual rainfall is 708 mm.

Table 1: Soil characteristic of the experimental field

Depth (cm)	Particle size distribution			Organic matter content (%)	Lime content (%)	pH (CaCl₂)
	clay (%)	silt (%)	sand (%)			
0 - 35	20	56	24	2.0	30.2	7.3
35 - 45	21	51	28	0.9	46.1	7.4
45 - 53	17	43	40	0.5	n.m. *)	7.4

*) not measured

The whole field was ploughed in autumn 1987; mineral fertilizer (215 kg/ha N, 48 kg/ha P and 48 kg/ha K) was broadcasted in early spring 1988 and pre-emergence herbicide was

applied after preparing the seedbed at end of April. At begin of May, when soil was at field capacity, a 7 m wide strip within the field was uniformly compacted by a tractor driven trailer, which had a load on tire of 33 kN and a pressure in tire of 0.5 MPa. The type of the tire was a Trelleborg 400 - 15.5 (tire width 400 mm and rim diameter 394 mm). Maize "LG 11" was planted on May 5th at a density of 70 000 plants per ha and harvested by combine at begin of November 1988; grain yield was measured by hand harvesting four 1.40 m wide representative plots of 4.0 m length.

Compaction effects were investigated by comparison of soil physical properties and plant growth (grain weight) of a compacted and a non-compacted plot: dry bulk density, pore size distribution and saturated hydraulic conductivity were measured on undisturbed soil samples of 200 cm³ size in the lab. Penetration resistance was measured by a hand held electronically recording BUSH Penetrometer (MURER et. al. 1991) at several times throughout the experimental period. Furthermore roots were sampled by soil cores taken within the plant rows at different growth stages of the maize and root length density was determined by washing and automatically counting (MURER 1990). Soil water suction was measured in 10, 20, 30, 40, 50 and 70 cm depth in the compacted and the non-compacted plot by means of gypsum blocks, which had been calibrated in the laboratory (STENITZER 1989); soil water storage was calculated from estimated water content which had been derived from the measured soil water suctions and the pF-characteristic of the respective soil horizons.

2.2. Simulation model

The model SIMWASER is designed to describe one-dimensional, vertical flow of water in a soil profile; inter-flow and preferential flow are neglected. Water balance and plant growth are linked together by the physiological interaction of assimilation and transpiration. The increase of dry matter production depends on taking carbon dioxide from the air in exchange for water vapour via the stomata. As long as the delivery of water to the stomata can satisfy potential transpiration, potential assimilation and potential plant growth take place. The actual plant growth is calculated from the potential production rate as the proportion of actual transpiration to potential transpiration (Equation (1).

$$P_{act} = P_{pot} * T_{act} / T_{pot} \tag{1}$$

P_{act}, P_{pot} actual and potential plant production
T_{act}, T_{pot} actual and potential transpiration

Potential evapotranspiration PET, is calculated according to the well known "Penman-Monteith- formula"; potential evaporation and potential transpiration are derived from PET in dependence on the development stage of the plants. Actual transpiration is equivalent to the root water uptake, which is the result of balanced forces at the root surface and is calculated according to equation (2).

$$WUR = (\Psi p - \Psi s)/(Rp - Rs) * RLD * H \tag{2}$$

WUR   water uptake by roots within a soil layer
Ψp plant water potential
Ψs soil water potential
Rp   plant resistance
Rs   soil resistance
RLD   root length density within the soil layer

H   thickness of the soil layer

The water balance on daily base is made at the soil surface with precipitation and irrigation as input and evaporation and transpiration as output. Interception is also taken into account. The water movement within the soil is calculated by Darcy's Law and the "continuity equation". Taking into account the soil physical parameters of each soil layer either capillary rise or seepage will be the result at the lower boundary of the soil profile.

Impact of soil compaction upon root growth is expressed by a so called "root growth factor RF", which represents the relation of actual current root growth to its potential value under ideal growing conditions. In the present version of the model RF is influenced by mechanical soil resistance against root growth only (Figure 1), poor aeration is supposed to influence root growth also and is represented by a "water logging factor WLOGF" (Equation. 3). Possible chemical or toxic influences are not taken into consideration at all!
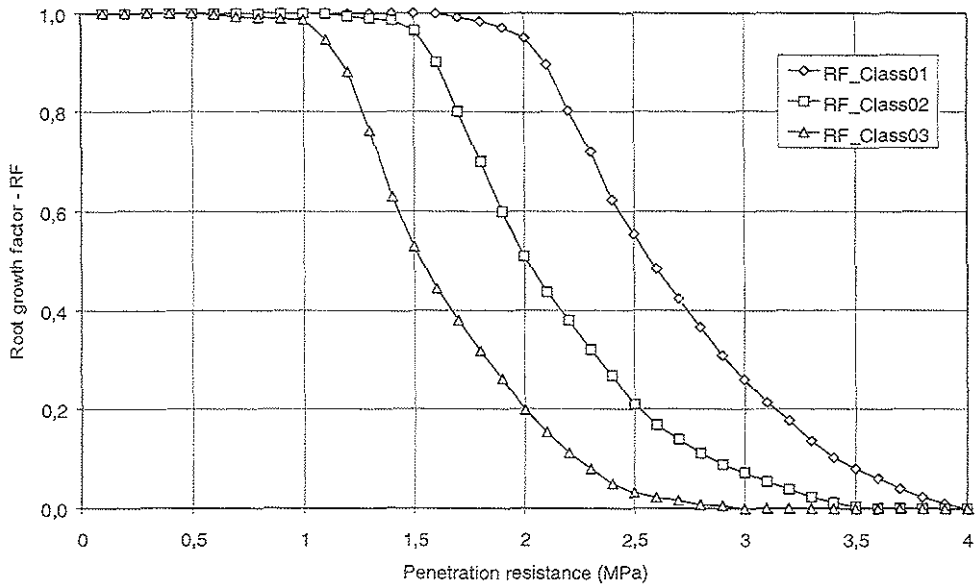
Figure 1: Theoretical Root Growth Factor RF for different root types (Class 01: very dense; Class 02: medium; Class 03: weak)

As long as the (vertically growing) root tips are growing within a soil layer (i), WLOGF of this layer is calculated as:

$$WLOGF(i) = \text{function of } ((WSAT(i)-W(i))/AIRMIN) \qquad (3)$$

WLOGF(i)   reduction factor due to poor aeration in soil layer (i)
WSAT(i)   water content at saturation (Vol.-%) of soil layer (i)
W(i)   soil water content (Vol.-%) within soil layer (i)
AIRMIN   minimum air volume necessary for good plant growth

Daily assimilation is influenced by the weighted mean value of all WLOGF(i) throughout the current rooting depth (Equation 4):

$$WLOGMEAN = SUM(WLOGF(i)*RDM(i))/SUMRDM \qquad (4)$$

WLOGMEAN   mean "Water logging" - factor
WLOGF(i)   reduction factor (s. equation 3)
RDM(i)   root dry matter within soil layer (i)
SUMRDM   total root dry matter

Soil resistance against root growth is represented by penetrometer resistance PE, which is supposed to be a soil physical parameter depending on soil texture, bulk density and water content (BORCHERT 1987). For running the model SIMWASER the soil physical parameters "pore size distribution" (Figure 2) and "capillary conductivity" (Figure 3) of each typical soil layer as well as its "penetrometer resistance" (Figure 4) must be available in a tabulated format as functions of the matric potential!
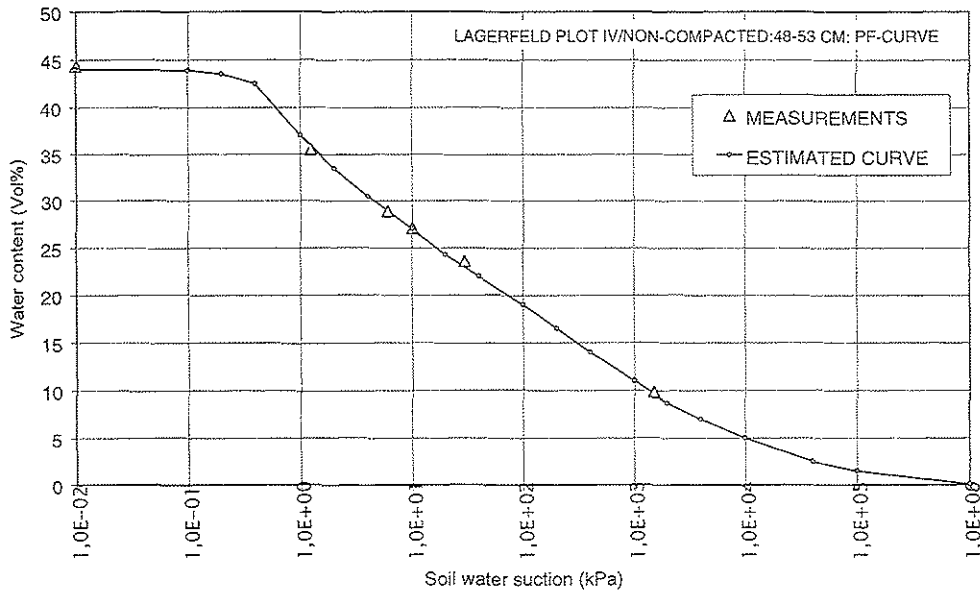
Figure 2: Pore size distribution in 50 cm depth at the experimental field
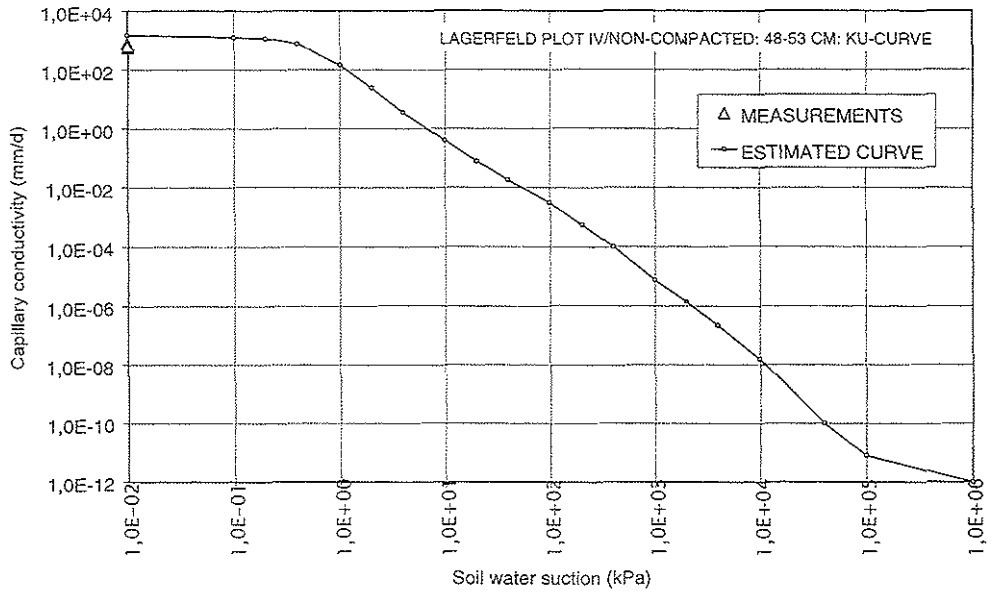
Figure 3: Capillary conductivity in 50 cm depth at the experimental field
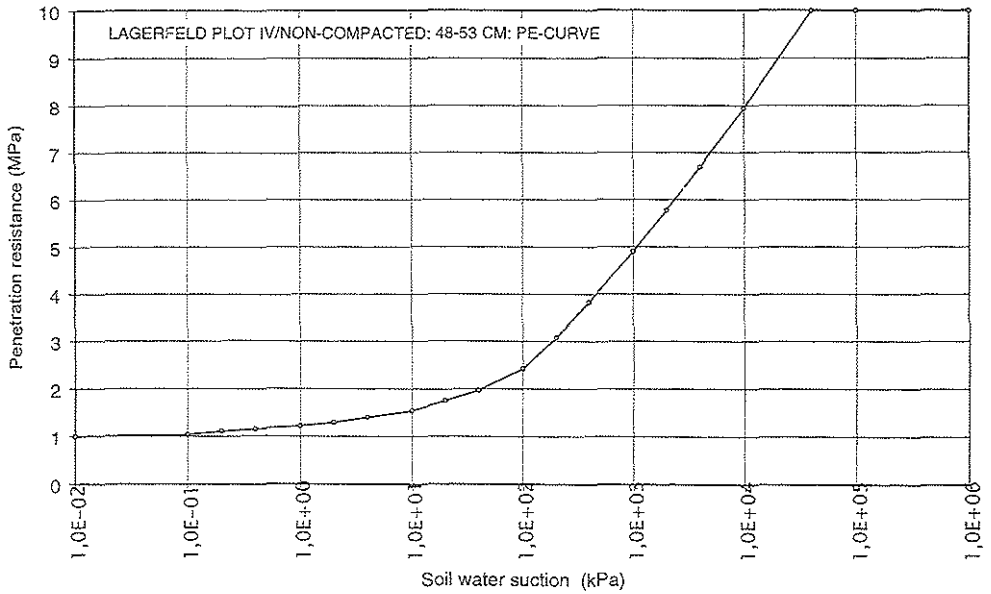
Figure 4: Penetration resistance in 50 cm depth at the experimental field

3. Results

3.1. Field experiment

Compression effects due to trailer traffic resulted in marked differences of physical and mechanical soil parameters in comparison with the uncompressed experimental plots down to a depth of about 30 cm: bulk density as well as penetration resistance clearly increase, while air filled pore space as well as infiltration rate were appreciable lower than in the untrafficed soil (Figure 5):
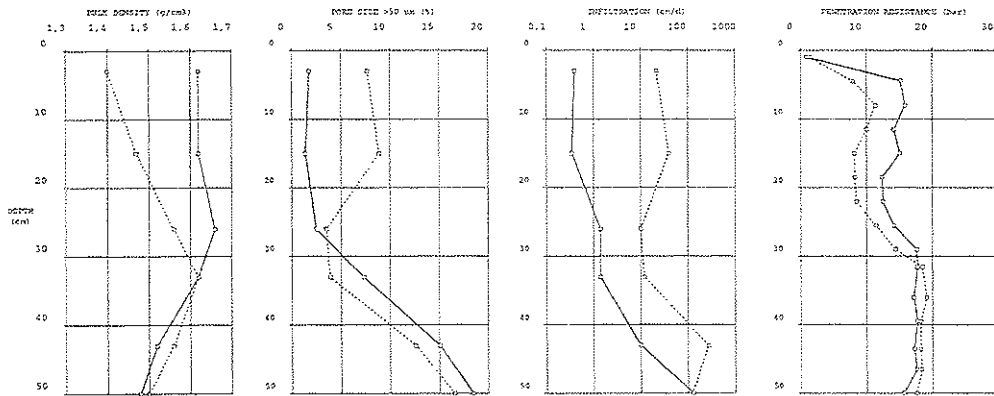
Figure 5: Soil physical and mechanical parameters of the compacted ·············· and non-compacted ———— experimental plots

Although there existed no differences in rooting depth some distinct deviations of the root length density (Figure 6) during vegetative growth period were found.
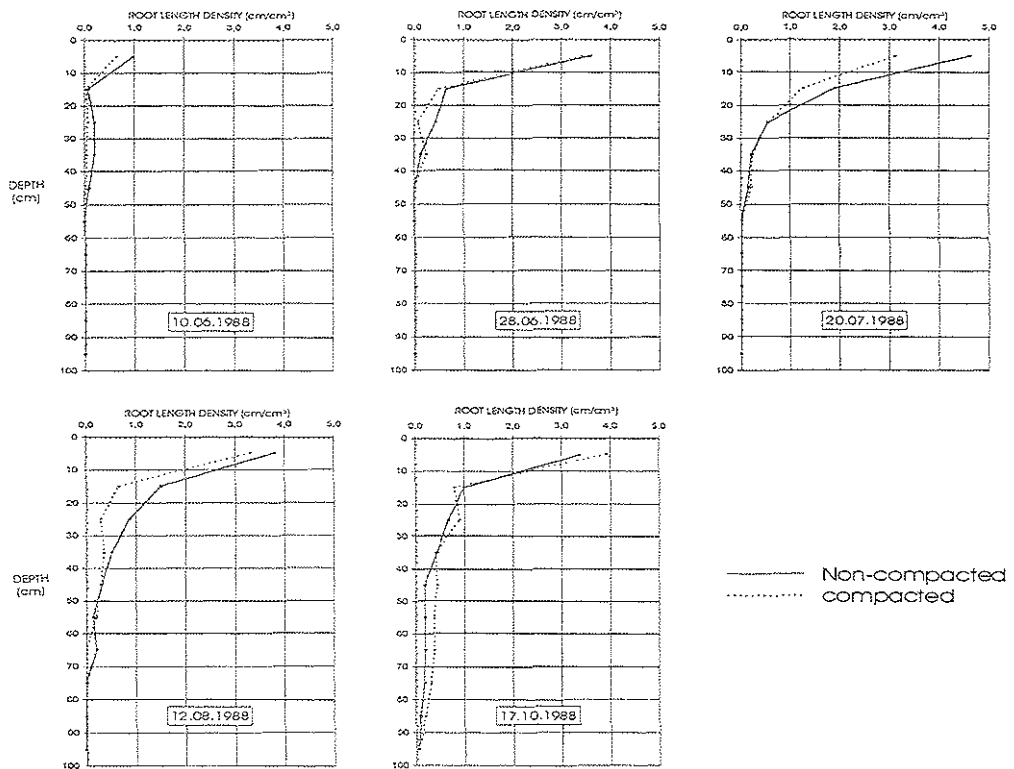
Figure. 6: Measured root length density of the compacted and the non-compacted plot

The overall effect was a clear yield depression (Table 2) within the compacted field strip.

Table 2: Grain yield (kg/ha dry matter)

non-compacted	7184 +/- 711
compacted	5272 +/- 500

Estimated soil water storage (derived from gypsum block measurements) showed, that water uptake during end of July and the second decade in August was higher in the non-compacted plot while water content during the rainy season in the first decade of August was higher in the compacted plot (Figure 7), the rooting zone of which therefore was less aerated than in the non-compacted plot.
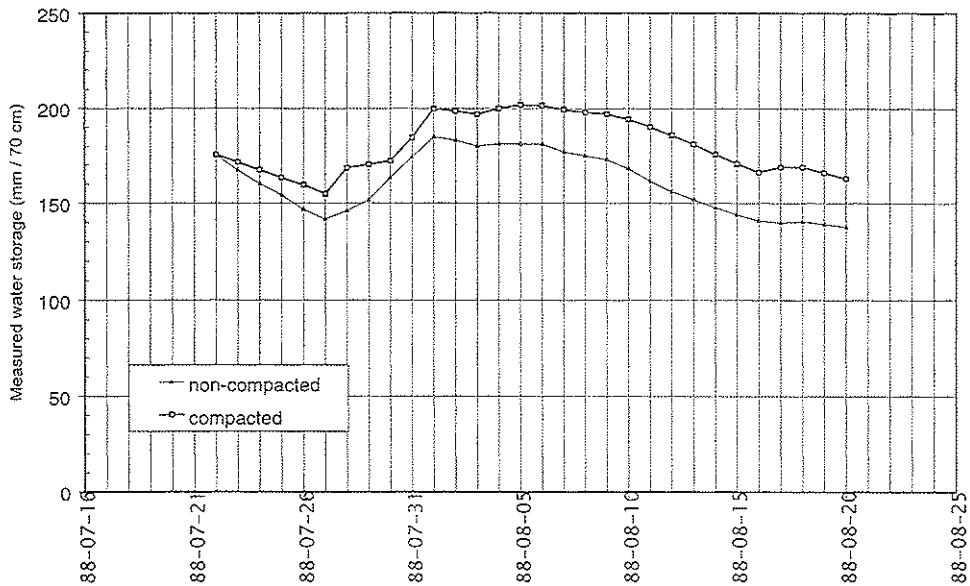
Figure 7: Water storage in the compacted and the non-compacted plot

3.2. Simulation results

SIMWASER estimates the dry matter of the whole crop; the simulated crop yields shown in Table 3 therefore had to be multiplied by an empirical "harvest index HI" for the maize crop at the experimental site to get grain yields which also are given in Table 3.

Table 3: Simulated crop yields (kg dry matter/ha)

	total crop	Harvest Index	grain yield
non-compacted	18 380	0.40	7 350
compacted	10 655	0.40	4 260

Simulated crop growth together with measured grain yields is shown in Figure 8: measured and simulated grain yield are at about the same level, which means, that the model was able to quantify the measured yield depression due to the compacted upper soil layers in the trafficed field strip.
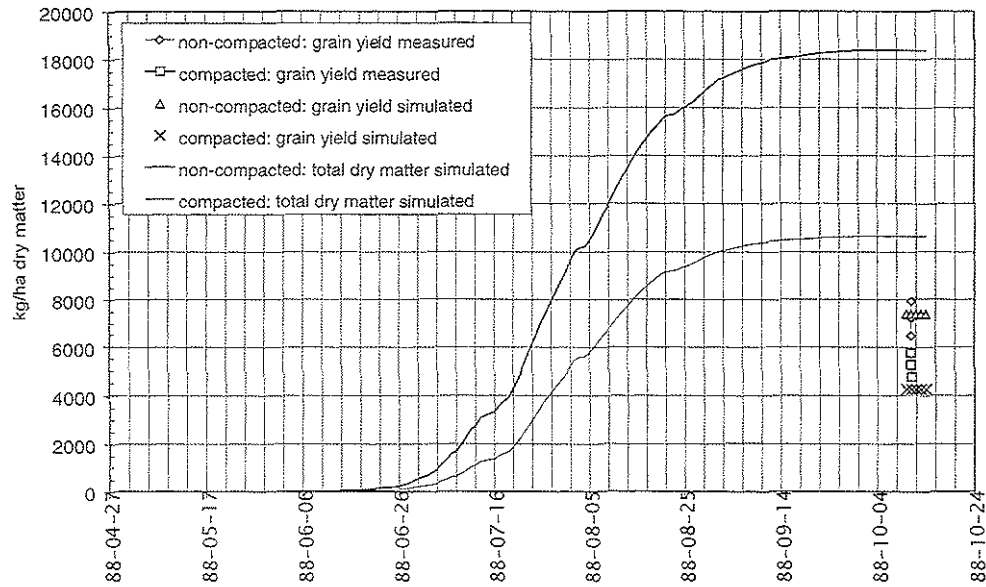
Figure 8: Comparison of simulated and measured maize yields

Simulated rooting depth did not differ much between the compacted and non-compacted plot (Figure 9), but simulated root length density in the compacted plot was lower than in the same depths of the non-compacted plot (Figure 10):
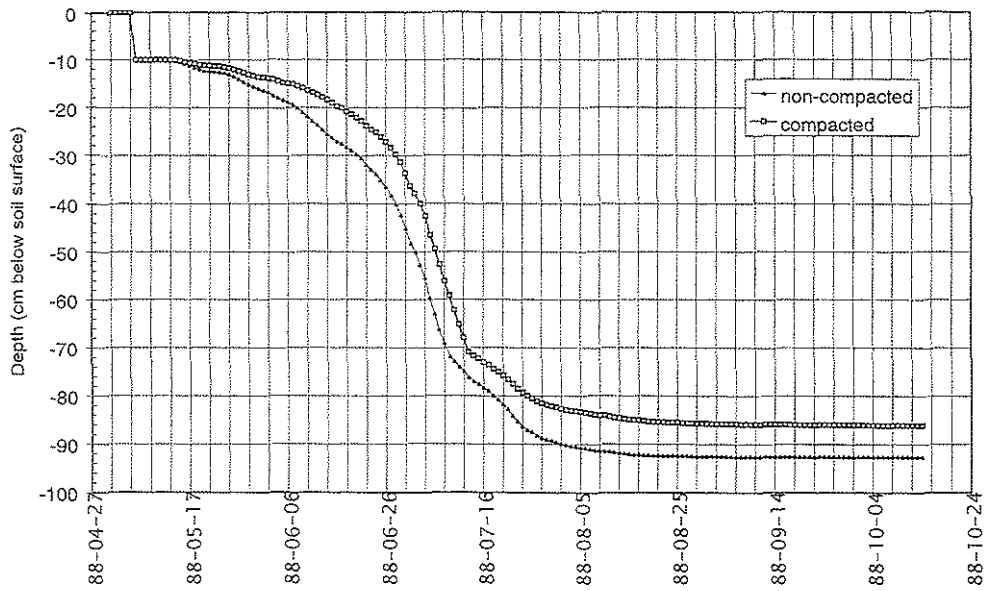
Figure 9: Simulated rooting depth
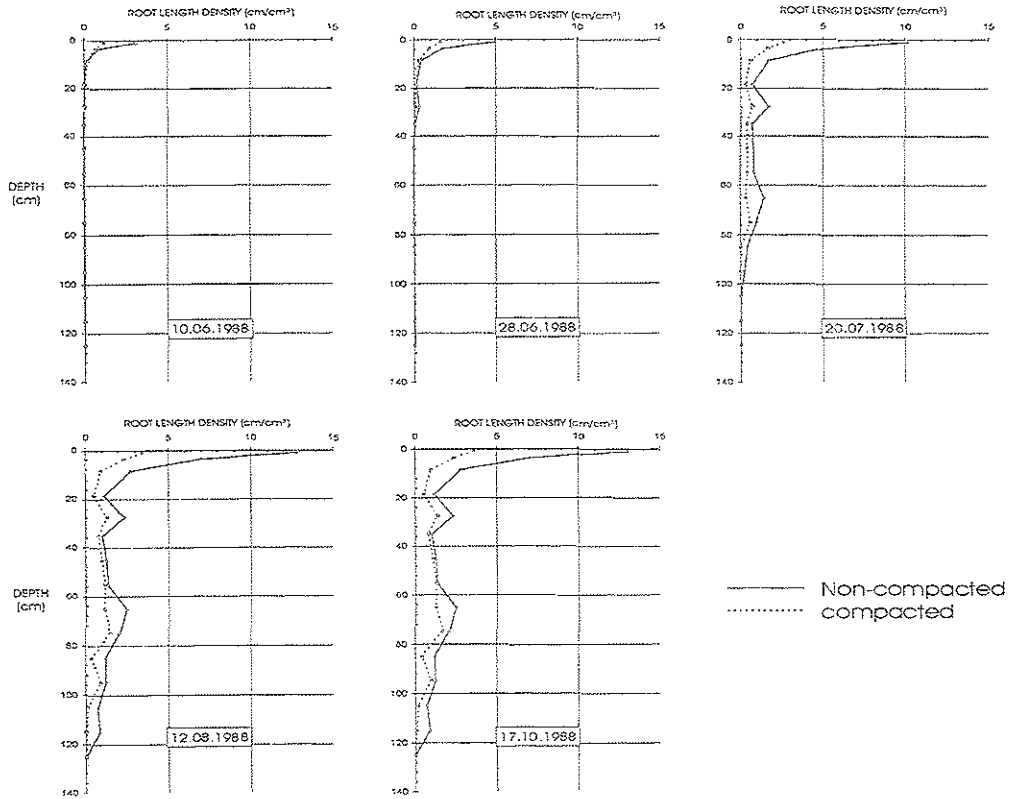
Figure 10: Simulated root length density at different growing stages

Differences in simulated soil water storage within 120 cm soil depth of the compacted and the non-compacted plot are shown in Figure 11.
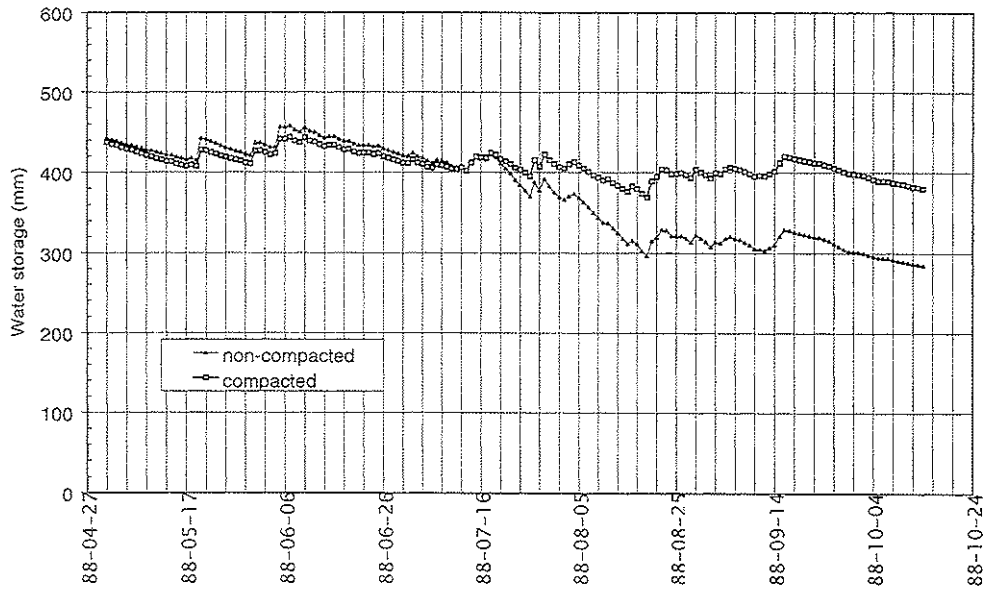
Figure 11: Simulated water storage

Simulated evapotranspiration, drainage and surface runoff are shown in figures. 12, 13 and 14; simulated water balance is given in Table 4.
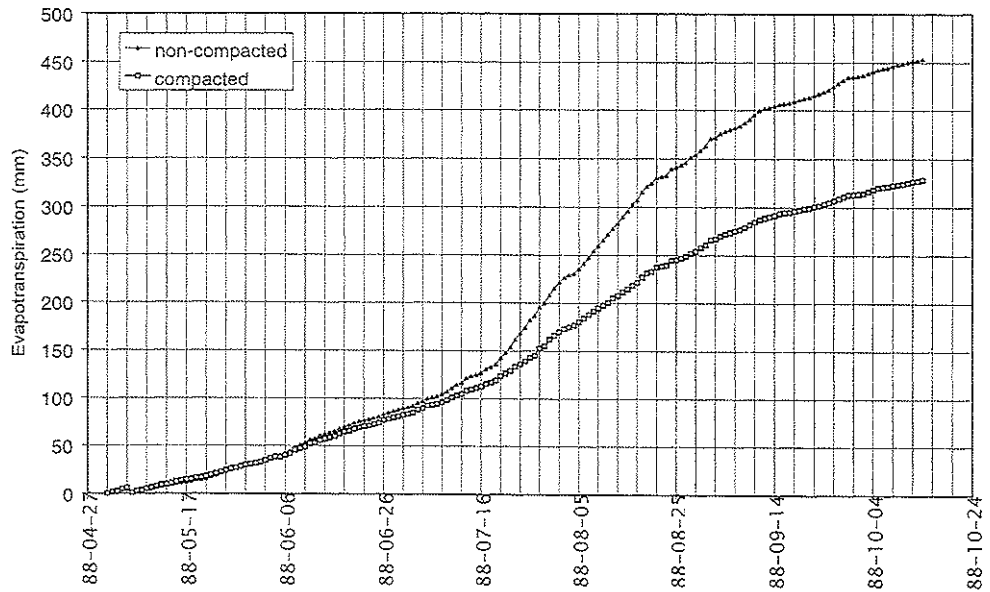
Figure 12: Simulated evapotranspiration
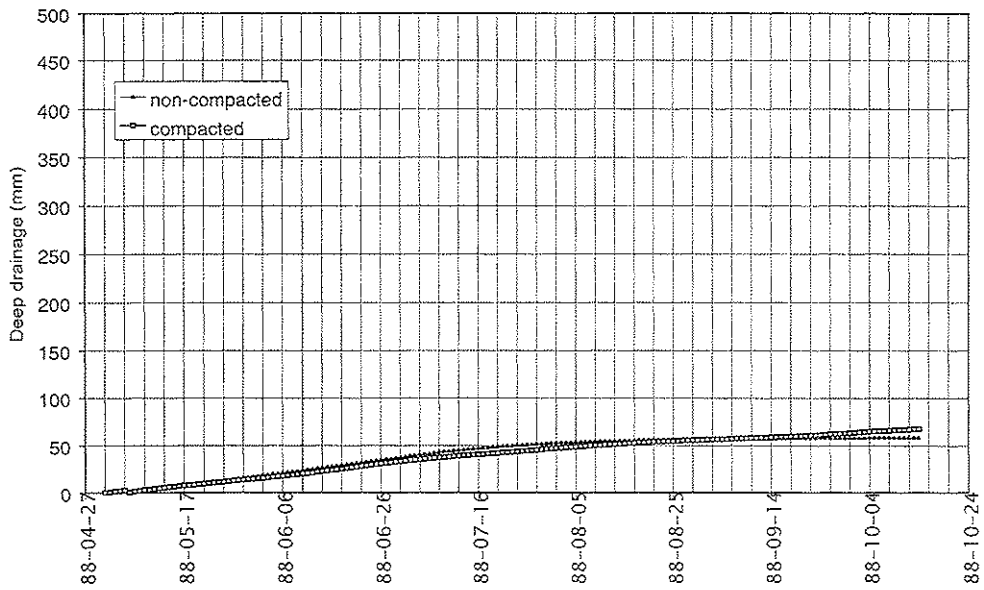
Figure 13: Simulated deep drainage
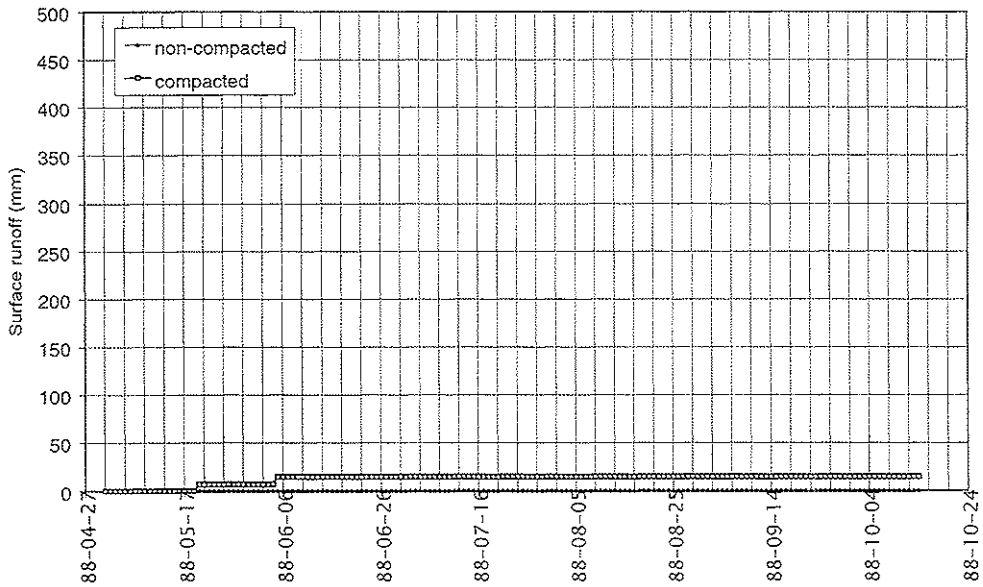
Figure 14: Simulated accumulated surface runoff

Table 4: Simulated soil water balance of maize crop (mm)

	Rain	Evapo-transpiration	Deep percolation	Surface runoff	Soil moisture extraction
Non-compacted	363	453	59	0	149
Compacted	363	329	68	15	49

4. Discussion

The simulation model SIMWASER was able to estimate fairly good the observed maize yield reduction within the compacted strip of the experimental field. The model assumptions in principle seem to enable realistic modeling of impact of soil compaction upon the interrelationship between soil water balance and plant growth. But it must be remembered that some essential model parameters were fitted according to the circumstances of the case study and may not be effective in other cases! For example, choice of the appropriate "root growth factor" (s. figure 1) of the crop on the one hand and setting a realistic "penetration resistance" (s. figure 4) of the soil on the other hand are of great importance for good simulation results. Another very important fact is that in case of fine textured soils with low percentage of air filled pores the model output is very sensitive to the hydraulic soil parameters determined in the laboratory, which in fact do not take into account aeration effects due to shrinking under field conditions. As far as the SIMWASER model is concerned, experimental data on these parameters are still missing to a great extent.

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Subsoil compaction caused by heavy sugarbeet harvesters. I. Results from six long-term field experiments in southern Sweden

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Abstract

The introduction of six-row sugarbeet harvesters, with total loads of approximately 35 tonnes on two axles, caused major concern among Swedish sugarbeet growers regarding the risk for subsoil compaction. A project was started in 1995, which included six long-term field experiments in southern Sweden. The objective was to study effects of heavy axle load traffic during harvest of sugarbeets on penetration resitance, saturated hydraulic conductivity, bulk density and crop yield. Three of the field sites were loams (Eutric Cambisols), two were sandy loams (Eutric Cambisols) and one was sand (Haplic Arenosol). Traffic was applied on one occasion and the treatments were: no traffic, 4 passes by a three-row harvester towed by a tractor (approximately 18 tonnes total load on four axles) and 1 and 4 passes by a self-propelled six-row harvester (approximately 35 tonnes total load on two axles).

In the spring after traffic, no significant changes in penetration resistance were found. When measured 2-4 years after traffic, significant changes between treatments were found to 45-50 cm depth on three sites. Differences between years are possibly an effect of age-hardening. Saturated hydraulic conductivity in the subsoil, measured on cores sampled in the spring after traffic, was in several cases reduced by about 90 percent after four passes with a six-row harvester. As an average for all sites, this traffic significantly reduced hydraulic conductivity and increased bulk density at 50 cm depth. At two sites, measurements were repeated 4 years after traffic and differences in hydraulic conductivity between treatments were approximately the same as on the first sampling occasion.

Despite the great effects on soil physical properties, differences in yield between treatments were mainly small and insignificant.

The results clearly demonstrate to farmers that heavy traffic during harvest of sugarbeet implies a major risk for compaction of the subsoil. The data concerning hydraulic conductivity may be useful for modelling the effects of subsoil compaction, for example on erosion and denitrification, since little such data is available in the literature.

Keywords: Subsoil compaction; Sugarbeet harvest; Penetration resistance; Saturated hydraulic conductivity; Bulk density; Crop yield

1. Introduction

Subsoil compaction is a major concern in agriculture, mainly due to its persistence. Whereas effects of topsoil compaction are alleviated in a few years when the soil is mouldboard ploughed (Arvidsson and Håkansson, 1996), effects of subsoil compaction persist much longer and may even be more or less permanent (Etana and Håkansson, 1994).

Compaction occurs when the applied stress exceeds the strength of the soil (Guerif, 1994; van den Akker, 1994). Generally the risk for subsoil compaction during traffic will be greater the greater the wheel load, since stresses distribute to a greater depth (Söhne, 1958). The soil strength will

generally be lower the higher the soil water content. Parameters often used to express soil strength are for example precompression stress and shear strength (Horn and Lebert, 1994).

So far, the greatest effort to study effects of high axle load traffic was initiated by the High Axle Load Group of ISTRO (International Soil Tillage Research Organization). A total of 24 experiments were started in Finland, Sweden, Norway, Denmark, Holland, USA and Canada, which all included a similar treatment: 4 passes on the soil with an axle load of 10 tonnes (5 tonnes wheel load). The results from most of these experiments were presented in a special issue of Soil Tillage Research (Håkansson, 1994). The main conclusions were: (1) 10 tonnes axle load traffic under wet conditions caused compaction to a depth of approximately 50 cm on most soil types, (2) the changes in soil phisical properties were very persistent, (3) the subsoil compaction caused reductions in yield long after the traffic was applied.

Despite these results, machinery weights have continued to increase. In 1993, self-propelled, six-row sugarbeet harvesters started to become more widely used in Sweden. These have wheel loads of approximately 9 tonnes fully loaded, which is much higher than wheel loads of the traditional harvesters, which are towed by a tractor. The risk for subsoil compaction was of great concern to sugarbeet growers and a project was started in 1995 to study the effects of the heavy traffic on the subsoil. A major reason for starting a new project to study the effects of heavy axle load traffic was that none of the previous Swedish experiments (Håkansson, 1985) was situated on the soil types found in southern Sweden, where most of the sugarbeet is grown. These soils are mainly formed on morainic till, in contrast to most other arable soils in Sweden which are formed on sedimentary deposits. One hypothesis put forward was that the morainic till soils, which have low porosities and were once compressed by a thick ice cover during the latest glaciation, should be less sensitive to compaction than other soils.

The whole project on subsoil compaction had three main objectives: (1) To study the effects of heavy traffic during sugarbeet harvest on soil physical properties and crop yield. (2) To develop a new technique for precise measurements of soil displacement (Arvidsson and Andersson, 1997), for example during traffic at different moisture conditions. Soil displacement would then be related to soil mechanical properties. (3) To calculate the risk for subsoil compaction during traffic at different times of the year. Calculations should be based on soil mechanical properties and simulations of soil water content. Results concerning these three objectives will be presented in Parts I and II of this study.

This paper describes the work concerning the first objective of the project: to study the effects of heavy traffic during sugarbeet harvest on soil physical properties and crop yield. Measurements were made in traditional field experiments after application of traffic by heavy sugarbeet harvesters.

2. Materials and methods

2.1. Field sites

Six experiments were started with two experiments per year, 1995-1997. The sites, Tornhill, Brahmehem, Sandby, Kronoslätt and Rinkaby, were all situated in the province of Skåne in southern Sweden. All soils are moraine deposits except Rinkaby, which consists of a windborne sand. Soil particle size analysis was carried out using the pipette method (Robinson, 1922) for 10-15, 30-35, 50-55 and 70-75 cm depths, the result for all sites shown in Table 1. Organic matter content (Table 1) was estimated by the loss on ignition during heating to 600 EC, corrected according to Ekström (1927). Tornhill, Brahmehem and Elvireborg are loam soils with clay

Table 1

Particle size distribution, organic matter content, porosity, water retention at 10 and 1500 kPa water tension and bulk density of the experimental sites

| | Particle sizes (g kg^{-1}) | | | Org matter | Porosity | Water (% v/v) | | Bulk |
	Clay	Silt	Sand	(g kg^{-1})	(%)	10 kPa	1500 kPa	density
Tornhill								
10-15 cm	219	317	463	21				
30-35 cm	256	312	433	9	38.4	30.3	16.3	1.66
50-55 cm	277	318	405	6	41.5	29.1	18.7	1.57
70-75 cm	274	310	416	4				
Brahmehem								
10-15 cm	191	300	509	25				
30-35 cm	234	292	474	6	37.3	30.1	16.3	1.68
50-55 cm	208	309	484	3	40.4	28.9	12.0	1.60
70-75 cm	166	308	526	4				
Sandby								
10-15 cm	121	245	634	19	43.4	26.1	8.0	1.49
30-35 cm	91	250	659	10	37.2	22.9	9.0	1.68
50-55 cm	114	277	609	5	41.4	23.2	7.2	1.54
70-75 cm	158	280	562	3				
Kronoslätt								
10-15 cm	129	256	616	20	43.7	26.5	8.3	1.47
30-35 cm	129	251	621	18	40.9	24.6	9.6	1.56
50-55 cm	169	270	560	8	35.6	21.3	13.7	1.72
70-75 cm	147	274	580	4	35.6	25.4	15.6	1.73
Elvireborg								
10-15 cm	200	320	480	21	45.4	30.0	12.5	1.50
30-35 cm	301	280	419	11	38.1	31.0	20.1	1.54
50-55 cm	366	347	288	3	38.3	28.5	10.5	1.62
70-75 cm	323	376	301	7	34.5	22.4	12.2	1.76
Rinkaby								
10-15 cm	35	50	915	32				
30-35 cm	23	27	949	14	48.5		2.7	1.38
50-55 cm	17	22	961	3	43.7		2.6	1.51
70-75 cm	19	16	965	3				

contents of around 200 g kg^{-1} in the topsoil. Sandby and Kronoslätt are sandy loams with clay contents of 120-130 g kg^{-1} in the topsoil, while Rinkaby is a sand with a clay content of less than 40 g kg^{-1} down to 70 cm depth. Based on classification of similar soils (Tiberg, 1998), Rinkaby can be classified as a Haplic Arenosol and the other sites as Eutric Cambisols.

Core sampling to determine porosity, soil water retention and bulk density was carried out at 30-35 and 50-55 cm depths, and sometimes also at 10-15 and 70-75 cm depths (Table 1). Three or four soil cores (72 mm in diameter and 50 mm high) were sampled in each layer. Bulk density was determined by weighing the soil after drying at 105 EC for 72 hours. Soil porosity was calculated from bulk density and particle density. Soil water retention at 10 kPa was determined by weighing the cores after they were equilibrated on sand tables.

Soil cores (25 mm high, 72 mm in diameter) were also sampled for uniaxial compression, from 30 and 50 cm depths from all sites. They were equilibrated at 6 and 30 kPa water tension, with two cores per tension and depth. The cores were then compressed in an oedometer described by

Eriksson (1974), by sequential stresses of 25, 50, 75, 100, 150, 200, 400 and 800 kPa. Each stress was applied for 30 minutes and the strain was measured at the end of each loading interval. The precompression stress was determined according to Casagrande (1936), results are presented in Table 3. It was not possible to determine a value of the precompression stress from the stress-strain curve for the very sandy Rinkaby soil.

2.2. Field plan

The experiments had a randomized block design with four replicates and the following treatments:

A=control (no traffic)
B=four passes track-by-track by a three-row sugarbeet harvester (approximately 18 tonnes total load on four axles)
C=one pass track-by-track by a six-row sugarbeet harvester (approximately 35 tonnes total load on two axles)
D=four passes track-by-track by a six-row sugarbeet harvester
E=four passes track-by-track by a six-row sugarbeet harvester under dry conditions

The load of the six-row harvesters were always carried by four wheels on two axles. Due to the high wheel loads it was not possible to weigh all the vehicles in the field, but on one occasion, one of the six-row harvesters was weighed. The total weight for the harvester used at Hemmesdynge, was 34.5 tonnes fully loaded. With the pickup lifted, the load on the front wheels was 20.8 tonnes (wheel load 10.4 tonnes). This may serve as an approximation for the weight of the other harvesters. The tyres used were 800 to 1050 mm wide and had inflation pressures ranging from 200 to 240 kPa.

The three-row harvesters (most often Edenhall 722 and 723) were towed by a tractor. The total load was approximately 11 tonnes on the harvester and 7 tonnes on the tractor. The harvester had bogie wheels on one side with tyres 16.9-34 (430 mm wide, wheel load approximately 2.75 tonnes) and a single wheel on the other side (750/60-30.5, 750 mm wide, wheel load approximately 5.5 tonnes). The inflation pressures were 200-250 kPa in the harvester tyres and 100-150 kPa in the front and rear tyres of the tractor.

Traffic was applied in wheat stubble, at Tornhill and Brahmehem in 1995, at Sandby and Kronoslätt in 1996 and at Elvireborg and Rinkaby in 1997. Traffic in treatments B-D was made under "wet"conditions in October or November, at the end of the period when sugarbeet harvest is carried out. "Dry" conditions in treatment E were obtained by applying traffic earlier in the autumn than for treatments B, C and D. The autumns of 1995, 1996 and 1997 were relatively dry, which meant that all traffic was carried out without deep rutting or intense smearing. The rut depth caused by 4 passes was normally in the range 5-10 cm. Soil water content at different depths when traffic was applied is shown in Table 3. In most cases, the difference between the water content during dry and wet conditions was relatively small. From the soil water retention curve it can be estimated that traffic was most often applied at soil water tensions slightly higher than 10 kPa (Tables 1 and 2).

Table 2
Water content (%w/w) during traffic

Depth (cm)	Tornhill Dry	Wet	Brahmehem Dry	Wet	Sandby Dry	Wet	Kronoslätt Dry	Wet	Elvireborg Wet	Rinkaby Wet
10	18.9	18.8	20.4	20.8	12.6	15.9	15.5	16.1	21.3	11.4
30	16.6	15.4	18.4	17.8	12.8	13.4	14.2	14.3	18.3	7.0
50	15.7	17.2	18.8	19.3	13.1	13.4	15.7	16.1	17.4	4.8
70	14.2	17.8	19.8	20.5	6.5	14.4	13.8	13.6	15.5	7.1

Table 3
Precompression stress (kPa) at 6 and 30 kPa water tension at 30 and 50 cm depth for the different sites. No precompression stress values could be obtained for the Rinkaby soil

	6 kPa		30 kPa	
	30 cm	50 cm	30 cm	50 cm
Tornhill	120	120	63	129
Brahmehem	83	81	120	126
Sandby	117	135	148	132
Kronoslätt	53	60	122	70
Elvireborg	53	56	65	95

2.3. Soil physical properties after traffic

In the spring after traffic was applied, measurements of soil physical properties were carried out on all sites, at a water content assumed to be close to field capacity. Soil cores (50 mm high and 72 mm in diameter) were sampled to determine saturated hydraulic conductivity and bulk density. Four cores per layer were taken at 30-35 and 50-55 cm depth in each plot. Samples were taken from all treatments except for Tornhill and Brahmehem in 1996, where only treatments A and D were sampled. Therefore, these sites were sampled again in 1999, this time in all treatments. Saturated hydraulic conductivity was determined by a constant-head method (Andersson, 1955). Bulk density was determined by weighing the soil after drying at 105 EC for 72 hours.

Soil penetration resistance was determined on the same occasion as core sampling with a Bush Recording Soil Penetrometer, fitted with a 12.8 mm diameter cone with a semiangle of 30E. Fifteen insertions to 50 cm depth were made in each plot. The penetrometer measurements were repeated at Brahmehem in 1998 and at Tornhill, Sandby, Kronoslätt and Elvireborg in 1999.

2.4. Crop yield

Sugarbeet was grown in the year after traffic was applied but, due to the high costs involved, these were not harvested experimentally. From the second year, the experiments were harvested experimentally. However, crop yield is missing from Brahmehem in 1997 due to a hail storm, and from 1999 when sugarbeet was grown. Crop yield is also missing from Rinkaby in 1999, due to a very uneven crop stand.

The harvested crops were spring barley (Hordeum vulgare, L.), winter wheat (Triticum

aestivum, L.), peas (Pisum sativum, L.) and winter oilseed rape (Brassica rapa, L. var oleifera, Metzg.)

2.5 Statistical analysis

For the statistical analysis, SAS (1982) was used. Arithmetic means for measured values within each plot were used for the analysis of variance and to calculate treatment means for penetration resistance, bulk density and crop yield. For saturated hydraulic conductivity the geometric means are presented and the analysis of variance was carried out on log-transformed values, since these are more likely to be normally distributed (Bathke and Cassel, 1991).

3. Results

3.1. Soil physical measurements

3.1.1. Bulk density and saturated hydraulic conductivity

Bulk density and saturated hydraulic conductivity at 30 and 50 cm depths in the spring after traffic for all sites are shown in Table 4. Bulk density was in most cases higher in treatment D than in A, although statistically significant (P<0.05) only at 30 cm depth at Brahmehem, Sandby and Elvireborg. As an average for all sites, bulk density was significantly higher in treatment D compared to A at 50 cm depth (Table 4).

In the first year after traffic, the hydraulic conductivity was generally lower at 30 compared with 50 cm depth, and in soils with high compared to low clay contents. It was in most cases lowest in treatment D and highest in treatment A, with intermediate values in treatments B, C and E. Statistically significant differences (P<0.05) were obtained at 50 cm depth at Tornhill and 30 and 50 cm depth at Sandby. The average conductivity at 50 cm depth for all sites was significantly lower in treatment D compared to A (Table 4).

When measurements at Tornhill and Brahmehem were repeated in 1999, there were still large and statistically significant differences in saturated hydraulic conductivity between treatments (Table 5). At 50 cm depth the conductivity at both sites was significantly lower in treatment D (four passes with a six-row harvester) than in B (four passes with a three-row harvester).

3.1.2. Penetration resistance

In the penetrometer measurements made in the spring after traffic was applied, there were no significant differences between treatments in the subsoil. On some sites there were significantly higher penetration resistances in the ploughed layer in compacted treatments compared to no traffic (data not shown).

Results from measurements made 2-4 years after traffic are presented in Fig. 1. At three of the sites, Tornhill, Brahmehem and Sandby, there were statistically significant differences between treatments in the subsoil (P<0.05). The greatest depth where significant differences were found was 45-50 cm on these three sites.
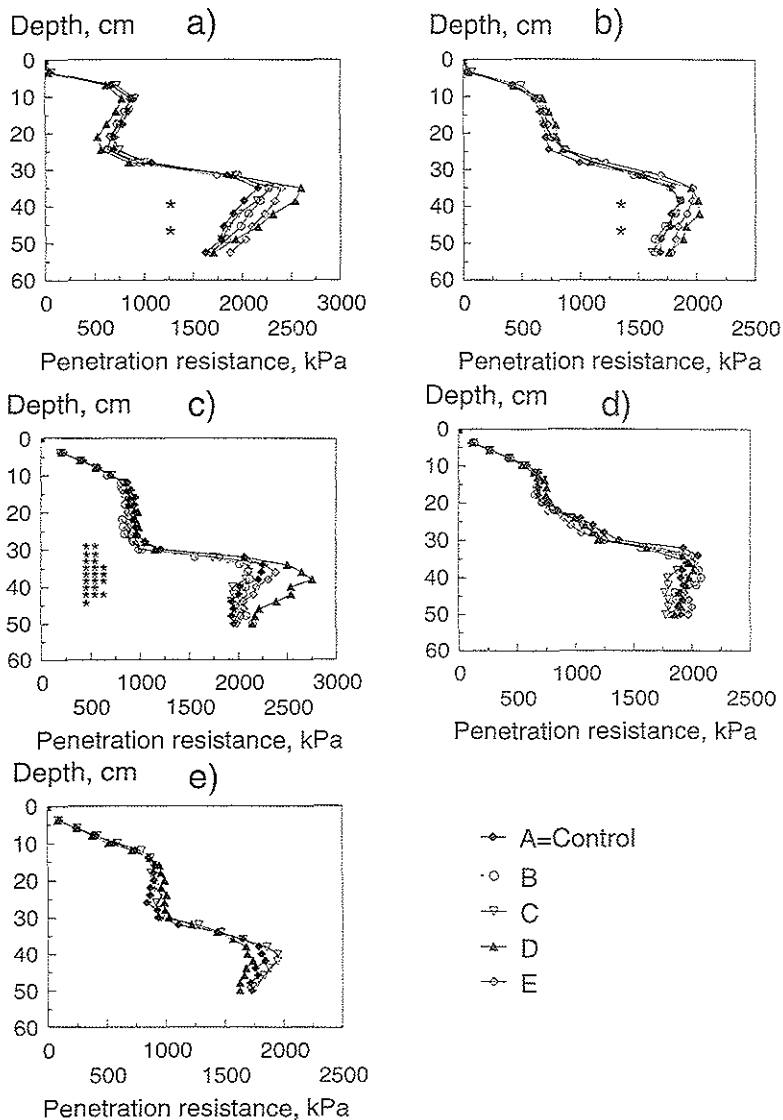
Fig 1. Penetration resistance measured 2-4 years after application of traffic. a) Brahmehem 1998 b) Tornhill 1999, c) Sandby 1999, d) Kronoslätt 1999, e) Elvireborg 1999. A=control (no traffic), B=four passes track-by-track with a three-row sugarbeet harvester (approx. 18 tonnes total load on four axles), C=one pass track-by-track with a six-row sugarbeet harvester (approx. 35 tonnes total load on two axles), D=four passes track-by-track with a six-row sugarbeet harvester, E=four passes track-by-track with a six-row sugarbeet harvester under dry conditions

Table 4
Saturated hydraulic conductivity and bulk density measured on soil cores sampled in the spring. Traffic was applied the previous autumn. Values not sharing the same letters are significantly different (P<0.05)

	Hydraulic conductivity (mm h^{-1})		Bulk density Mg m^{-3}	
	30 cm	50 cm	30 cm	50 cm
Tornhill				
A[1]	21.8	45.7a	1.66	1.57
D	4.7	4.0b	1.67	1.63
Analysis of variance	n.s.	*	n.s.	n.s.
Brahmehem				
A	7.4	80.6	1.68b	1.60
D	0.8	5.7	1.74a	1.69
Analysis of variance	P=0.11	P=0.06	**	n.s.
Sandby				
A	24.5a	28.3	1.71b	1.71
B	13.0ab	15.4	1.73b	1.71
C	7.6ab	14.3	1.76b	1.72
D	0.8c	2.8	1.84a	1.79
E	6.3b	20	1.77b	1.71
Analysis of variance	***	P=0.06	*	n.s.
Kronoslätt				
A	5.6	43.7	1.70	1.64
B	2.6	26.2	1.75	1.67
C	6.6	15.1	1.74	1.66
D	9.6	36.7	1.69	1.67
E	3.1	28.6	1.76	1.69
Analysis of variance	n.s	n.s.	n.s.	n.s.
Elvireborg				
A	1.3	6.2	1.66	1.57
C	0.61	2.7	1.70	1.62
D	0.69	5.5	1.71	1.60
Analysis of variance	n.s.	n.s.	*	n.s.
Rinkaby				
A	116	458	1.38	1.51
B	252	160	1.57	1.49
C	161	274	1.48	1.54
D	184	193	1.56	1.49
Analysis of variance	n.s.	P=0.09	P=0.11	n.s.
All sites				
A	12.2	48.4a	1.63	1.60b
D	3.9	11.6b	1.70	1.64a
Analysis of variance	n.s.	*	P=0.06	*

[1]A=control (no traffic), B=four passes track-by-track with a three-row sugarbeet harvester (approx. 18 tonnes total load on four axles), C=one pass track-by-track with a six-row sugarbeet harvester (approx. 35 tonnes total load on two axles), D=four passes track-by-track with a six-row sugarbeet harvester, E=four passes track-by-track with a six-row sugarbeet harvester under dry conditions

Table 5
Saturated hydraulic conductivity and bulk density measured on soil cores sampled in the spring 1999. Traffic was applied in the autumn 1995. Values not sharing the same letters are significantly different (P<0.05)

	Hydraulic conductivity (mm h^{-1})		Bulk density Mg m^{-3}	
	30 cm	50 cm	30 cm	50 cm
Tornhill				
A[1]	11.4	45.3a	1.64	1.58
B	9.1	19.8a	1.67	1.63
C	7.7	7.6ab	1.69	1.57
D	3.2	1.3b	1.63	1.59
E	2.6	11.4a	1.68	1.64
Analysis of variance	n.s.	*	n.s.	n.s.
Brahmehem				
A	2.3ab	23.8ab	1.76	1.66
B	3.4ab	36.3a	1.71	1.60
C	9.5a	39.0a	1.74	1.64
D	0.33c	4.7b	1.78	1.70
E	0.97bc	4.3b	1.78	1.68
Analysis of variance	*	*	P=0.11	P=0.08

[1]A=control (no traffic), B=four passes track-by-track with a three-row sugarbeet harvester (approx. 18 tonnes total load on four axles), C=one pass track-by-track with a six-row sugarbeet harvester (approx. 35 tonnes total load on two axles), D=four passes track-by-track with a six-row sugarbeet harvester, E=four passes track-by-track with a six-row sugarbeet harvester under dry conditions

3.2. Crop yield

Crop yields from the second year after traffic are presented in Table 6. Differences between treatments were in most cases small. Only in two experimental years (at Tornhill the second year after traffic and Sandby the third year after traffic) were there statistically significant differences (P<0.05), with the lowest yield in treatment D. On average for all experiments (n=9) there was a yield loss of 1 % in treatment D compared to A.

Table 6
Relative crop yield (No traffic=100) after traffic by heavy sugarbeet harvesters

Site	Year	Crop	Rel. crop yield (A[1]=100)					Analysis of variance
			A	B	C	D	E	
Tornhill	1997	Spring barley	100	99	101	95	95	*
Tornhill	1998	Oilseed rape	100	105	105	106	105	n.s.
Brahmehem	1998	Winter wheat	100	102	103	103	105	n.s.
Sandby	1998	Peas	100	101	91	91	98	n.s.
Kronoslätt	1998	Spring barley	100	102	100	99	101	n.s.
Tornhill	1999	Winter wheat	100	101	102	104	103	n.s.
Kronoslätt	1999	Winter wheat	100	100	103	101	101	n.s.
Elvireborg	1999	Spring barley	100		101	94		n.s.
Sandby	1999	Winter wheat	100	102	98	97	99	*
Mean (n=9)			100		100	99		n.s.
Mean (n=8)			100	102	100	100	101	n.s.

[1]A=control (no traffic), B=four passes track-by-track with a three-row sugarbeet harvester (approx. 18 tonnes total load on four axles), C=one pass track-by-track with a six-row sugarbeet harvester (approx. 35 tonnes total load on two axles), D=four passes track-by-track with a six-row sugarbeet harvester, E=four passes track-by-track with a six-row sugarbeet harvester under dry conditions

4. Discussion and conclusions

In the experiments presented here, statistically significant changes in bulk density, saturated hydraulic conductivity and penetration resistance were found at 30 and 50 cm depth (Tables 4, 5, Fig. 1).These results are consistent with those of previous experiments (Håkansson, 1994) where high axle load traffic most often caused detectable differences in soil physical properties to around 50 cm depth.

Despite low total porosity of the moraine soils, the air-filled porosity at 10 kPa water tension was in most cases 10 % or higher (Table 1). Precompression stress values (Table 3) were not high compared to those reported for example by Lebert (1989), Salire et al. (1994), Dios Jr and Pierce (1995) and Veenhof and McBride (1996). Tijink (1998) calculated the soil stress for a sugarbeet harvester with a wheel load of 10 tonnes to approximately 230 and 165 kPa at 30 and 50 cm depth, respectively. These stresses are higher than the values of precompression stress at 6 and 30 kPa tension for the experimental sites in this study. Soil stresses higher than the precompression stress indicate a risk for compaction during traffic (van den Akker, 1994). The precompression stress values, as well as the soil physical properties after traffic, clearly state that the moraine soils in southern Sweden are susceptible to subsoil compaction.

Traffic with the six-row harvester caused greater subsoil compaction than the three-row harvester, which may be explained by the higher wheel load. Values in treatment B were often intermediate to those of treatments A and D, but differences between treatments B and A were generally not significant (Tables 4, 5). However, it seems likely that the three-row harvester also caused some compaction of the subsoil.

Four passes with the six-row harvester caused much greater subsoil compaction than one pass

(Tables 4, 5, Fig. 1). This is consistent with results from similar experiments (Etana and Håkansson, 1994; Schjønning and Rasmussen 1994) and measurements of subsoil displacement (Arvidsson and Andersson, 1997). This means that the effects of several wheelings are mainly additive, and that a rather large number of wheelings seems to be needed before the soil does not compact any further. The difficulty in obtaining statistically significant differences in the subsoil from traditional methods such as core sampling, also makes it necessary to exaggerate the compaction treatment, hence the four passes in this study. There were no statistically significant differences between one pass with a six-row sugarbeet harvester and the control treatment, for any of the soil physical parameters investigated.

An interesting result in this study is that significant differences in penetration resistance between treatments were found 2-4 years after traffic, but not in the spring following autumn traffic. Increased penetration resistances in the subsoil due to high axle-load traffic were reported for exampe by Alakukku and Elonen (1994), Alblas et al. (1994), Etana and Håkansson (1994), Schjønning and Rasmussen (1994) and Stewart and Vyn (1994) in measurements made several years after traffic. Hammel (1994) reported similar results for penetration resistance measured immediately after traffic compared to three years later, while Lowery and Schuler (1994) found significant differences between treatments at greater depth 3 years after traffic compared to measurements made in the same year. One possible reason for different results in different years is the process of age-hardening (Dexter et al., 1988), which is the development of soil strength with time. Semmel et al. (1990) reported increased aggregate strength with increasing number of drying cycles. In the experiments presented here, it is possible that an increase in strength only developed after one or more drying cycles. The results show one of the difficulties in using penetration resistance to measure effects of soil compaction.

Since compaction mainly affects the largest pores, which govern the saturated hydraulic conductivity, the latter parameter may be a more sensitive indicator of compaction than bulk density (Dawidowski and Koolen, 1987; Horton et al., 1994). The saturated hydraulic conductivity, in contrast to bulk density, is also an important parameter in assessing soil structure and in modelling transport processes in the soil. However, it is a highly variable parameter, in space and in time (Messing, 1993). The results from our experiments confirm that moderate changes in bulk density may decrease the saturated hydraulic conductivity dramatically, although in some experiments, no differences could be detected. At Tornhill, Brahmehem and Sandby, the saturated hydraulic conductivity in treatment D was five to hundred times lower than in treatment A (Tables 4, 5). In many of these cases compaction reduced the conductivity so that soil drainage may be restricted. The data concerning saturated hydraulic conductivity are probably the most valuable scientific result from this study, since there are relatively little data on the effects of traffic on the saturated hydraulic conductivity of the subsoil. Exceptions are for example Hammel (1994), Lowery and Schuler (1994) and Alakukku (1997). Such data may be important for future use, for example in modelling runoff, erosion and denitrification as possible consequences of subsoil compaction. An important result is also that differences in hydraulic conductivity between treatments at Tornhill and Brahmehem were similar in 1999 and 1996 (Tables 4, 5). This indicates that compaction effects on hydraulic conductivity in the subsoil may be very persistent, just as for soil strength as shown by Etana and Håkansson (1994). It would be of great value to repeat the measurements of hydraulic conductivity in the future to study their persistence.

Despite the clear effect on soil physical properties, there were only small effects of traffic on yield. Statistically significant changes were only obtained in one experimental year, at Tornhill the second year after traffic (Table 6). This yield loss may also be due to residual effects of traffic in the topsoil, which normally persist for 3-4 years (Arvidsson and Håkansson, 1996). Furthermore, in previous experiments on subsoil compaction, yield effects were on average small

(Håkansson and Reeder, 1994). In a short-term perspective, it seems clear that topsoil compaction generally has a much larger impact than subsoil compaction on crop yield.

In conclusion, it is obvious that heavy axle loads during sugarbeet harvest often may cause subsoil compaction in this region, including increased penetration resistance and reduced hydraulic conductivity, which can be seen as a long-term threat to soil productivity. On the other hand, yield effects were very small, which makes it difficult for farmers to economically justify costs for reducing subsoil compaction. However, it may be considered to be in the interests of society to avoid subsoil compaction, in order to promote sustainable agriculture and to reduce environmental effects.

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Modelling compaction of agricultural subsoils by tracked heavy construction machinery under various moisture conditions

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Abstract

In recent years agricultural land in Switzerland has been increasingly used as temporary access way for heavy machinery in road and pipeline construction operations. We studied the compaction sensitivity of a loess soil at different soil moisture conditions in a field traffic experiment and by a numerical model on computer. Two plots, one with wet soil and one with dry areas, were traversed by heavy caterpillar vehicles during construction of a large overland gas pipeline. Compaction effects were determined by comparing precompression stresses of soil samples taken before and after the passage. A finite-element model based on the concept of critical state soil mechanics was used to interpret the outcome of the field trials.
Both direct measurement and modelling showed that the dry soil was strong enough to resist compaction. The wet soil was too weak to resist compaction in the top layers, strong enough in the ploughpan, and probably was also strong enough in the subsoil. In the wet soil, it seems likely that the pore water pressures increased beneath the vehicles, and that these increased pressures only partially dissipated during the two minutes that the vehicles loaded the soil. The precompression stress was a useful indicator of the likely compaction.

Keywords: Compaction, modelling, precompression stress, soil water potential, critical state soil mechanics

1. Introduction

In recent years, Swiss agricultural land has become increasingly affected by temporary use as access ways for heavy machinery in the course of overland gas pipeline construction.
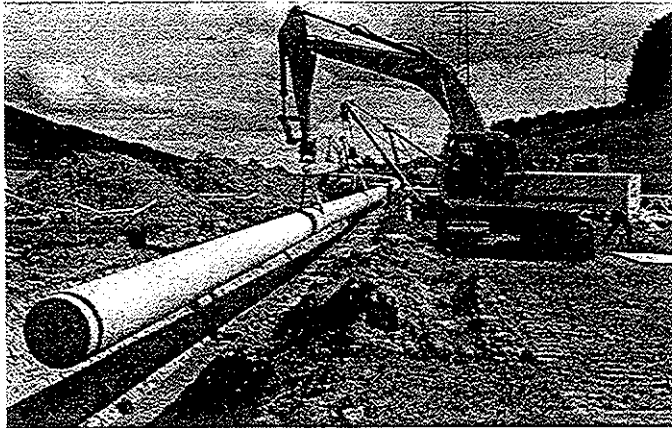
Fig. 1: Placement of pipeline tubes

A typical construction sequence consists of the removal of the topsoil in the trench area, excavation of a trench 2 - 3 m deep, placement of the pipes (see Figure 1) and the refilling of the trench followed by recultivation of the trench area. Many of the excavators weigh more than 40 tons, some even more than 60 tons unloaded. The tracked machinery for placing the pipes is in general also very heavy, weighing 30 tons and more without load. Trafficking agricultural land with such heavy machines inevitably will increase the risk of undesired compaction of the subsoil.

To characterise the sensitivity of a soil for compaction, Horn (1988), Horn and Lebert (1994) and Kirby (1991a) proposed using the precompression stress. Compaction leads to increase of the soil strength, and the precompression stress is a measure of strength which is useful. The slow moving, heavy construction equipment with wide, rigid steel tracks is expected to compact the soil and increase the precompression stress. Blunden et al. (1994) showed that compaction by tracked and tyred vehicles significantly affected the precompression stress of an earthy sand at 4 % moisture content. Kirby et al. (1997) simulated the results of Blunden et al. (1994) using a critical state, finite element model. They concluded that, while the simulated results agreed with the measurements, the latter had a large range and the comparison was not useful. Kirby et al. (1997) also simulated the results of several soil bin tests, and concluded that agreement between measurement and model was poor, because the precompression stress varied greatly in small distances (due to the gradient of compacting stresses beneath the tyre) and samples taken for precompression stress were too large to observe these changes. Apart from the problem of dealing with the spatial heterogeneity, a major difficulty in the application of such models to practical field situations with variably saturated soil arises from the dependence of precompression stress on soil moisture content.

Addressing these problems, an opportunity was presented during the course of the construction of a gas pipeline to carry out a field experiment with the heavy machinery used in that work. Our aim was to measure the compaction caused by the machinery, and to investigate whether the precompression stress was a useful indicator of the likely compaction.

The experiment was performed on two plots immediately adjacent to the trench. One plot was artificially wetted by sprinkling, the other was kept dry. One part of each plot was mechanically stressed by the heavy machinery used to place the tubes into the trench (Figure 1). The idea of the experiment was to compare the precompression stress of the soil under the tracks with the precompression stress of non-affected soil beside the tracks in order to assess compaction effects. Measured precompression stresses were compared with vertical stresses calculated with the critical state soil mechanics model „Modified Cam Clay".

2. Material and methods

The experimental site was an arable field, located on the „Ruckfeld", a loess plain to the north-west of Zurich, Switzerland.

Tab. 1: Soil parameters of the wet plot

depth [cm]	sand [g g^{-1}]	silt [g g^{-1}]	clay [g g^{-1}]	stones [cm^3 cm^{-3}]	organic matter [g g^{-1}]	bulk density [g cm^{-3}]
7-17	0.31	0.55	0.14	< 0.01	0.033	1.31
27-37	0.28	0.60	0.12	< 0.01	0.011	1.57
47-57	0.26	0.57	0.17	< 0.01	0.011	1.51
67-77	0.25	0.57	0.18	< 0.01	0.010	1.52

Tab. 2: Soil parameters of the dry plot

depth [cm]	sand [g g^{-1}]	silt [g g^{-1}]	clay [g g^{-1}]	stones [cm^3 cm^{-3}]	organic matter [g g^{-1}]	bulk density [g cm^{-3}]
7-17	0.23	0.57	0.16	< 0.01	0.031	1.36
27-37	0.22	0.55	0.16	< 0.01	0.025	1.53
47-57	0.22	0.58	0.16	< 0.01	0.015	1.54
67-77	0.25	0.56	0.17	< 0.01	0.012	1.61

Data on soil texture, organic matter content and bulk density are given in Table 1 and 2. Stone content was less than 1 % by volume over the entire profile. Soil type was a Haplic Luvisol (FAO, 1990). The field was under crop rotation and covered by grass during the season of the experiment.

The two test plots (5 m long and 6 m wide) were chosen adjacent to the trench. The plot to be wetted was sprinkled during five days at a rate of 100 mm d^{-1}. After that the soil was left to redistribute the infiltrated water for one more day. Water potentials were monitored by tensiometers set at depth of 12, 32, 52 and 72 cm (mean depth of ceramic cup).

Three different construction machines were used. Relevant characteristics are given in Table 3.

Tab. 3: Machinery used for the experiment

machine type	net machine weight [kg]	length of the contact area [m]	width of the contact area (twice track width) [m]	mean pressure in the contact area [kPa]
Fiat FH 300	30200	4.0	1.8	42
Fiat Allis PL 40 C	25600	3.5	1.4	51
Cat 583	38000	3.2	1.5	78

In the experiment, a Fiat FH 300 was followed by a Fiat PL 40 C, a Cat 583 and a second Fiat FH 300. These machines drove at speeds between 10 and 20 cm s^{-1}, stopping on each of the plots for 2 minutes. They did not perform any „work" relating to the pipeline construction, carrying no load during these passages. These contact pressures are similar to those experienced in agricultural operations using low ground pressure tyres (e.g. Vermeulen and Perdok, 1994) or tracks (e.g. Kirby and Blunden, 1992).

After the vehicle pass, soil profiles were opened across the plots at right angles to the direction of the pass, and soil cores of 1000 cm^3 volume were sampled using sharpened metal cylinders of 10.9 cm height and 10.8 cm inner diameter. We took samples from wet and dry trafficked and non-trafficked soil from 7 - 17, 27 - 37, 47 - 57 and 67 - 77 cm depth (6 replicas per treatment and depth) and conditioned them to 6 kPa initial soil water potential. Uniaxial compression tests were performed on them and precompression stress was estimated from these tests. We were thus able to compare the precompression stress of trafficked and non-trafficked soil at the same initial soil water potential. Other samples of non-trafficked soil from 7 - 17, 27 - 37, 47 - 57 and 67 - 77 cm depth were brought to a range of initial soil water potential between 1 an 32 kPa (5 replicas per soil water potential and depth), and uniaxial compression tests performed, from which the precompression stresses were determined. We were thus able to derive a quantitative relationship between soil water potential and precompression stress. With this relationship we could estimate the precompression stress in the field, immediately before the machinery trafficked the soil, this value being required for use in the finite element model.

For the confined uniaxial compression tests samples were kept within the coring cylinders, built into the compression cell and subsequently subjected to stepwise increased pressure. Pressure was applied through a piston, which fitted the opening of the cylinders. Each compression step lasted for 30 minutes after which the pressure was increased to the next level. A maximum duration of 30 minutes for each compression step was chosen because this represented the time of a machine staying at the same place during normal construction work. Precompression stress was determined from the resulting stress-strain curves using the graphical procedure of Casagrande (1936).

Soil-vehicle interaction calculations were performed on the continuum with the finite-element program „Sage Crisp" Version 4.02 using the constitutive model „Modified Cam Clay" to describe the mechanical behaviour of the soil in terms of critical state soil mechanics (Britto and Gunn 1987). The experiment was modelled as a plane strain problem with the rigid track acting as an infinite strip load. Symmetry required only half the problem domain to be modelled, which was chosen to be 2 m wide and 2.8 m deep (Figure 2). The finite-element mesh com-

prised 420 triangular elements ranging in size from 0.05 * 0.05 m near the track to 0.2 * 0.6 m in the corner farthest away from the track. The load exerted by the rigid steel track onto the soil surface was considered to be uniformly distributed over the entire contact area. The load was assumed to be a vertical pressure of 78 kPa applied on a 0.75 m wide strip, which is equivalent to the mean pressure and the width of the contact area under the heaviest machine used for the experiment. Shear tractions at the surface were ignored, because the vehicles were either standing still or moving slowly without draft, and so shear tractions were probably small. For the partially drained analysis, the vertical pressure was applied in 20 steps of 3.9 kPa lasting for 1 s each and a constant pressure of 78 kPa lasting for 120 s.
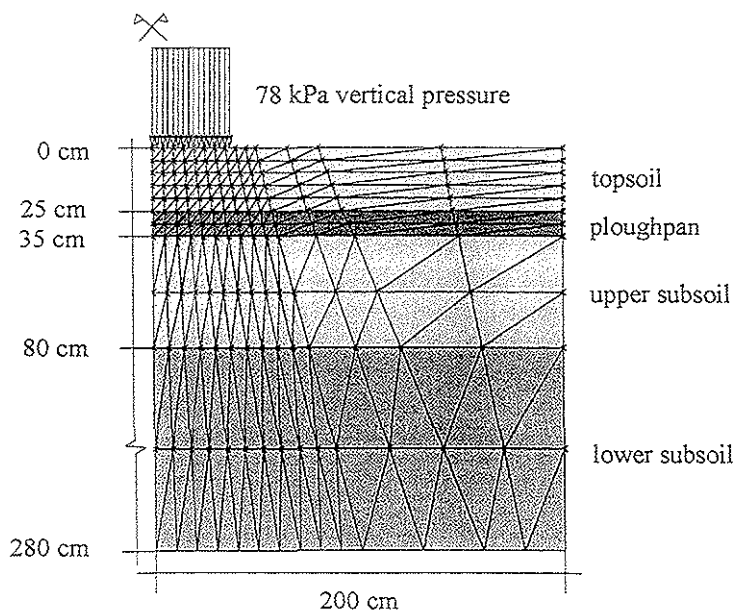
Fig. 2: The finite-element mesh chosen for the calculation

The finite-element mesh was divided into four layers with different critical state soil properties. For the topsoil (0 - 25 cm), the ploughpan (25 - 35 cm) and the upper subsoil (35 - 80 cm), the slope of the normal consolidation line, λ, the slope of the unload-reload line, κ, and the initial void ratio on the critical state line, e_{cs}, were determined from the stress-strain relationships obtained from the uniaxial compression tests on samples from the non-trafficked wet and dry plots described above. The slope of the critical state line, M, was determined by direct shear tests for these layers, measured separately on samples from non-trafficked soil. These tests were carried out with undisturbed samples (2 cm thick, 10 cm diameter) taken from non-trafficked soil and also conditioned to an initial soil water potential of 6 kPa in the laboratory by applying a hanging water column. After consolidation for 30 min, the samples were sheared in a direct shear box with a constant shear velocity of 30 μm min^{-1}. During consolidation and shearing, a constant vertical pressure was imposed on the samples. The shear tests were carried out under normally consolidated conditions which means that the vertical pressure applied to the sample was higher than the precompression stress. The angle of internal friction ϕ was determined graphically as the slope of the Mohr-Coulomb failure line. The slope of the critical state line, M, was calculated from the angle of internal friction ϕ according to Britto and Gunn

(1987, p 173). The mechanical properties of the lower subsoil (80 - 280 cm) were taken from triaxial and oedometer tests carried out by Rosal (1997) for the same site and were assumed to be the same for both plots. Poisson's ratio ν was assumed to be 0.3 for the whole soil profile of both plots.

For the continuum calculation, the critical state soil properties M, λ, and κ were assumed to be constant during the traffic experiments. The initial precompression stress was taken from the experimentally determined relationship between precompression stress and soil water potential. The resulting values are given in Table 5. The initial in situ vertical stress was considered to be the weight of the overlying soil. To calculate the initial horizontal stress, the initial vertical stress was multiplied by the initial coefficient of earth pressure at rest K_o. K_o was assumed to be 0.55 for the whole profile of the wet and the dry plot based on a simplified version of Jaky's empirical formula (Britto and Gunn, 1987, p.180) considering measured angles of internal friction ϕ between 26 and 28°.

For the dry plot, vertical stress was calculated under fully drained conditions. Since in the dry plot, soil water potentials were much higher than field capacity (= 6 kPa, see Table 4), air was assumed to be the continuous mobile phase „draining" freely under compaction. For the wet plot, two scenarios were compared with the simulations. In the first scenario, fully drained conditions were assumed, whereas in the second scenario, conditions were assumed to be partially drained. To calculate fully drained conditions, we used an uncoupled model – meaning one in which only the solid stress-strain was considered, and there was no fluid in it all. By a partially drained model we used a coupled model, in which both the solid stress-strain and the fluid pressure-flow were considered. At all boundaries we used a constant fluid pressure boundary and set the excess fluid pressure to zero. That is, these boundaries could drain perfectly freely. At the part of the boundary representing the track, we put on a total stress 78 kPa, and left it there for 2 minutes. Since the track had gaps, and also the grass would act as a drainage zone, we also set it to a constant pressure boundary with zero excess fluid pressure. This had the effect of generating a fluid pressure, which dissipated as the air and water drained away, at a rate controlled by the air and water conductivity, and the pressure was transferred to the solid. Because the time (2 minutes) was insufficient for all the excess water pressures to dissipate, we called this a partially drained simulation. Air was also assumed to be mobile in the second scenario for the topsoil, whereas air was assumed to be immobile and water mobility was considered to control compaction for the plough pan and the subsoil. For the continuum calculation, air and water conductivity were assumed to be constant. Air and water conductivity values required for the calculations under partially drained conditions were estimated from Richard and Lüscher (1983, Lokalform „Riedhof") (Table 4).

3. Results and Discussion

Tab. 4: Tensiometric soil water potential of the dry and wet plot and estimated air and water conductivity (Richard and Lüscher 1983) of the wet plot immediately before the passage of the machines

depth [cm]	soil water potential of the dry plot [kPa]	soil water potential of the wet plot [kPa]	air[a] and water conductivity of the wet plot [m s^{-1}]
12	100.0	5.2	$5 \cdot 10^{-4}$ [a]
32	85.0	2.0	$5 \cdot 10^{-8}$
52	33.4	0.7	$5 \cdot 10^{-7}$
72	16.3	0.2	$5 \cdot 10^{-7}$
> 80	6.0	0	$3 \cdot 10^{-6}$

Immediately before the passage of the machines, the tensiometric soil water potential was between saturation and field capacity (= 6 kPa) in the wet plot and from field capacity up to more than 85 kPa in the dry plot. As the water potential in the topsoil of the dry plot was beyond the measurement range of tensiometers (70 to 85 kPa), a conservative estimate of 100 kPa was taken, based on extrapolation of the observed trend in the time beforehand. Soil moisture conditions of the lower subsoil (> 80 cm) were estimated to be at the field capacity for the dry condition and at saturation for the wet plot.

Tab. 5: Estimated precompression stresses and 95 % confidence interval of the two test plots immediately before the passage of the machines

depth [cm]	average precompression stress of the wet plot [kPa]	95 % confidence interval of the precompression stress of the wet plot [kPa]	average precompression stress of the dry plot [kPa]	95 % confidence interval of the precompression stress of the dry plot [kPa]
12	47	+/- 24	107	+/- 17
32	97	+/- 16	178	+/- 91
52	55	+/- 9	139	+/- 39
72	51	+/- 7	146	+/- 51

Table 5 shows that the estimated values of the precompression stresses obtained for the dry plot were mostly two to three times higher than those of the wet plot. Despite considerable variability within each plot, the differences between the dry and wet plots were significant except for 32 cm depth. The precompression stresses of the wet ploughpan (32 cm depth) and the entire dry plot were larger than the mean pressure in the contact area of the heaviest machine used for the traffic experiment (Table 3).

Tab. 6: Critical state soil properties of the wet and the dry plots, assumed to be independent of soil moisture

critical state soil properties	plough layer 0 - 0.25 m depth	plough pan 0.25 - 0.35 m depth	upper subsoil 0.35 - 0.8 m depth	lower subsoil 0.8 - 2.8 m depth
	wet plot			
slope of the normal consolidation line, λ	10^{-1}	$4.61 \ 10^{-2}$	$7.53 \ 10^{-2}$	$4.8 \ 10^{-2}$
slope of the unload-reload line, κ	$1.19 \ 10^{-2}$	$3.04 \ 10^{-3}$	$3.08 \ 10^{-3}$	$1.2 \ 10^{-2}$
initial void ratio on the critical state line at ln (p') = 1, e_{cs}	1.10	0.79	0.92	0.79
	dry plot			
slope of the normal consolidation line, λ	$9.21 \ 10^{-2}$	$5.76 \ 10^{-2}$	$7.23 \ 10^{-2}$	$4.8 \ 10^{-2}$
slope of the unload-reload line, κ	$4.99 \ 10^{-3}$	$3.06 \ 10^{-3}$	$2.21 \ 10^{-3}$	$1.2 \ 10^{-2}$
initial void ratio on the critical state line at ln (p') = 1, e_{cs}	1.02	0.81	0.88	0.79
slope of the critical state line, M	1.02	1.07	1.07	1.11

For the upper subsoil the λ, κ, and e_{cs} given are the arithmetic mean of λ, κ, and e_{cs} determined from samples from 47 - 57 and 67 - 77 cm depth. For the plough pan and upper subsoil the slopes of the normal consolidation line λ and the unload-reload line κ of both plots were comparable. While for the topsoil, the slopes of the normal consolidation line λ were also comparable, the slope of the unload-reload line κ of the dry plot was much smaller than that of the wet plot, although the samples were conditioned at the same initial soil water potential. The values of κ are from 4 (lower subsoil) to about 33 times (upper subsoil of the dry plot) smaller than λ. Kirby (1991b) found the same range of values for λ and κ and that the values for κ are about 20 times smaller than those for λ for different Vertisols in Australia.
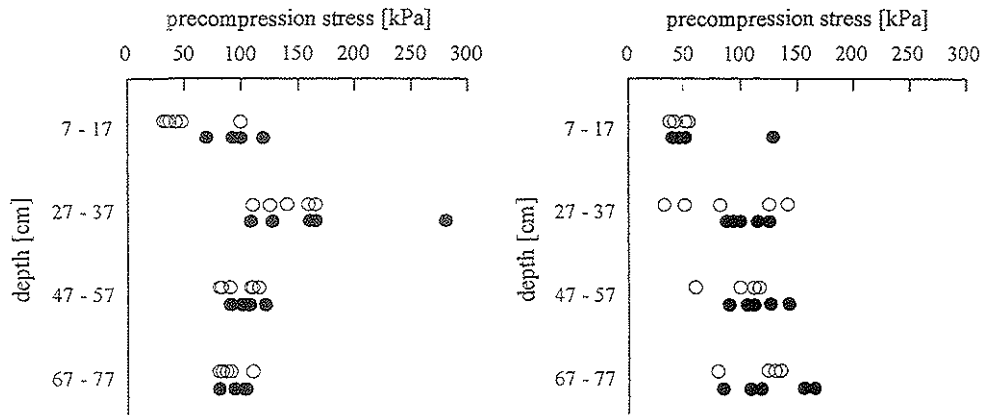
Fig. 3: Precompression stress of the trafficked (black circles) and non-trafficked soil (open circles) of the wet (left graph) and dry plot (right graph) determined at 6 kPa initial soil water potential.

In the topsoil of the wet plot we found a significant difference between the precompression stress of the non-trafficked soil (median 41 kPa) and the trafficked soil beneath the centre line of the tracks (median 97 kPa), while no such effect was evident in the topsoil of the dry plot. In the subsoil, neither the wet nor the dry plot showed a significant effect of trafficking on precompression stress.
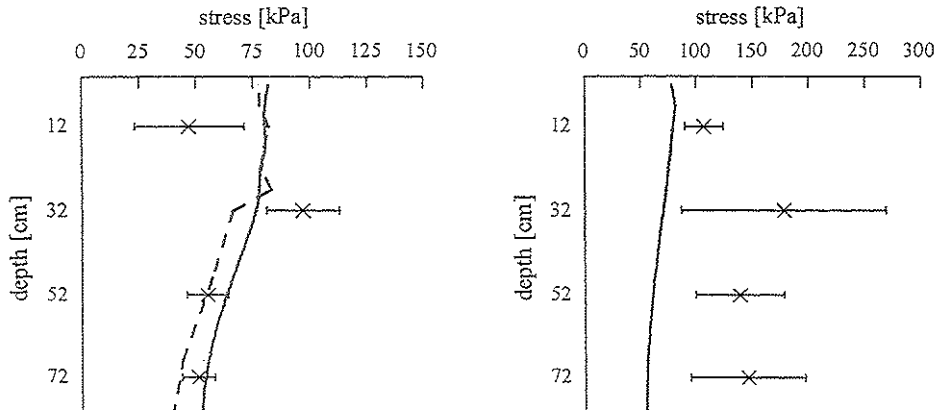
Fig. 4: Estimated precompression stresses (crosses with 95 % error bars, accounting for sample variability but not for the uncertainty of transforming precompression stresses measured at 6 kPa to actual field soil water potential) from laboratory tests in comparison to effective vertical stresses calculated under fully (solid line) and partially (dotted line) drained conditions of the wet (left graph) and dry plot (right graph)

The calculated vertical stress acting on the wet topsoil (12 cm depth) was larger than the estimated precompression stress, while the estimated precompression stresses of the non-trafficked wet ploughpan (32 cm depth) and the entire dry plot were larger than the calculated vertical stresses. For the subsoil of the wet plot, the stresses predicted by the model exceeded the estimated precompression stresses about 8 kPa at 52 cm and were about equal at 72 cm depth. The predicted stresses were within the 95 % error bars at both depths. It therefore appears likely that the measured precompression stress would not have changed significantly (bearing in mind the statistical variability in the parameter) at 52 cm or perhaps not at all at 72 cm. Furthermore, the fully drained analysis gives the maximum stresses that could have compacted the soil. In fact, the pore water pressure in the soil probably increased when the vehicle drove over the soil, and then dissipated slowly due to drainage. The resulting effective stresses (i.e. those transmitted via, and related to the compression of, the solid skeleton) would be less than those predicted by the fully drained analysis. The partially drained analysis modelled this situation. Figure 4 shows that the effective vertical stresses predicted by the partially drained analysis were indeed less than those of the fully drained case. It appears likely from this analysis that the measured precompression stress would not have changed at all. It was found experimentally that the precompression stresses before and after traffic were not significantly different in the wet subsoil. This agrees with the more probable, partially drained analysis, and with the „worst case", drained analysis.

4. Conclusion

Heavy, tracked machinery used to construct pipelines in Switzerland exerts stresses on agricultural soils of a similar magnitude to those commonly experienced in agriculture using low ground pressure tyres or tracks. Experiments showed that a dry plot in a loess soil was not compacted by the vehicles, whereas a wetted plot in the same soil was compacted in the top layers by not in or below the ploughpan. Both direct measurement and modelling (using a critical state finite element model) showed that the dry soil was strong enough to resist compaction. The wet soil was too weak to resist compaction in the top layers, strong enough in the ploughpan, and probably was also strong enough in the subsoil. In the wet soil, it seems likely that the pore water pressures increased beneath the vehicles, and that these increased pressures only partially dissipated during the two minutes that the vehicles loaded the soil. The precompression stress was a useful indicator of the likely compaction.

5. Acknowledgement

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Subsoil reaction on heavy wheel loads as affected by soil preconsolidation stress and cohesion. FEM results

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Abstract

Measuring data of a Lobith loam soil includes preconsolidation stress, compression index and swelling index, all as a function of depth. Using these three types of soil parameters calculations have been done for tyre sizes, inflation pressures and wheel loads that occur with heaviest sugarbeet harvesters available on the European market. Because no values on soil cohesion were available, the calculations were done for several cohesion levels. The results include the detection of regions with Mohr-Coulomb plasticity and regions with cap plasticity (compaction hardening). For the soil studied – a typical soil strength profile for arable land in the Netherlands – all studied combinations of wheel load and inflation pressure did not induce compaction in the subsoil. It appeared that, although soil modeling may use a great number of soil parameters, the most important parameters seem to be: preconsolidation stress and cohesion. There is an urgent need for data of these parameters that are measured on a great range of subsoils and subsoil conditions.

Keywords: Subsoil; Soil compaction; Critical state soil mechanics; Sugarbeet harvester; Finite element method

1. Introduction

The sugar beet harvest has a potential risk with regard to compaction when heavy harvesting and transport equipment is used and beets have to be lifted and transported under wet conditions (Märländer et al., 1998). Existing sugarbeet harvesters have wheel loads up to 12.9 Mg (Van der Linden and Vandergeten,1999). A convenient parameter for characterization compaction resistance of soil is preconsolidation stress. The concept of preconsolidation stress originated in civil engineering in relation to slow compression of saturated soils. In agricultural research, the concept of preconsolidation stress is applied to less slow compression of unsaturated soils. Values are usually measured with uniaxial compression tests, but measuring series that present the compaction resistance of the upper half meter of a soil profile at one point of time are hardly available. On an autumn day in 1977, core samples were taken at different depths of the 20-60 cm layer of a Lobith loam soil (16-19% clay minerals, 3.5-1% organic matter) after potato harvesting (Konijn,1978). The preconsolidation stress was measured on the samples at the water contents at sampling. The results showed that there was a strong layer under the arable layer. The preconsolidation stress was highest in the strong layer, and, at larger depths, diminished with depth. This soil profile and the water content at sampling time may be seen as a very normal soil condition for sugarbeet harvesting in the Netherlands. Soil stresses under large sugarbeet harvester tyres and wheel loads can be calculated for such a soil condition using a Finite Element Method (FEM) like PLAXIS Finite Element Code Version 7 (PLAXIS, 1999), and by modeling tyres by circular areas

carrying a uniform distribution of normal stress. The radius of such a circle can be calculated by dividing the vertical wheel load by the assumed vertical contact stress. It is often assumed that the vertical contact stress is equal to 1.25 times the tyre inflation pressure. Following this approach the calculated soil stresses underpredict the stresses in the ploughed layer (and therefore sinkage), but provide realistic values for the subsoil stresses. Values for tyre inflation pressures can be obtained from tyre specifications. The whole range of typical wheel loads of harvesters can be measured during a harvesting demonstration. The above mentioned soil condition can be modeled by the PLAXIS Cam-clay type model. This model combines elastic behaviour, Mohr-Coulomb behaviour and soil compaction (plastic hardening), and accounts for the preconsolidation stress. The next sections present PLAXIS calculation results for tyres and tyre inflation pressures of current sugarbeet harvesters, applying to the above-mentioned Lobith soil condition.

2. Materials and methods

During a sugarbeet harvesting demonstration (Van der Linden and Vandergeten,1999), measurements were done on a range of large sugarbeet harvesters that are typical for the European market. A summary of the measuring results is given in Table 1.

Table 1. Gross vehicle weight, vehicle weight, tanker capacity, and wheel loads of sugar beet harvesters (Van der Linden and Vandergeten, 1999).

machine	gross vehicle weight (Mg)	vehicle weight (Mg)	tanker capaci- ty (Mg)	wheel load at full tanker (Mg)					
				front		middle		rear	
				left	right	left	right	left	right
Agrifac ZA 215 EH	44.0	24.1	19.9	11.0	11.5			11.7	9.8
Franquet Tetra	32.8	22.2	10.6	7.5	7.5			8.8	9.0
Gilles (2-fase syst)	41.0	22.5	18.5	5.3	5.1	6.5	6.8	8.6	8.7
Holmer Terra Dos	46.1	27.4	18.7	10.4	9.9			12.9	12.9
Kleine SF 40	51.8	28.5	23.3	7.5	7.3	9.2	7.9	9.2	10.7
RiecamRBM300-S	40.1	24.6	15.5	10.9	12.4			7.6	9.2
Ropa Euro Tiger	58.9	31.4	27.5	10.1	9.4	10.9	11.7	8.4	8.4
Vervaet 17-T	38.2	22.6	15.6	11.4	11.4			7.7	7.7
Vervaet 12-TGV	27.6	16.0	11.6	8.8	9.0			4.7	5.1
WKM 9000	27.8	18.6	9.2	9.8	9.8			3.6	4.6
WKM Big Six II	44.7	26.2	18.5	8.3	6.4	7.6	6.5	9.1	6.8

The results included ranges of measured wheel loads of 12 modern sugarbeet harvesters with full tankers, 4 tyre brands, and 14 tyre types. The measurements included 4 Good Year tyre types. The measured ranges for the 800/65 R32, 73x44.00-32, 66x43.00-25 and 710/70 R38 were76-90, 11-13, 81-84 and 73-75 kN, respectively. The measurements included 7 Michelin tyre types. The measured ranges for the 800/65 R32 M28, 750/65 R26 M27, 1050/50 R32 M;égaXbib, 1050/50 R32 M609, 710/75 R34 M28, 620/70 R38 M27 and1000/50 R25 M609

were 67-124, 50-68, 87-118, 78-107, 63-85, 75-76 and 88-90 kN, respectively. The measurements included the Nokia 700/50-26.5 tyre with range 35-46 kN, and the 2 Trelleborg types 850/60-38 and 750/50-30.5 with ranges 98-115 and 47-52 kN, respectively.

PLAXIS calculations were performed for 4 tyre types: Good Year 73x44.00-32; and Michelin 710/75 R34 M28, 800/65 R32 M28 and 1050/50 R32 MégaXbib. Calculations were done for series of load – inflation pressure combinations at cyclic loading, which were selected from tyre data books of the tyre manufacturers. In addition, calculations were done for tyre - load - inflation pressure combinations that occurred in practice (i.e., that were measured at the demonstration).

A PLAXIS version 7 (released in 1999) was used for the drained condition, with automatic mesh generation, and with updated mesh analysis, i.e., the geometry of the mesh is continuously updated during the calculation. The tyre – soil system is modeled by an axisymmetric loading case where the tyre is simulated by a circular area with evenly distributed vertical stresses and the soil is modeled by a vertical cylinder with a fixed bottom side and with an outer wall the points of which are also fixed. The radius r of the loaded area is calculated from:

vertical wheel load = (1.25 x tyre inflation pressure) x πr^2

The radius and height of the soil cylinder are 4 and 1 m, respectively. Because of the existing axisymmetry, the calculations only consider the cylinder half to the right of the vertical cylinder axis. The soil cylinder is layered. Each soil layer has specific values of the soil parameters that are needed by PLAXIS. Because compactible soil is modeled, PLAXIS needs the following Cam-clay type model parameters: Poisson's ratio v, modified compression index λ^*, modified swelling index κ^*, cohesion c, angle of internal friction φ, dilatancy angle ψ, preconsolidation stress σ_c. With this model, v becomes important in unloading phases. This implies a low v value. According to the PLAXIS manual this v will usually be in the range between 0.1 and 0.2 . We used the value $v = 0.15$. Well-known are the International compression index C_c , the International swelling (recovery in unloading) index C_s and the preconsolidation stress σ_c , all applying to the uniaxial (confined) compression test. These parameters are defined in the void ratio e – log σ_1 graph of the results of a one-dimensional compression test (Atkinson and Bransby, 1994). PLAXIS considers, for this test, vertical strain ε_1 rather than void ratio e, and defines a modified compression index λ^* and a modified swelling index κ^* using a vertical strain ε_1 – log σ_1 graph. The PLAXIS manual gives equations to transform C_c and C_s values into λ^* and κ^* values. These equations include a void ratio e that is supposed to be constant. For this one can use the average void ratio that occurs during the test or just the initial value. We used initial values. The equations are

$$\lambda^* = \frac{C_c}{2.3(1+e)} \qquad\qquad \kappa^* \approx 1.3\frac{1-v}{1+v}\frac{C_s}{1+e}$$

We assumed that dilatancy is absent.

On November 7th, 1977, Konijn(1978) took core samples at different depths of the 20-60 cm layer of a Lobith loam soil after potato harvesting and measured, in uniaxial compression testing, void ratio – σ_1 relationships and preconsolidation stresses on the samples at field water content. Each test was quick, i.e., was performed wihin a few seconds. Porosities, air contents, water contents and preconsolidation stresses are presented in Fig. 1. It can cearly be seen that there was a strong layer, its pore space and air content at time of sampling being 39-40% and 6-8%, respectively. For the PLAXIS calculations, the soil profile was divided into 10 layers, with depths 0-20, 20-25, 25-30, 30-35, 35-40, 40-45, 45-50, 50-55,55-60, 60-100

cm. For each layer the necessary PLAXIS parameters could be derived from (Konijn, 1978) as follows (it was assumed that the 0-20 and 60-100 cm layers had the same properties as the 20-25 and 55-60 cm layers, respectively). Values for σ_c were read from the graph in Fig. 1. Poodt (1999a) estimated for each layer c and φ. Values of c were estimated from soil water suction values according to $c = \chi \, s_w \tan \varphi$, for which values of s_w were obtained from the field water contents through a water retention curve of a similar soil (Wösten et al., 1987), and χ was set at
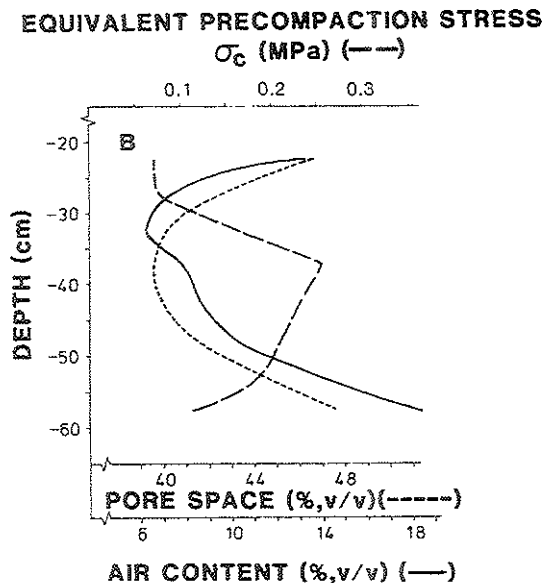
Fig. 1. State of compaction of a Lobith loam soil profile (Koolen and Kuipers, 1989).

the value 1. For unsaturated soil the angle of internal friction φ varies between 25° (moist, relatively loose, fine particles) and 45° (drier, relatively dense, coarse particles). Parameter φ was given the value of 35°. Poodt (1999b) determined for each assumed layer C_c and C_s values from the void ratio – σ_1 relationships in (Konijn, 1978), and transformed these values into λ^* and κ^* values using the above PLAXIS equations. Initial bulk densities were also taken from Konijn (1978).

Table 2. PLAXIS parameters of a Lobith loam soil profile.

Depth of soil , cm	cohesion, kPa	C_c	C_s	λ^*	κ^*
0- 25	5.8	0.226	0.005	0.052	0.0024
25- 30	4.0	0.114	0.005	0.029	0.0025
30- 35	14.3	0.102	0.003	0.026	0.0019
35- 40	19.1	0.172	0.002	0.045	0.0014
40- 45	21.9	0.176	0.002	0.046	0.0009
45- 50	21.9	0.247	0.004	0.063	0.0022
50- 55	22.7	0.300	0.003	0.073	0.0017
55-100	29.1	0.339	0.006	0.077	0.0029

3. Results

Table 2 presents for each distinguished soil layer the c , C_c , C_s , $\lambda*$ and $\kappa*$ values that were derived, and used in the FEM calculations. Fig. 2 shows the initial layered soil condition with an anticipated circular load and fixed boundary conditions at the right and bottom sides. The left line is an axis of symmetry of this axisymmetric case. Along this axis, only vertical soil movements are allowed. The generated mesh can be seen in Figs. 3-5. Fig. 3 shows a calculated mesh deformation. It applies to a Good Year 73 x 44.00 – 32 with inflation pressure = 180 kPa that has been loaded to a vertical load = 12890 kg. Fig. 4 applies to the same loading case. It shows regions under the loaded tyre where plastic yielding due to the tyre load has occurred. The empty squares indicate plastic yielding according to the Coulomb failure condition (perfect plasticity). The squares with crosses indicate the occurrence of so-called cap plasticity (plastic hardening) The plastic hardening is soil compaction. One calculation was done with a cohesion that deviates from Table 2. This resulted in Fig. 5, applying to the same case as Fig. 4, but with a c = 50 kPa across the entire depth. Figs 6 – 9 give calculated vertical stresses under centre of loaded tyre as a function of depth. Each Figure includes the σ_c – depth relationship of the considered soil profile. The further curves are calculation results for series of tyre inflation pressures. For each tyre and inflation pressure the tyre has been vertically loaded to the maximum load that is allowed (according to the tyre specifications) at that inflation pressure (tyre loads and inflation pressures are indicated in the lower left corners of the Figs.). Each of these Figs also includes a curve for a load – inflation pressure combination that has been measured in practice.

4. Discussion

The C_c and C_s values are relatively low, probably because measuring started on undisturbed soil structure and occurred at a compression rate that was not low. Calculated stresses showed no decrease with depth in the ploughed layer, which may be due to the presence of a relatively rigid strong layer. Comparing Fig. 4 with Fig. 9, it can be seen that, for this soil – tyre system, cap plasticity (compaction) only occurs if vertical stress exceeds preconsolidation stress. Other results which are not included, indicate the same. Fig. 4 shows large regions of Coulomb plasticity, which is due to the low (minimum) cohesion values that were used: for the one calculation with a more realistic c = 50 kPa value these Coulomb regions almost vannished (Fig. 5). The net effect of the occurrence of Coulomb plasticity is not clear yet. The involved particle movements may harm soil structure, but may also be accompanied by dilation (soil loosening). Coulomb plasticity is a flow phenomenon. If load duration is short, the movements are small. It seems that, as far as soil parameters are concerned, calculation results primarily depend on preconsolidation stress and cohesion. It is likely that these parameters may be estimated from cone tests and shearvane tests.

5. Conclusion

A relatively strong layer on top of the subsoil can protect subsoils from compaction by high wheel loads. For the soil studied – a typical soil strength profile for arable land in the Netherlands – all measured combinations of wheel load and inflation pressure of sugar beet harvesters did not induce compaction in the subsoil. Compression and swelling indices should preferably be measured on undisturbed samples at high strain rates. There is an urgent need for soil parameters that reflect the mechanical properties of agricultural soil profiles.

These parameters should fit into finite element models, but the methods to measure them should be easy. Important parameters are preconsolidation stress and cohesion. They may be estimated from cone tests and shearvane tests.

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Fig.2. Right half of the axisymmetric loading case

Fig.3. Good Year 73x44.00 – 32   load: 12890 kg   inflationpressure: 180 kPa

Deformed Mesh
Extreme total displacement 23.42*10⁻³ m
(displacements scaled up)
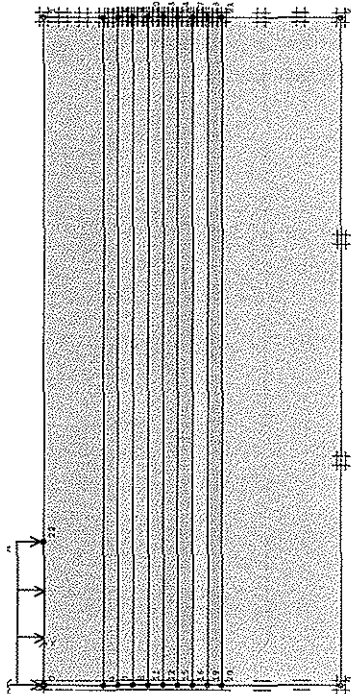
Fig. 4. Good Year 73x44.00 – 32   load: 12890 kg   inflationpressure: 180 kPa

Plastic Points

☐ Plastic Mohr-Coulomb point   ▨ Tension cut-off point
▨ Plastic cap point
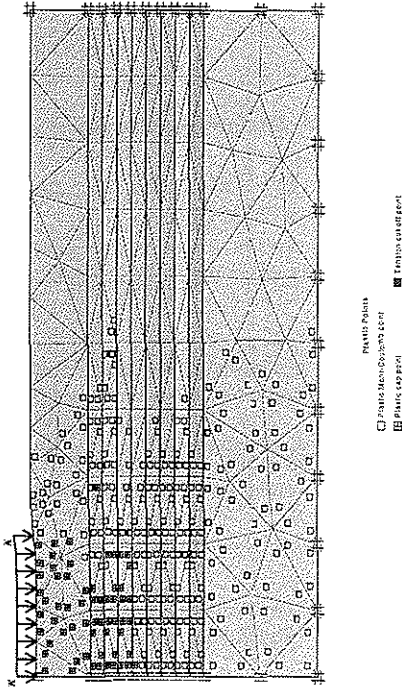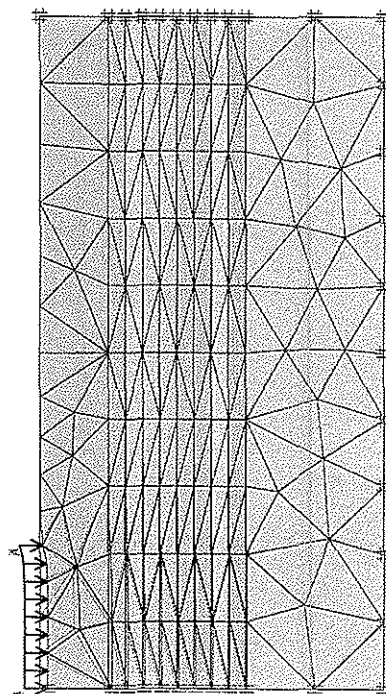
Fig.5. Good Year 73x44.00 – 32   load: 12890 kg   inflationpressure: 180 kPa
Cohesion: 50 kN/m²
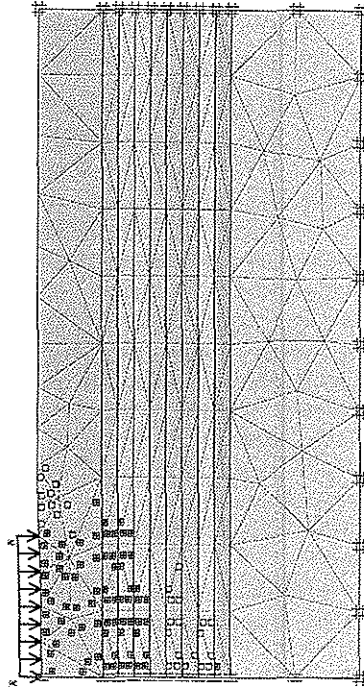
96

Fig.6. Soilpressures beneath the center of the tyre Michelin 710/75R34XM28

Stress [kN/m²]
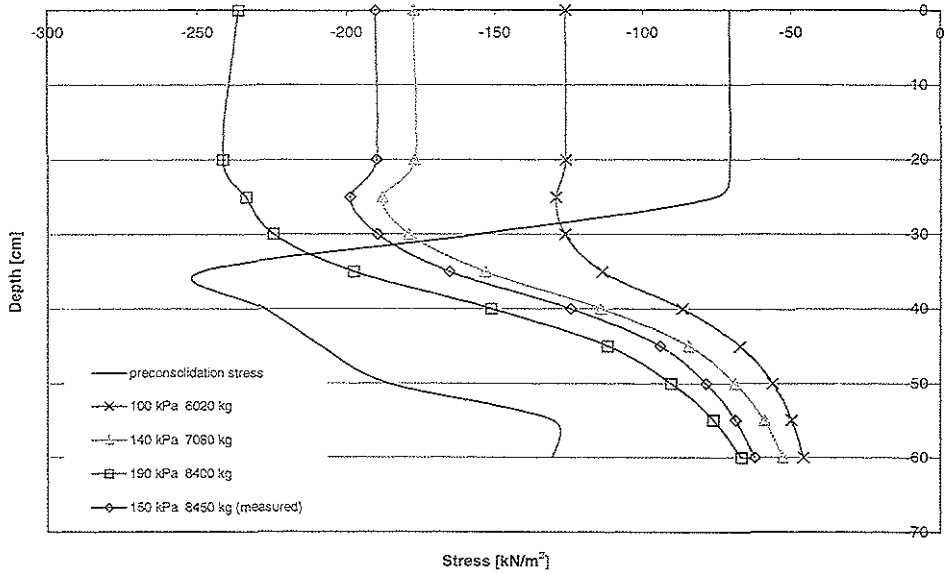
Fig.7. Soilpressures beneath the center of the tyre Michelin 800/65R32M28

Stress [kN/m²]
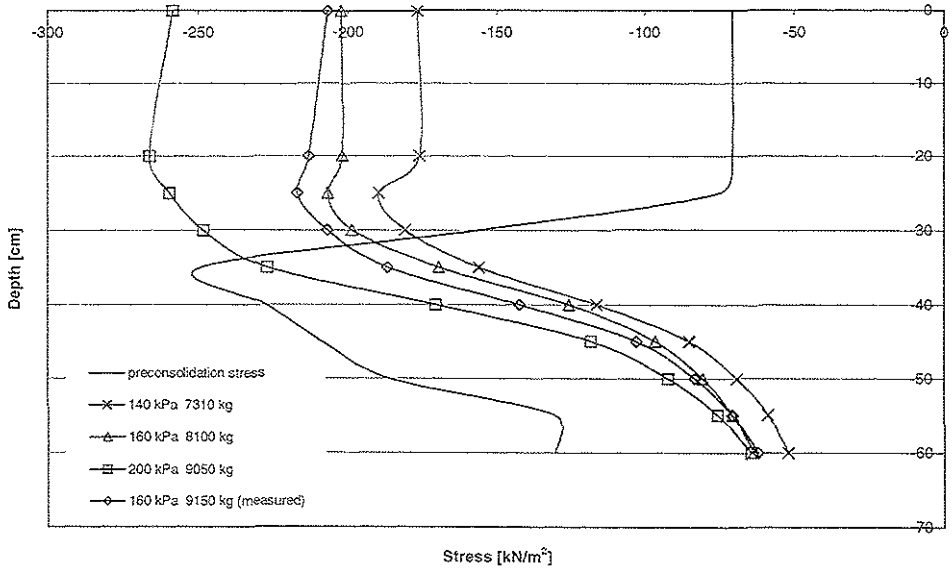
Fig.8. Soilpressures beneath the center of the tyre Michelin 1050/50R32 megaXbib

Legend:
- preconsolidation stress
- 100 kPa 8250 kg
- 180 kPa 10370 kg
- 270 kPa 12750 kg
- 160 kPa 11750 kg (measured)

Depth [cm]

Stress [kN/m²]
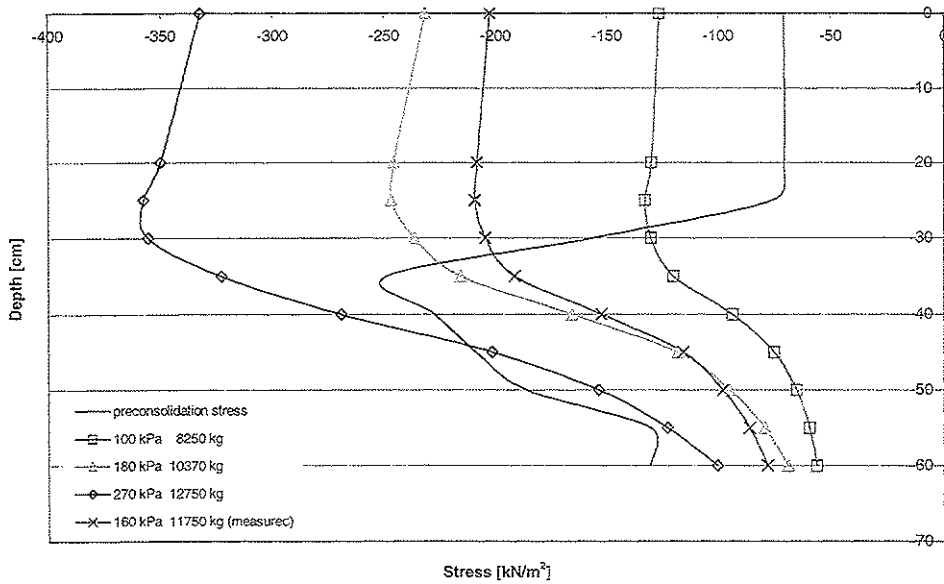
Fig.9. Soilpressures beneath the center of the tyre Good Year 73x44.00 - 32

Legend:
- preconsolidation stress
- 140 kPa 8820 kg
- 180 kPa 10045 kg
- 280 kPa 13230 kg
- 180 kPa 12890 kg (measured)

Depth[cm]

Stress [kN/m²]
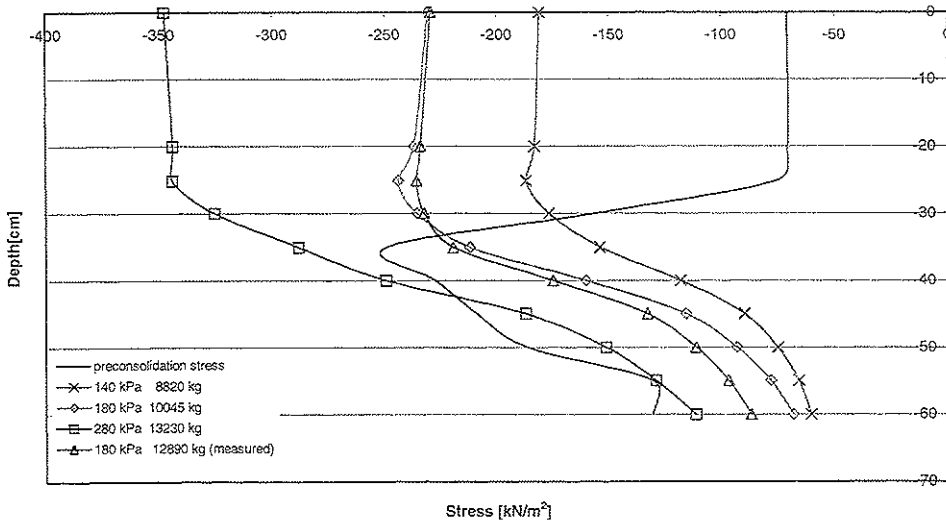
Subsoil compaction caused by heavy sugarbeet harvesters. II. A model to prevent subsoil compaction

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Abstract

The objectives of the work presented here were (1) to measure soil compaction under high axle load at different water contents, and relate this to the soil mechanical properties, and (2) to simulate the soil susceptibility to compaction during the year using a soil water model (SOIL). A model to prevent subsoil compaction, based on soil mechanical properties and soil water simulations run by meteorological data, is proposed.

Measurements were conducted on a sandy clay loam in southern Sweden. The following measurements were made: (1) Water content in the soil profile, root growth and plant development throughout the growing season. (2) Soil displacement during traffic (axle load approximately 16 tonnes) in the autumn at different water contents. (3) Soil mechanical properties at each displacement measurement, and at specified water tensions. (4) Soil water retention and saturated hydraulic conductivity to 1 m depth.

The subsoil water content was very low in late summer, but increased during the autumn. Soil displacement occurred from 0.3 m depth in the driest soil, down to 0.7 m depth in the wettest soil. Model predictions of compaction correlated well with the depth to which displacement was measured in the field.

Using meteorological data, the soil water content was simulated for a 25 year period, and the risk for subsoil compaction under a wheel load of 8 tonnes and a ground pressure of 220 kPa was calculated. The compaction risk at 50 cm depth was estimated to increase from around 25 to nearly 100 % between September and late November, which is the period when the sugar beets are harvested.

1. Introduction

In an international series of field experiments, high axle loads (10 tonnes) were shown to cause subsoil compaction on different soil types in different parts of the world (Håkansson, 1994). Subsoil compaction is a severe problem mainly due to its persistence; effects may even be permanent (Håkansson, 1994).

In Sweden, heavy sugar beet harvesters, with axle loads of approximately 20 tonnes, were introduced in the 1990s. This caused a major concern among sugarbeet growers about the effects on the subsoil. A research project was started in 1995, including traditional field experiments to study the effects of traffic on soil properties and crop yield. Within the project, a new method to measure soil displacement was developed in 1996 (Arvidsson and Andersson, 1997). The project also included measurements of soil mechanical properties, and the development of a model on how to prevent subsoil compaction. In this article measurements of soil displacement during wheeling at different water contents are presented together with risk calculations of compaction for traffic during different times of the year.

2. Methods

2.1. A method for measuring vertical soil displacement and soil stress

The method to determine soil displacement is based on the physical principle of the pressure of a liquid being proportional to its height. A plexiglass cylinder containing silicon oil was installed laterally into the soil through a hole that was drilled from a dug pit, as described by Arvidsson and Andersson (1997). The liquid was connected through a hose to a pressure transducer in the pit. When the soil moved under traffic, the height of the liquid column changed, and the soil displacement was registered as a change in pressure by the transducer.

2.2. Field measurements

Measurements were conducted on a sandy clay loam at Elvireborg (23 % clay, 25 % silt, 50 % sand, 2 % organic matter in the topsoil) in southern Sweden. At this site, the following measurements were made: (1) Soil water content, root growth and plant development throughout the growing season. (2) Measurements of soil displacement during sugarbeet harvest in the autumn at different water contents. (3) Sampling for determining soil mechanical properties at each wheeling test, and at specified water tensions. (4) Determination of soil water retention to 1 m depth.

(1) The gravimetric soil water content was determined to 1 m depth in 10 cm layers from sowing until the sugarbeets were harvested. Sampling was done every two weeks with a soil drill. Maximum root depth was measured at the same occasion.

(2) The measurements of soil displacement were made during harvest with a six-row sugarbeet harvester, weighing approximately 35 tonnes fully loaded and 22 tonnes without load. The front tyres were Trelleborg TWIN 850/60-38 and the rear tyres Continental 800/65 R32, with inflation pressures 200 and 170 kPa, respectively. The wheelings were made at two occasions, 15 and 28 Oct, in sugarbeets and in wheat stubble. One area in the sugarbeet field was covered from 10 Oct to prevent precipitation, and one area in the wheat stubble was irrigated with 120 mm of water. For each water content, one pit was dug in the soil. The harvester was driven fully loaded on one side of the pit, and without load on the other side. Measurements of soil displacement were made at three depths: 30, 50 and 70 cm.

(3) From each pit, cylinders were taken from unwheeled soil to determine soil mechanical properties at 30, 50 and 70 cm depth. Twelve samples (34 mm in height, 61 mm in diameter) per depth were taken for determination of shear strength, and two samples (25 mm in height, 72 mm in diameter) per depth to determine precompression load at the time of wheeling. Eight samples per depth were taken to determine precompression stress at specified water tensions: 6, 30, 60 and 150 kPa.

(4) Three cylinders (50 mm in height, 72 mm in diameter) per 10 cm layer were taken to determine the water retention properties and the saturated hydraulic conductivity of the soil.

2.3. Measurements of soil mechanical properties

Determination of soil shear strength were made as described by Schønning (1986). Shearing of the samples were made with a grousered shear annulus with a mean shearing rate of 46 mm s^{-1} at four normal loads: 40, 80, 120 and 160 kPa, using three cylinders at each load.

The cylinders sampled for uniaxial compression were compressed in an oedometer described by Eriksson (1974) at sequential stresses of 25, 50, 75, 100, 150, 200, 400 and 800 kPa. Each stress was applied for 30 minutes, and the strain was measured while the soil was still loaded.

The precompression stress was determined according to Casagrande (1936).

2.4. Soil water simulations

Soil water content was simulated with the model SOIL (Jansson, 1998), which represents water and heat dynamics in a layered soil profile. Simulations for 1997 were mainly based on measured crop and soil properties at Elvireborg (for example root depth, vegetation cover and soil water retention) and on meteorological data. The model was calibrated using the measured data from 1997, and then soil water content was simulated using meteorological data for the years 1963-1988.

2.5. Model computations of compaction

The estimated depth of compaction was calculated using SOCOMO (SOil COmpaction MOdel, van den Akker, 1988). The major and minor principal stresses were calculated assuming a uniform ground contact pressure of 220 kPa, a tyre width of 850 mm and a wheel load of 8 and 5 tonnes for the loaded and the unloaded harvester, respectively. The concentration factor was set to 5 (Koolen and Kuipers, 1983).

Two failure criterions were used: (1) The calculated major principal stress was higher than the precompression stress of the soil. (2) Shear failure according to the Mohr-Coulomb law (Koolen and Kuipers, 1983).

2.6. Risk calculations

From the oedometer measurements, the precompression stress was derived as a logarithmic function of soil water tension. These values were combined with the soil water simulations for a 25 year period, and compaction was estimated to occur when the calculated soil stress at a certain depth was higher than the precompression stress.

3. RESULTS AND DISCUSSION

3.1. Soil water content

The measured and simulated volumetric water content at 30 and 50 cm depth are shown in Fig. 2, a and b. The water content gradually decreased until September, when it started to increase. There was a better agreement between measured and simulated values at 50 than at 30 cm depth. Precipitation in 1997 was approximately 600 mm, which is close to the average for this site.

3.2. Soil displacement

Results from wheeling tests at three different water contents with the harvester fully loaded are shown in Fig. 3, a, b and c. At 30 cm depth there was a plastic deformation during all tests. At 50 cm depth there was a plastic deformation in the wetter soil, whereas there was only an elastic displacement in the driest soil. Results from all wheeling tests are shown in Table 1. It can be seen that the soil water content had a much larger influence on the soil displacement than the load of the harvester. The results are consistent with earlier research, where axle loads of 10 tonnes have compacted the soil to approximately 50 cm on different soil types (Håkansson, 1994).
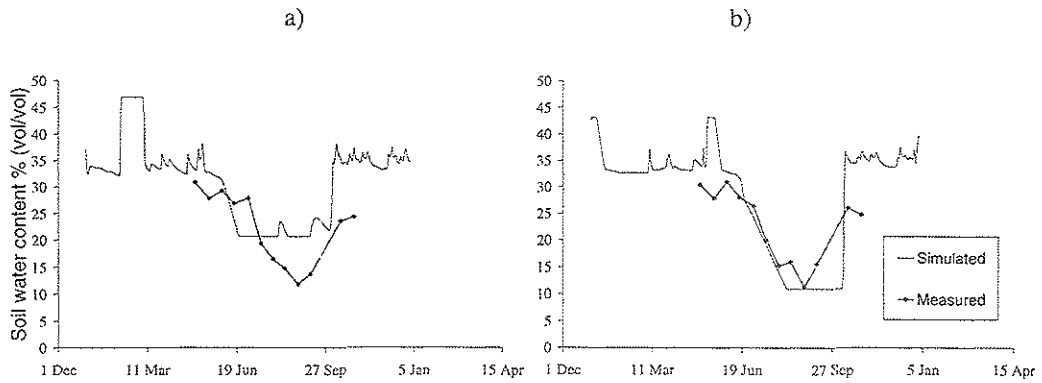
Fig 2. Measured and simulated soil water content at a) 30 cm depth b) 50 cm depth.

3.3. Soil mechanical properties

The cohesion and the angle of internal friction of the soil at each wheeling occasion are shown in Table 1. The lowest value for the cohesion was 74 kPa at 30 cm depth in the wettest soil. The cohesion was greater at greater depth and at lower water contents. The driest soil was too hard to install the shear annulus. Precompression stress values ranged from 150-200 kPa in the driest soil to 60-70 kPa in the wettest soil.

3.4. Modelling of compaction depth

The calculated depth of compaction using SOCOMO is presented in Table 1. For the fully loaded harvester, it ranges from 0.41 m in the driest soil to 0.92 m in the wettest soil (Table 1, Fig. 4). There is in general a good agreement between the estimated depth of compaction, and the depth at which it was measured in the soil.
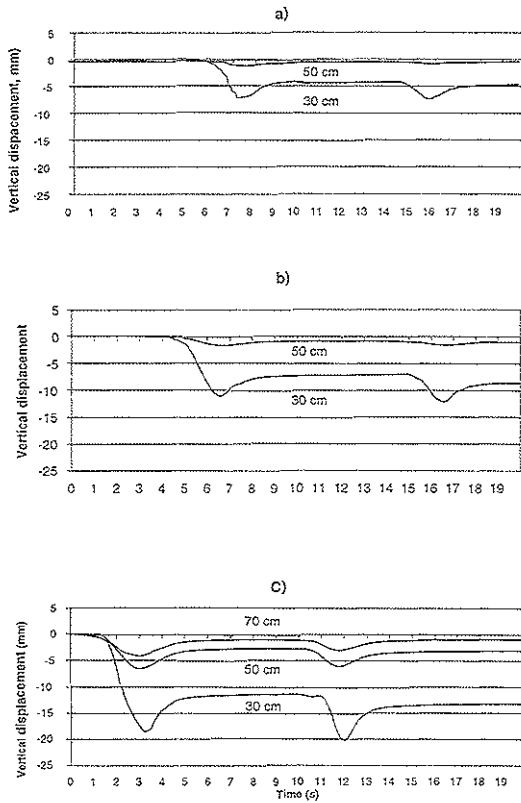
Fig. 3. Soil displacement 28 Oct during wheeling with a sugar-beet harvester (total weight approx. 35 tonnes). Each "dip" represents the pass of a wheel. a) Soil covered from 10 Oct. b) Natural water content. c) Irrigated.
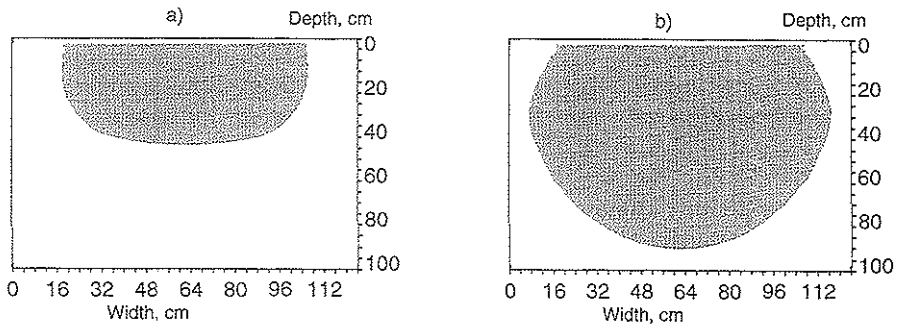
Fig. 4. Model computations of area subjected to compaction under the wheel of a fully loaded sugarbeet harvester (wheel load 8 tonnes, inflation pressure 220 kPa). a) Soil covered from 10 Oct. b) 28 Oct., soil irrigated.

Table 1. Soil water content (w), cohesion, angle of internal friction (v), precompression stress (P_c) and vertical soil displacement at 0.3, 0.5 and 0.7 m depth at a total load of approximately 22 and 35 Mg. Results are given for the different wheeling occasions at Elvireborg, together with the estimated depth of compaction using SOCOMO

Treatment	Depth	w	Coh.	v	P_c	Displac. (mm)		Est. depth of comp. (m)	
	(m)	(% w/w)	(kPa)		(kPa)	22 Mg	35 Mg	22 Mg	35 Mg
Plot covered	0.3	17.6	87	35	123	-3.7	-4.2	0.34	0.41
since 10 Oct.	0.5	11.0	>154 [a]	-	165	-0.2	0.0		
	0.7	11.8	>154 [a]	-	202	-[b]	-[b]		
Sugar beets	0.3	17.0	129	27	79	-1.6	-1.9	0.51	0.66
15 Oct.	0.5	16.2	140	26	89	-0.7	-[b]		
	0.7	12.9	147	47	100	-[b]	-[b]		
Stubble	0.3	18.0	129	41	64	-4.5	-4.9	0.47	0.59
15 Oct.	0.5	20.8	125	30	98	-1.1	-2.1		
	0.7	16.6	166	40	122	-[b]	-[b]		
Sugar beets	0.3	17.2	91	37	77	-5.5	-8.5	0.48	0.73
28 Oct.	0.5	17.3	103	31	95	-1.3	-0.9		
	0.7	16.8	154	31	89	-0.3	0.0		
Irrigated,	0.3	18.6	74	46	60	-10.9	-13.2	0.66	0.92
28 Oct.	0.5	20.0	96	25	68	-0.9	-3.0		
	0.7	21.4	118	46	69	-0.1	-0.5		

(a) Estimated value, the soil too hard to install the shear annulus by hand.
(b) The missing values are in most cases caused by the soil being too hard to install the measuring equipment

3.5. Risk calculations

An example of the precompression stress as a function of soil water tension is shown for 70 cm depth in Fig 5. The estimated frequency of compaction due to traffic in different times of the year with a wheel load of 8 tonnes and a mean ground contact pressure of 220 kPa is shown in Fig. 6. The risk is always high in the spring, rather low in late summer at 50 and 70 cm depth, and increases gradually in the autumn. For example, at 50 cm depth the risk was estimated to increase from around 25 to nearly 100 % between September and late November, which is the period when the sugar beets are harvested.
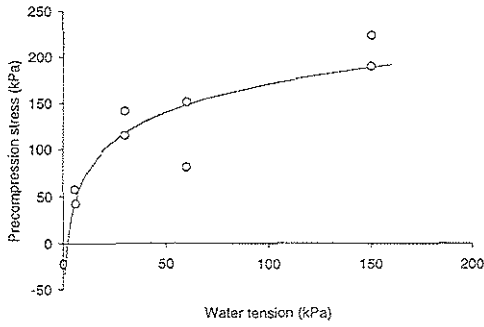
Fig. 5. Precompression stress as a function of soil water tension for 70 cm depth at Elvireborg.
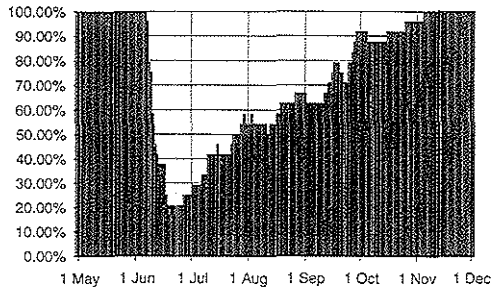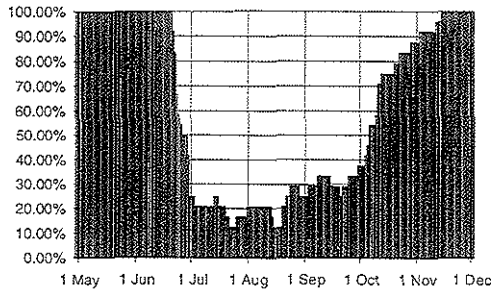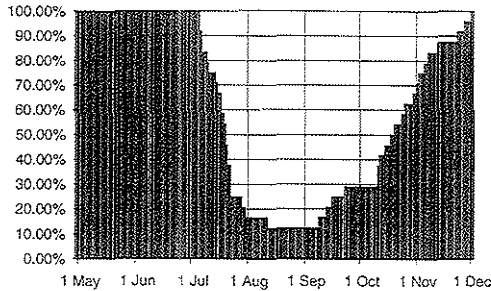
Fig 6. Calculated risk of compaction at Elvireborg for traffic with a wheel load of 8 tonnes and a contact pressure of 220 kPa at a) 30 cm b) 50cm and c) 70 cm depth. Estimations are based on simulations of soil water content for the period 1963-1988.

4. CONCLUSIONS

The results of this research confirms that traffic by heavy axle loads may compact the subsoil to more than 50 cm depth, especially at high soil water contents. Model predictions of compaction correlated well with the depth to which displacement was measured in the field.

The type of measurements and simulations made in this study is also suitable for developing a more general model to prevent subsoil compaction (Fig. 7). Soil compaction could be predicted from determination of soil mechanical properties at different water contents, and calculation of soil stresses and soil water content. Field measurements should be used to validate and calibrate the model. This could form the basis for locally adjusted recommendations of permissible wheel loads and tyre inflation pressures as proposed by van den Akker (1994). Based on meteorological data for a large number of years, it is possible to predict the risk for the soil to have high water content and low strength. This could be made for different soils and crops at the time for different field operations, such as tillage, manure spreading and harvest.

The technique for soil displacement measurements presented here is suitable for the field validation of the estimated soil compaction. The most difficult task is probably how to correlate the mechanical properties to the compaction obtained in the field.
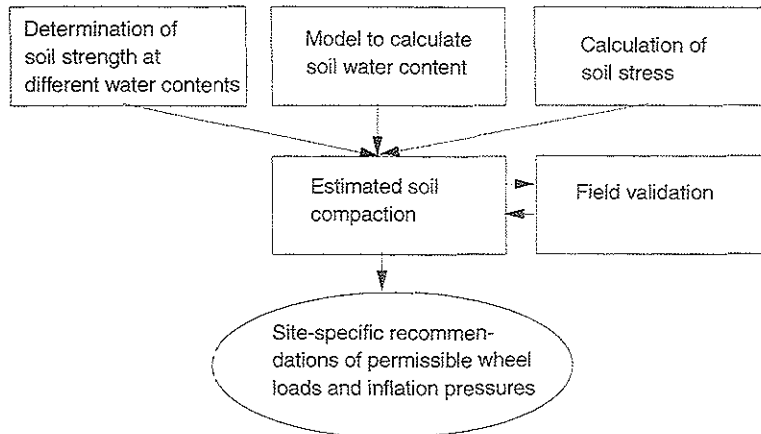
Fig. 7. A proposed scheme how to develop recommendations of allowable wheel loads and inflation pressures for traffic at different soil water contents.

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Soil-tyre/track interaction. A review of the last ten years studies

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Abstract

This paper reviews the studies published in English during the last ten years on the soil-tyre/track interaction topic, as related to the traffic-induced soil compaction.
Both for tyres and tracks the interactions with the soil and their consequences were basically studied in three different ways as shown in the following block diagram.
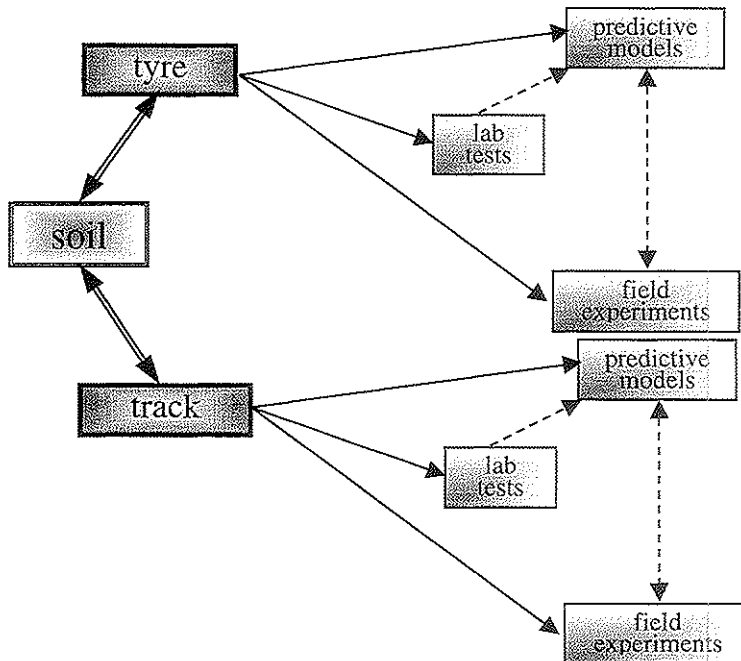
Field traffic experiments were carried out to study the compaction induced in different soils at various depths by tracks or tyres, varying type of track/tyre, axle load, inflation pressure, soil conditions, traffic or tillage systems etc.
Lab tests were set up in soil bins for examining more closely the phenomenon, for relating the interactions to the consequences and for building up formulae and/or models to predict the stress produced in the soil under the wheel.
Mathematical and simulation models (some using the finite element method) were developed to predict soil compaction induced by different running gears and/or to evaluate the effect of field traffic on various soil characteristics (bulk density, water potential, air permeability, porosity, etc.).
In some cases the models were evaluated in field experiments; in other cases the results of field or laboratory experiments were used to develop the models.
The review photographs the state of the art and aims to suggest future research needs.

Prediction of the mechanical strength and ecological properties of subsoils for a sustainable landuse

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Abstract
Methods to quantify the mechanical strength in order to assess the trafficability of agricultural soils are presented and evalidated by pedotransfer functions. The relationship between the precompression stress and the depending soil parameters is shown. By using tables for the values of the cohesion and the angle of the internal friction, the precompression stress can be calculated and assessed by multiple regression equations. Horizon spezific values concerning the mechanical stability of arable soils can be determined for various moisture contents. Changes in dependence of gravel are also given. The stress transmission for specific soil horizons can be calculated by using classified values of the concentration factor. The mechanical stability for the whole soil is determined and assessed by comparing the actual pressures for the specific soil horizon with the corresponding value of the precompression stress. Stress dependent changes of soil physical properties only occur exceeding the value of the precompression stress. If the internal soil strength is exceeded, intensively changes of physical properties are induced, which is especially a function of soil moisture, texture, structure and applied stress. Such regression equations can be used to calculate the change in physical soil properties.

Keywords: precompression stress, shear strength, soil structure, stress transmission, compressibility, physical soil properties

1. Introduction
Over the past decades farming soils have been deteriorated by heavy machines. Increasing loads of the used machines led towards subsoil compaction which can be partly classified as irreversible. This compaction partly causes a decrease of soil productivity (Arvidsson and Hakansson 1991, Wiermann 1998, Vorhees 2000). Additionally water erosion may increase, especially in the traffic lanes and on the top of the plowpan layer (Fleige and Horn 2000). In order to prevent those negative developments, agicultural soils should only be wheeled at suitable times. Especially using heavy machines should be balanced with the compressibility of the soil. Methods to quantify soil strength in order to determine the trafficability are required also looking from the point of view, that the federal soil conservation law came into force in Germany in 1998. It is important to include in the appropriate guidelines and regulations not only advices on methods to be used in the field, but also values which can be used for the prediction of the extent to which arable soils can be stressed.

2. Theory
The main data derive from confined compression and frame shear tests of undisturbed aggregated and unsaturated soils, which resulted in precompression stress and shear strength data. Of which we assume that the elastic stress part i.e. stresses smaller than the precompression stress do not change the pore system and its function, we can also determine the stress dependent changes in the virgin compression load range. From the vertical stress measurements in the various soil horizons due to wheeling with conventional agricultural machinery stress and contact area dependent concentration factors can be derived as a

function of the precompression stress. According to the method of Newmak, the concentration factor vk can be calculated by

(1)

$$vk = \frac{\log\left(\frac{\sigma 0}{\sigma 0 - \sigma z}\right)^2}{\log\left[\left(\frac{r}{z}\right)^2 + 1\right]}$$

where:

σ_0 = Contact area or soil pressure
          (normal stress at the surface) (kPa)
σ_z = Pressure in the depth z (kPa)
r = Radius of the tyre contact area (load area), calculated as
          equivalent radius of a circle (cm)
z = Soil depth (cm)

This equation holds true for a circular contact area of the tractor tire, although it has normally an oval form depending on the tire inflation pressure and the tire form. Figure 1 shows the principle coherence between load and stress transmission in the soil. The values of the concentration factor vk vary between 2 and 9. The higher the concentration factor, the more unstable is the horizon. Thus the stress is more restricted in a soil volume around the perpendicular down to depth. The smaller the concentration value vk is, the greater the stress compensation. Consequently the applied stresses are attenuated in a smaller soil volume.
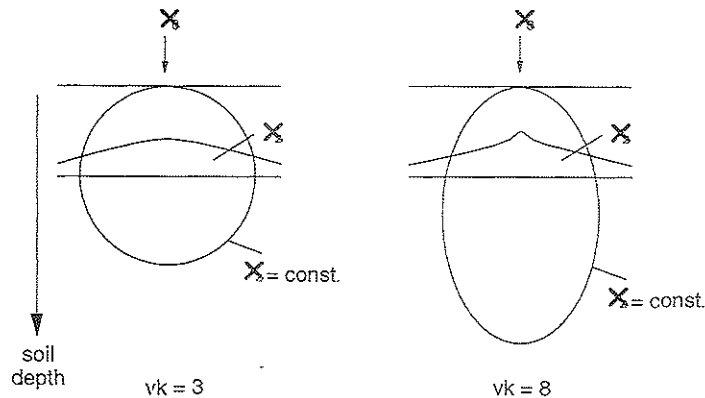
Figure 1. Stress distribution in soils at different concentration factors

The measurements for the determination of the mechanical stability (technique see Horn 1981a, Horn 1981b) were carried out for at least 116 representative argricultural soils with different soil textures and structures in Germany with up to 5 horizons per soil during the last 20 years (e.g. Horn 1981a, Lebert 1989, Horn et al. 1991, Semmel 1993, Kühner 1997, Wiermann 1998, Nissen 1999). Basing on those data, pedotransfer functions were found to predict the mechanical stability of soils. The results are summarized in 3 leaflets *"structure stability of agricultural mineral soils"* in Germany (DVWK Vol. 234 (I)/1995, Vol. (II)/1997, Vol. 236 (III)/2000).

3. Results

3.1. Derivation of the precompression stress

The dependent variable precompression stress and the independent variables are listed in Table 1. The parameters cohesion c and angle of the internal friction ɸ indicate the pattern of the Mohr Coulomb failure line. This curve describes the relation between the static load and the shear strength, whereby the shear strength characterizes the resistance which a soil can set against a deformation.

Table 1. Variables for the calculation of the mechanical stability of soils

Variable	Sign	Dimension
Dependent variables:	$Pv_{1.8}$, $Pv_{2.5}$	kPa
Preconsoldation stress		
Independent variables:		
Bulk density	⑬t	$g\ cm^{-3}$
Air capacity	$Lk_{1.8}$, $Lk_{2.5}$	Vol-%
Available water capacity (pF 1.8 - 4.2)	$nFK_{1.8}$, $nFK_{2.5}$	Vol-%
Non plant water capacity (pF >4.2)	TW	Vol-%
Saturated water capacity *	kf	$(cm\ s^{-1})\ 10^{3}$
Organic matter	org	Wt.-%
Cohesion	$c_{1.8}$, $c_{2.5}$	kPa
Angle of the internal friction	$ɸ_{1.8}$, $ɸ_{2.5}$	Degree
* At a kf of >300 cm/d or <1cm/d the calculation is carried out with 500 cm/d or 0.5 cm/d respectivly		

The mean values of the parameters c and ɸ apply as a function of soil texture (Figure 2) and structure of the various soil horizons are listed in Table 2.
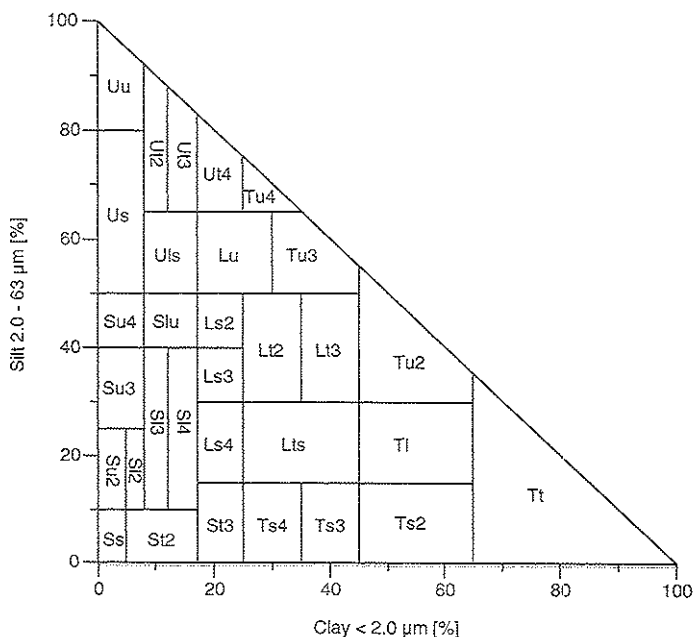
Figure 2. Percentages of sand, silt and clay of the German soil texture classes (AG Boden 1994)

Table 2. The shear strength parameters: cohesion c and angle of internal friction φ in dependence of different water tensions (pF 1.8 and 2.5) for various texture and structure at a mean bulk density of 1.4 to 1.75 g cm^{-3}. Static loads range between 0 and 400 kPa.

Soil texture	Soil structure	pF 1.8		pF 2.5	
		c (kPa)	φ (°)	c (kPa)	φ (°)
X	sin	0	25	0	26
Ss, Su 2-4	sin	8	26	12	28
Sl 2-4	sin	8	30	10	32
Slu	coh/pri	12	34	14	37
	pol	15	39	18	41
St 2-3	coh/pri	13	38	15	40
	pol	20	41	23	43
Uu, Us	sin	2	29	4	30
Us	coh/pri	10	35	15	39
	cru	8	37	12	40
Ut 2-4	coh/pri	12	35	26	37
Uls	pol	18	35	20	38
	sub/cru	44/40	40/43	50/45	42/45
Lu	coh/pri	10/12	30/35	15	32/36
	pol	16	35	18	37
	sub/cru	34	38/39	44	40/46
Ls 2-4	coh/pri	10	22/25	14	31/33
Lts	pol	19	30	26	35
	sub/cru	26/22	36/38	38/33	39/42
Lt 2-3	sin	1	19	2	23
	coh/pri	15	28/32	26/34	36/38
	pol	30	36	41	40
	sub	46	39	66	43
Tu	coh/pri	32	22/28	45	30/32
	pol	40	30	70	34
	sub	45	36	40	42
Tt	sin	0	16	0	20
Tl, Tt	coh/pri	30/40	24/32	34/45	38/42
Ts 2-4	pol	50	44	60	48
	sub	50	48	70	56

X = coarse fragment (> 80 Wt.-%), sin = single-grain, coh = coherent, pri = prismatic, pol = blocky, sub = subangular, cru = crumb

The calculation of the precompression stress by multiple linear regression equations for different soil texture groups and different water tensions (pF 1.8 and pF 2.5) is shown in Table 3. The value of the precompression stress can be predicted highly significant. It has to be taken into account, that not every listed variable in Table 1 is necessary to describe the precompression stress. For not or only low structured soils (e.g. sandy soils) the precompression stress can be predicted especially by the bulk density and the water content at pF >4.2. With increasing aggregate formation the value of the precompression stress is determined especially by the shear strength parameters c and φ. Additionally the influence of air capacity and the available water capacity gets more important in stronger aggregated soils. The influence of the type of clay minerals, the cation exchange capacity and the state of humification on the precompression stress cannot be characterized yet in detail.

Table 3. Calculation of the precompression stress (Pv) by multiple linear regressions for different soil texture groups at pF 1.8 and pF 2.5

Soil texture group	Regression	
Ss, Su. Slu,	$Pv_{1.8}$ =	$438.10\ \text{®t} - 0.0008\ (\text{∞})^3 - 3.14\ TW - 0.11\ (nFK_{1.8})^2 - 465.60$
Sl, St2	$Pv_{2.5}$ =	$410.75\ \text{®t} - 0.0007\ (\text{∞})^3 - 3.41\ TW - 0.35\ (nFK_{2.5})^2 - 384.71$
St3, Ls	$Pv_{1.8}$ =	$169.30\ \text{®t} - 29.03\ (org)^{0.5} + 6.45\ kf + 32.18\ \log\ (c) -$
		$9.44\ \text{∞}\quad + 27.25\ \sin\ (TW) + 119.74\ \log\ (nFK_{1.8}) + 19.51$
	$Pv_{2.5}$ =	$89.50\ \text{®t} - 23.99\ (org)^{0.5} - 2.89\ kf + 125.76\ \log\ (c) -$
		$1.14\ \text{∞}\quad + 26.90\ \sin\ (TW) - 51.46\ \log\ (nFK_{2.5}) - 77.25$
Uu, Us, Uls,	$Pv_{1.8}$ =	$374.15\ \text{®t} - 4.10\ org + 3.38\ LK_{1.8} - 1.58\ (kf)^{-0.5} + 1.79\ c +$
Ut2, Ut3		$1.09\ TW - 6.37\ (\text{∞})^{0.67} + 0.088\ (nFK_{1.8})^2 - 472.77$
	$Pv_{2.5}$ =	$460.71\ \text{®t} - 20.33\ org + 9.08\ LK_{2.5} - 2.38\ (kf)^{-0.5} + 2.86\ c +$
		$4.50\ \text{®t} - 20.96\ (\text{∞})^{0.67} + 0.304\ (nFK_{2.5})^2 - 610.62$
Lu, Ut4, Lt2,	$\log Pv_{1.8}$ =	$0.843\ \text{®t} - 0.544\ (kf)^{0.33} - 0.022\ TW + 7.03\ (c)^{-1} + 0.024\ \text{∞} -$
Ts4		$0.015\ nFK_{1.8} + 0.725$
	$\log Pv_{2.5}$ =	$0.844\ \text{®t} - 0.456\ (kf)^{0.33} - 0.026\ TW + 12.88\ (c)^{-1} + 0.003\ \text{∞} -$
		$0.016\ nFK_{2.5} + 1.419$
Lt3, Tu, Lts,	$Pv_{1.8}$ =	$4.59\ \text{®t} - 1.02\ org - 16.43\ (kf)^{0.33} + 0.31\ TW - 1.57\ nFK_{1.8} +$
Ts2, Ts3, Tl, Tt		$3.55\ c + 1.18\ \text{❸} - 18.03$
	$Pv_{2.5}$ =	$70.65\ \text{®t} - 0.55\ org - 7.01\ (kf)^{0.33} + 1.32\ TW - 1.08\ nFK_{2.5} +$
		$1.72\ c + 1.05\ \text{❸} - 100.94$

The classification of the precompression stress ranges between very low to extremely high (Table 4).

Table 4. Classification of the precompression stress Pv

Classification	Class value	DV-sign	Precompression stress (kPa)
Very low	1	Pv1	< 30
Low	2	Pv2	30-60
Mean	3	Pv3	60-90
High	4	Pv4	90-120
Very high	5	Pv5	120-150
Extremly high	6	Pv6	> 150

The influence of the actual moisture content decides about reduced and increased values. If the soil horizons get moister than pF 1.8, the stabilty of the soil in the same soil class decreases, whereby with increasing amount of clay the reductions become greater (Table 5). The stability completely vanishs at pF 0, which can occur in the topsoil after a heavy rainfall. On the other hand the soil stability increases with increasing drying of the soil. The precompression stress at pF 2.5 is generally reached by drying in summer. If the pore volume is increased by a high humus content, the shear strength can become lower. The equations are generally applicable for humus contents between 0-15%. Above 15% a clear reduction of the shear strength has to be expected. Peats under natural conditions are completely unstable.

Table 5. Reduction of the class value of the precompression stress at pF <1.8

Soil texture	Class value					
DV-sign	1	2	3	4	5	6
Ss, Su, Slu, Sl, St2,	0	0	0	0.5	1	2
St3	0	0.5	0.5	1	1.5	2
Uu, Us, Uls, Ut2, Ut3	0	0.5	1	1.5	2	2.5
Lu, Ut4, Lt, Ts, Tu, Lts	0	1	1.5	2	2.5	3
Tl, Tt	0	1	2	2.5	3	3.5

The influence of the coarse fragments on the precompression stress is considered by a surcharge depending on the amount of the coarse fragments (Table 6).

Table 6. Surcharge of the class value of the mechanical strength with regard to the coarse fragments

Coarse fragment (Wt.-%)	Coarse fragment (Vol.-%)	DV-sign	Surcharge
15 - 40	10 - 25	x3, g3, gr3	1
40 - 60	25 - 50	x4, g4, gr4	2
60 - 80	50 - 75	x5, g5, gr5	3
> 80	> 75	X, G, Gr	4

3.1.1. Application example

In the following the calculation of the precompression stress of a single soil horizon will be demonstrated. The corresponding horizon specific input parameters are given in Table 7. The calculation of the precompression stress is based on the equations of table 3. The qualitative assessment refers to Table 4. Results can neither exceed 6 or undergo 1 if reductions and surcharges are taken into account (Table 5 and 6).

Table 7. Application example for the calculation of the precompression stress

Input-data	
Soil texture:	Lt3
Coarse fragments (> 2 mm)	20%
Soil structure:	pol
Water tension:	pF 1.8
Bulk density	1,55 g/cm^3
Organic matter	1.5 wt.-%
Saturated hydraulic conductivity	25 cm d^{-1} = 2,9 *10^{-4} cm s^{-1} = 2.9*10^{-1} = 0.29
Non plant water capacity (pF >4.2)	26 vol-%
Available water capacity (pF 1.8 – 4.2)	15 vol-%
Output-data	
Cohesion (Table 2)	30 kPa
Angle of the internal friction (Table 2)	36°
Pv$_{1.8}$ (Table 3)	4.59 x *1.55* – 1.02 x *1.5* - 16.43 *(0.29)*$^{0.33}$ + 0.31 x *26* - 1.57 x *15* + 3.55 x *30* + 1.18 x *36* -- 18.03 = 110.1 kPa
Classification (Table 4)	4 (high)
Reduction at pF 1.8 (Table 5)	2 (low)
Surcharge at 20% coarse fragments (x3) (Table 6)	5 (very high)

3.2. Calculation of the stress transmission

In order to get informations about the specific ability of a horizon concerning the stress compensation, it is necessary to get the concentration factor vk for the different soil texture groups.

3.2.1. Calculation method for single horizons

The determination of the concentration factor vk as a measure of the stress transmission is carried out by the equation of Newmark.

For σ_z the following notation (equation 2) arises after the equation (1):

(2)

$$\sigma z = \sigma 0 \left[1 - \frac{1}{\sqrt{\left[\left(\frac{r}{z}\right)^2 + 1\right]^{vk}}} \right]$$

Table 8 shows the concentration factors for the main soil texture groups in dependence of the equivalent radius of the tire contact area, the effective soil pressure (load) at the top of the respective horizon and the precompression stress of a horizon. At the same soil texture and same equivalent radius of the tire contact surface as well as at comparable load at the top edge of the respective soil horizon the concentration factor decreases with increasing precompression stress. That means the horizon becomes more stable. At the same precompression stress and increasing load at the top edge of a horizon the value of the concentration factor increases. The bigger the equivalent radius of the tire contact area becomes, the smaller the value of the concentration factor is at the same value for the precompression stress and increasing load.

Table 8. Mean values of the concentration factor vk for the main soil texture groups: silt, loam and clay in dependence of the equivalent radius of the tire contact area, the precompression stress of the single soil horizons and the effective soil pressure $\oplus_0$ at the top of the respective horizon at pF 2.5

Equivalent radius of the tire contact area (cm)	Contact area or soil pressure (kPa)	Silt Precompression level				Loam Precompression level				Clay Precompression level			
		2-3	4	5	6	2-3	4	5	6	2-3	4	5	6
< 10	<100	4.1	3.7	2.1	2.0	3.8	3.3	3.1	2.8	4.0	3.7	2.9	2.8
	100-150	4.3	3.8	3.1	2.3	4.3	3.5	3.5	-	4.7	4.0	3.3	2.8
	150-200	4.5	3.9	3.4	2.5	4.7	3.8	3.8	-	4.8	4.3	3.6	3.0
	>200	4.7	4.2	3.8	2.9	5.0	-	-	-	4.9	4.5	3.9	3.1
10-15	<100	3.4	3.3	2.6	-	3.7	3.1	2.7	2.7	4.1	3.6	2.8	2.7
	100-150	3.6	3.4	2.8	-	3.9	3.3	3.2	-	4.3	3.8	3.3	3.0
	150-200	3.7	3.5	2.9	2.8	4.3	3.5	-	-	4.5	3.9	3.6	-
	>200	3.9	3.7	-	-	4.8	3.8	-	-	4.8	4.4	3.8	-
15-20	<100	3.0	2.6	2.3	-	3.2	3.2	2.9	2.7	4.0	3.6	-	-
	100-150	3.3	2.7	2.4	-	3.5	3.3	3.0	-	4.2	3.7	-	-
	150-200	3.5	3.0	2.6	-	3.7	3.6	-	-	4.3	3.9	-	-
	>200	3.7	3.1	2.8	-	4.2	-	-	-	4.5	4.0	-	-
20-25	<100	2.5	2.3	2.1	-	3.0	2.9	2.7	2.6	3.7	3.5	3.0	2.8
	100-150	2.9	2.7	2.5	-	3.2	3.1	2.9	-	3.9	3.5	-	-
	150-200	3.4	3.0	2.7	-	3.7	3.5	-	-	4.0	3.5	-	-
	>200	3.6	3.3	2.9	-	3.9	-	-	-	4.1	3.6	-	-

- = not defined because these value combinations do not or seldom exist under natural conditions

3.2.2. Calculation and assessment of the stability and compressibility of the whole soil
The stabilty of a whole soil can be determined by the horizon specific precompression stress, the soil pressure and the concentration factor of the respective horizon. It can further be deduced up to which depth additional deformations can be expected due to pressure which exceeds the strength of a horizon.

The following steps have to be executed in order to calculate the compressibility of mineral soils:

A. Steps, which have to be executed for all horizons with regard to the impact of a load.
1.   Determination of soil texture and structure and other soil parameters according to Table 1,
2.   Determination of c and $\wp$ (Table 2),
3.   Calculation of the precompression stress Pv (Table 3),
4.   Classification of the precompression stress (Table 4),
5.   Consideration of reductions and surcharges (Table 5 and 6),
6.   Determination of the vertical stress σ_n at the soil surface and the radius r of the pressure stamp according to the given question.

B. The following steps have to be executed from above to below for all horizons i (i = 1, 2, ...), using i for the current calculation horizon. σ_i is the vertical stress, which appears at the lower edge of the horizon i. Thus σ_{i-1} is the vertical stress at the upper edge of the horizon i or at the lower edge of the horizon i-1. For the topmost horizon (i = 1) σ_0 equals the contact area pressure at the soil surface. The horizon i is followed below by the horizon i + 1.

7.   i = 1,
8.   Determination of vk_i (Table 8) by σ_{i-1}, the soil texture and the precompression stress of the horizon i,
9.   Calculation of $\sigma_{z,i}$ for the horizon i, whose lower edge is in the depth z_i (equation 2),
10.   i = i+1,
11.   Return to step 9 if the last calculated $\sigma_{z,i} > 0$ and further informations about other horizons are still available,
12.   Decision whether and in which horizon the calculated vertical stress σ_i exceeds the precompression stress of the horizon (i+1). If σ_i is higher than the precompression stress of the horizon i+1, then this horizon becomes plastically deformed.

3.2.2.1. Application example

In the following the mechanical strength of a Luvisol derived from loess is demonstrated. It shall be calculated up to what depth are applied stresses at a given contact area (radius of the tire contact area: 10 cm, contact area pressure: 210 kPa) will be transmitted into the soil.

The horizon specific precompression stress can be calculated by the equations of Table 3 and the knowledge of some physical values of the soil (Table 1). Informations about the concentration factor of a soil texture group, the contact area pressure and the precompression stress level can be taken from Table 8. The remaining stress in the depth z at the top of the following soil horizon can be calculated by the equation of Newmark.

According to Table 8 and a radius of the tire contact area of 10 cm, a contact area pressure of 210 kPa and a calculated precompression stress of 55 kPa results for an Ap-Horizon with the soil texture Ls3 a concentration factor of vk = 5.0.

Using the equation of Newmark for the given values a precompression stress of 49 kPa for the depth z = 30 cm (start of the following E-horizon) results. The following E-horizon (up to the top edge of the Bt-horizon) has a precompression stress value of 18 kPa.

$$\sigma zAp = 210 \left[1 - \frac{1}{\sqrt{\left[\left(\frac{10}{30}\right)^2 + 1 \right]^{5.0}}} \right] = 49 kPa \qquad \sigma zAp = 48.6 \left[1 - \frac{1}{\sqrt{\left[\left(\frac{10}{20}\right)^2 + 1 \right]^{4.1}}} \right] = 18 kPa$$

Table 9 shows the gradual calculation of the soil stress transmission.

Table 9. Calculation of the stress transmission in a Luvisol of loess on the base of calculated precompression stress values and an effective contact area pressure of 210 kPa at the top edge of the soil

Horizon	Ap	E	Bt	C
Depth (cm)	0-30	30-50	50-80	> 80
Soil texture	Uls	Uls	Lu	Uls
Precompression stress Pv (kPa)	55	20	100	60
Calculated contact area pressure at the edge to the next horizon	210	48.6	17.8	2.8
Concentration factor vk (Table 8)	4.7	4.1	3.3	4.1
Ratio P_v/σ_0	0.3	0.4	5.6	21.4

The assessment of the results with regard to further compaction of the soil always requires the comparison of the values for specific precompression stress of the horizon with the remaining stresses in the horizon. As long as the precompression stress is greater than the calculated pressure in the given soil depth, the soil horizon there is still stable and the properties remain constant. However, if the ratio P_v/σ_0 is smaller than 0.8 the soil is to be classified as instable (Table 10).

Table 10.Classification of the effective soil load by the relationship of precompression stress Pv to soil pressure σ_0

Ratio P_v/σ_0	Classification
> 1.5	Very stable, elastic deformation
1.5 –1.2	Stable
1.2 - 0.8	Unstable
< 0.8	Unstable, additional plastic deformation, fluent

3.3. Stress dependent changes of ecological relevant properties

Physical properties and the ecological properties change by exeeding the internal soil strength. Usually a decrease of the total pore volume due to compaction occurs. First, air filled coarse pores become reduced, as they can be easily deformed, resulting in a decrease of air capacity and air conductivity. At the same time the amount of water filled pores increases. Though, with increasing load the available water (pF 1.8-4.2) decreases while fine pores (pF >4.2) increases. The changes of the soil properties in addition depend on soil properties like aggregation, humus content and soil texture(Figure 3).
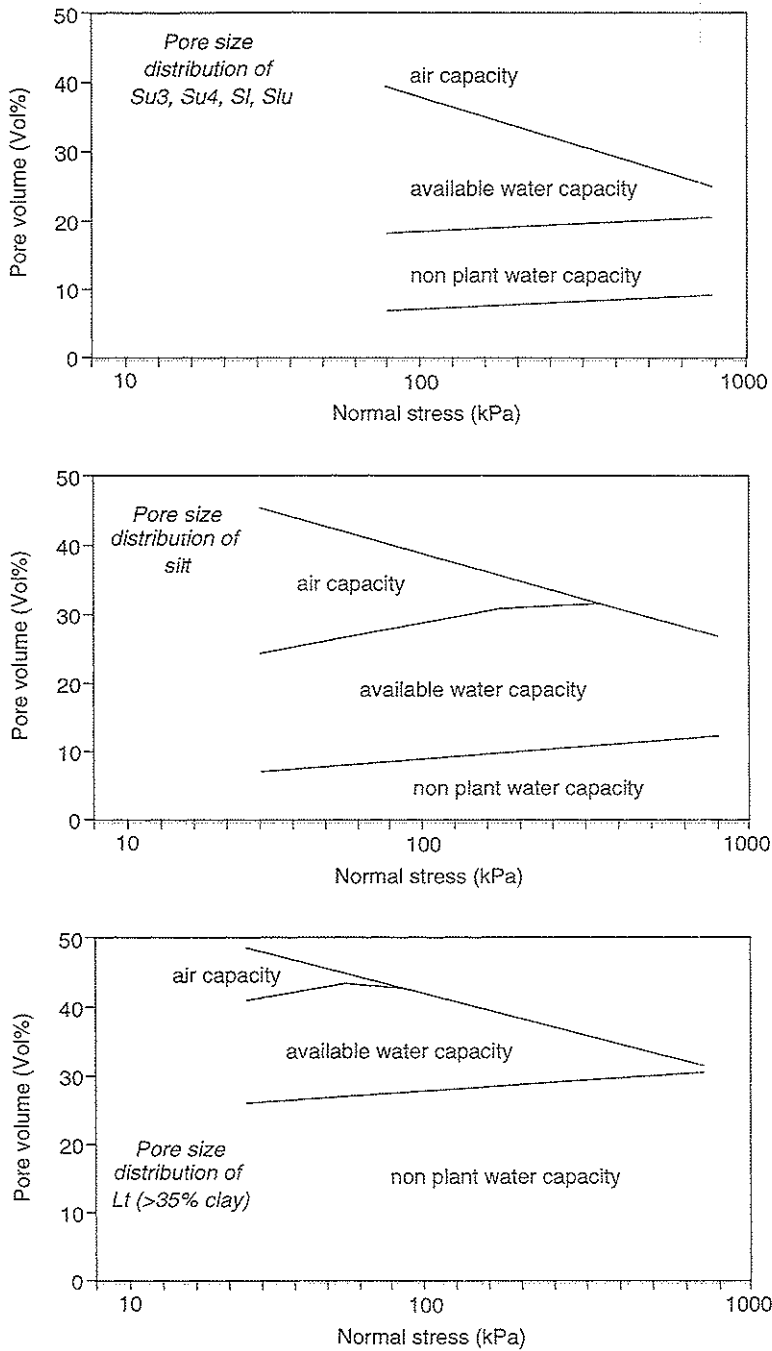
Figure 3. Change of the total pore volume and the pore size distribution after exceeding the precompression stress in dependence of the load for different soil textures (drainage at pF 1.8)

The classification of load depending values for soil physical properties is given in Table 11.

Table 11. Classification of load depending soil physical properties

Classification	Class value	Void ratio (-) sign: ≈	Air permeability (Vol%) sign: LK	Air conductivity (cm/s 10⁻⁴) sign: kl	Available water Capacity (Vol%) sign: nFK	Non plant available water (Vol%) sign: TW
Very low	1	<0.43	<2	<5.5	<6	<4
Low	2	0.43 - 0.61	2 - 4	5.5 -12	6 - 14	4 – 8
Mean	3	0.61 - 0.85	4 - 12	12 - 25	14 - 22	8 – 16
High	4	0.85 - 1.17	12 - 20	25 - 55	22 - 30	16 – 24
Very high	5	>1.17	>20	>55	>30	>24

3.3.1. Derivation of the load dependent changes of soil physical properties
The derivation of the load dependent change of soil physical properties is shown for the air conductivity and the available water capacity. For the other properties equations were determined, too.

Air conductivity (kl):
Loads, exceeding the precompression stress of a soil and thus leading to irreversible deformations reduce the "unstable" coarse pores in diameter and volume. A reduction of air conductivity has generally to to be expected (Figure 2).
The calculation of the air conductivity (kl) can be carried out either by a linear or a nonlinear regression equation (Table 12):

$$kl = b \times log10^{(c/b)} + 1$$
with $\quad c = a1 \times log \textcircled{\scriptsize n}_n + a0$

Table 12. Regression equations for the determination of load dependent air conductivity after exceeding the precompression stress (pF 1.8 and 2.5)

Soil texture	pF	Regression
SS, Su2		Due to the experiment there could not be found any decreases
Sl, Slu, Su3, Su4, St2	pF 1.8	-4.85 log ($\textcircled{\scriptsize n}_n$)+ 16.42
	pF 2.5	-16.59 log ($\textcircled{\scriptsize n}_n$) * 49.43
Uu, Us, Ut2, Ut3, Uls	pF 1.8	b = 5; al = -19.57; a0 = 50.74
	pF 2.5	14.68 log ($\textcircled{\scriptsize n}_n$) + 44.92
Ts4, Lt2, Tu4, Lts	pF 1.8	b = 20; al = -41.59; a0 = 76.45
	pF 2.5	b = 0.1; al = -20.70; a0 = 51.18
Tt, Tu2, Lt3, Ts2	pF 1.8	b = 2; al = -7.97; a= = 17.00
	pF 2.5	b = 0.5; al = -4.99; a0 = 12.75

Available water capacity (nFK):
As can be seen in figure 2 the tendency of change of the plant available water capacity after exceeding the precompression stress is no longer linear, because it may increase at first and later decrease at higher stresses. Within silty, clayey and loamy soils and partly in loamy sands the available water firstly rises due to a change in the pore system, promoting the evolution of medium pores. With further loads the amount of medium pores also decreases, wheras the amount of fine pores increases now. Thus the water content >pF4.2 also rises.
Table 13 shows the regression equations of the available water capacity.

Table 13. Regression equation for the determination of load dependent available water capacity after exeeding the precompression stress (pF 1.8 and 2.5)

Soil texture	pF	Regression
SS, Su2	pF 1.8	$-0.67 \log (\circledcirc_n) + 10.73$
	pF 2.5	$-0.03 \log (\circledcirc_n) + 5.21$
Sl, Slu, Su3, Su4, St2	pF 1.8	Total pore volume – air capacity – water content >pf 4.2
	pF 2.5	$-0.16 \log (\circledcirc_n) + 11.22$
Uu, Us, Ut2, Ut3, Uls	pF 1.8	Total pore volume – air capacity – water content >pf 4.2
	pF 2.5	Total pore volume – air capacity – water content >pf 4.2
Ts4, Lt2, Tu4, Lts	pF 1.8	$-9.27 \log (\circledcirc_n) + 31.64$
	pF 2.5	Total pore volume – air capacity – water content >pf 4.2
Tt, Tu2, Lt3, Ts2	pF 1.8	$-11.19 \log (\circledcirc_n) + 32.65$
	pF 2.5	$-9.40 \log (\circledcirc_n) + 28.70$

3.3.2. Application examples

The change of air conductivity and available water capacity by exceeding the precompression stress can be predicted from Table 12 and 13. The horizon already mentioned in chapter 3.2.1 serves as an example with the following properties of the Ap-horizon.

Soil texture:	Lt3
Soil structure:	pol
Water suction:	pF 1.8
Organic matter:	1.5 Wt.-%
Precompression stress:	110 kPa

What change of the air permeability and available water capacity can be expected, if the soil at the surface is stressed by 210 kPa ?

The calculation of the air permeability is carried out after the equation:

$$kl = b \times \log 10^{(-7.97 \log 210 + 17)/2} + 1$$
$$= 0.14$$

The classification of the air permeability is *very low* according to Table 11.

The calculation of the available water capacity (nFK) is carried out after the equation:

$$nFK = -11.19 \log 210 + 32.65$$
$$= 6.5$$

The classification of the air permeability is *low* according to Table 11.

4. Conclusion

The prediction of the precompression stress as a mean to assess the mechanical stabity in a soil by using shear strength parameters as well as independent soil variables in multiple regression equations proved to be significant. The equations are taking into account soil texture and structure as well as soil moisture, thus specific loads can be calculated for several types of soils under different water conditions. The calculation of the load dependent changes of soil physical properties after exceeding the precompression gives informations about the ecolocical consequences of subsoil compaction. By the leaflets *"structure stability of agricultural mineral soils"* a tool for recommendations for a sustainable landuse in Germany

in order to avoid subsoil compaction is available now. How far this approach and these equations can be also applied under various climatic and landuse systems has to be tested.

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Subsoil compaction caused by machinery traffic at different soil water contents.

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Abstract

The objective of this research is to test the hypothesis that 1) the amount of soil compaction during field traffic depends largely on the soil water content 2) the depth to which the soil is compacted during wheeling can be predicted on the basis of soil mechanical properties and calculation of soil stresses.

In 1999, measurements were made of stresses and vertical soil displacement during traffic with axle loads of 4, 6, 10 and 14 Mg at different soil water contents. This was combined with determinations of soil precompression stress at the time of the traffic, and predictions of the soil compaction with the soil compaction model SOCOMO.

The experimental site was near Uppsala, Sweden. The soil was a swelling/shrinking clay loam classified as Eutric Cambisol.

Soil vertical displacement increased with increased axle load. The load had a much larger effect on soil displacement than the water content or the precompression stress. With an axle load of 14 Mg there was a tendency that the soil displacements at 0.5 and 0.7 m depth were larger when soil was dry and the precompression stress high. An implication of the results is that the precompression stress does not always provide a good indication of the risk for subsoil compaction. A practical consequence is that subsoil compaction in some soils may occur even when the soil is very dry.

SOCOMO predicted the soil displacement relatively well when the soil water content was highest. On all other wheeling occasions, the model failed to predict any soil compaction, even at high axle loads.

1. Introduction

Compaction of the subsoil should be avoided since soil productivity may be reduced, and the effects are very persistent, maybe even permanent (Håkansson and Reeder, 1994). Mechanical loosening to improve the structure of the subsoil is expensive and has often proved unsuccessful, and in some cases even negative (Håkansson and Reeder, 1994).

Different strategies have been proposed to avoid subsoil compaction. In Sweden, a general recommendation to limit the load to 6 Mg per axle has been given to farmers since 1974 (Håkansson and Danfors, 1981). Grecenko et al. (1997) argued against an "all-encompassing" axle- or tire load, and suggested that recommendations of axle load should be given for specific tires. Van den Akker (1994) suggested giving limits for permissible wheel loads and tire inflation pressures depending of the mechanical properties of the subsoil.

In 1999, a project was started in Sweden to develop local recommendations to farmers about the maximum permissible combinations of axle load and tire pressure on different soils at different times of the year. As a part of this project, measurements of vertical stress and soil displacement during traffic at different soil water contents are made using a technique developed by Arvidsson and Andersson (1997). The objective is to test the hypothesis that
1) the amount of soil compaction during field traffic depends largely on the soil water content
2) the depth to which the soil is compacted during wheeling can be predicted on the basis of soil mechanical properties and calculated of soil stresses.

In 1999 measurements were made of stresses and vertical soil displacement during traffic with axle loads of 4, 6, 10 and 14 Mg at different soil water contents. This was combined with determinations of soil precompression stress at the time of the traffic, and predictions of the soil compaction with the analytical soil compaction model SOCOMO (Van den Akker, 1988). In this paper the main results obtained in 1999 are summarised.

2. Materials and methods

2.1. The experimental site

The experimental site was established at Ultuna (N 59≡ 49' E 17≡ 39') near Uppsala, Sweden. The soil was a swelling/shrinking clay loam classified as Eutric Cambisol, table 1.

Table 1. Particle size distribution at experimental site, Ultuna.

Depth (mm)	<0.002 mm g kg-1	0.002-0.006 mm g kg-1	>0.06 mm g kg-1	Org. matter g kg-1	
100	400	397	184	20	
300	533	386	79	2	
500	454	469	78	0	
700	435	442	122	0	

The experimental site was ploughed in the autumn 1998. After harrowings in the beginning of May 1999, wheat was sown. Measurements of wheeling effects were carried out at natural soil water content on May 11, June 8, July 15, August 14, September 10, October 27 and December 1.

Weather data (table 2) was obtained from the meteorological station at Ultuna, about 1 km from the site. The whole experimental period except September was considered considerably drier than normal.

Table 2. Monthly precipitation at the meteorological station at Ultuna, in 1999 and in 1961-1990.

	1999 (mm)	Mean 1961-1990 (mm)
April	82.9	29.3
May	15.4	32.8
June	32.6	45.9
July	11.9	70.5
August	32.8	66.4
September	68.4	57.0
October	25.6	49.6
November	9.2	50.6

2.2. The vehicle used for traffic

A tractor-towed trailer was constructed to apply traffic with controlled axle loads. It could be loaded from 4 up to 14 Mg on one axle. The right wheel of the trailer run outside the rut created by the tractor wheels. This was done to avoid compacting before the passage of the trailer wheel. The trailer was equipped with Trelleborg TWIN 700-26.5 tyres. At each

wheeling occasion, axle loads of 4, 6, 10 and 14 Mg were used. The inflation pressure was 140 kPa with axle loads of 4, 6 and 10 Mg, and 240 kPa for 14 Mg.

The contact area on a hard surface was measured by parking the tire on cloth and spraying around the tire. The contact area was thereafter cut out of the cloth, and transferred to paper which was then weighed.

2.3. Soil displacement and stress measurements

Soil vertical displacement during wheeling was measured as described by Arvidsson and Andersson (1997). The technique is based on the principle that the pressure of a liquid column is proportional to its height. The probe contains a Plexiglas cylinder filled with silicone-oil (fig. 2). The oil is connected through a hose to a pressure transducer. Vertical movement of the cylinder changes the height of the oil-column and the output signal of the pressure transducer. The transducer can measure a displacement of 6102 mm with a repeatability of 0.1 mm (Arvidsson and Andersson, 1997). A pressure cell is mounted on top of the Plexiglas cylinder to measure the vertical, normal soil stress during wheeling. The probe-head is attached to a 1095 mm long steel rod.

Each probe was installed into the soil through a hole approximately one meter long with a radius of 6 cm. The hole was drilled horizontally from a dug pit, and a steel tube with the same diameter as the hole was inserted to stabilise the hole. At the end of the hole, 10 cm of soil was removed by a square reamer (35x35mm) so that the cylinder would be firmly embedded in soil relatively undisturbed by the installing procedure. Before each wheeling occasion, probes were installed at 0.3 m, 0.5 m and 0.7 m depth under the center-line of the wheel track.
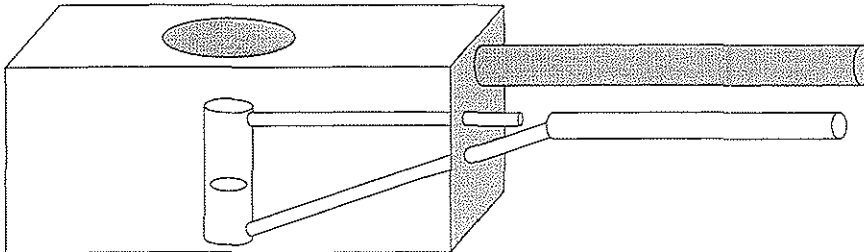
Fig. 1 Displacement sensor with a pressure cell attached on top. It contains a cylinder with silicone-oil connected to a pressure transducer through a hose. The pressure cell on top has a radius of 8.5 mm. The length of the "probe-head" is 70.0 mm, and the width 35.0 mm. The head is 35.2 mm high in the front and 36.0 mm high in the back. A 1095 mm long steel rod is attached to the head. The probe is installed horizontally into the soil, and registers soil vertical stress and movement simultaneously.

2.4. Soil water content and precompression stress

At each wheeling occasion, the gravimetric soil water content was determined at to 1 m depth by sampling soil at intervals of 0.1 m. The soil plastic limit was determined according to the British Standard 1377 (1975) with five replicates per depth.

At 0.3, 0.5 and 0.7 m depth two undisturbed soil cores (25 mm in height, 72 mm in diameter) were sampled per depth for determination of the soil precompression stress at the soil water content at the time of each wheeling. Uniaxial loading of the soil cores were done at this soil water content, in most cases in a oedometer described by Eriksson (1974). Each stress was applied for 30 minutes, and at the end of that period, the strain was determined. The soil cores sampled on the 10 September were tested in a "Universal-Prüfpresse" UP 100. Stresses of 13, 50, 75, 100, 150, 200, 400, 800, 1000, 1600, 3200, and 4800 kPa were applied sequentially. Each stress was applied for 30 minutes before the amount of strain was determined. The precompression stress was determined according to Casagrande (1936).

2.5. Modelling the soil compaction

The soil compaction was predicted using the analytic soil compaction model SOCOMO (Van den Akker, 1988). The model is based on the well-known principles of stress distribution described by Söhne (1958). It calculates the depth to which the stresses propagate into the soil. The major and minor principal stresses were calculated from the measured contact area, the calculated average ground contact stress and the axle load. A concentration factor of 5 was used for soft soil according to Koolen and Kuipers (1983)

The failure criterion used was that the calculated major stress was higher than the precompression stress of the soil.

3. Results

3.1. Soil water content

The precipitation in April 1999 was well above average. At the wheeling occasion on May 11, except in the surface layer, the soil water content was near the field capacity, and the highest recorded for the seven wheeling occasions. It was nearly the same as the plastic limit of the soil (Fig.2).

During the summer, the precipitation was well below the average and the soil water content decreased. In the autumn, especially after a rather wet September, the soil water content increased but did not reach the same level as on the first wheeling occasion on May 11.

3.2. Contact area

In table 3, the average ground contact stress was calculated from the axle load and the measured contact area on a hard surface. For all loads the calculated average ground contact stress was close to the inflation pressure.
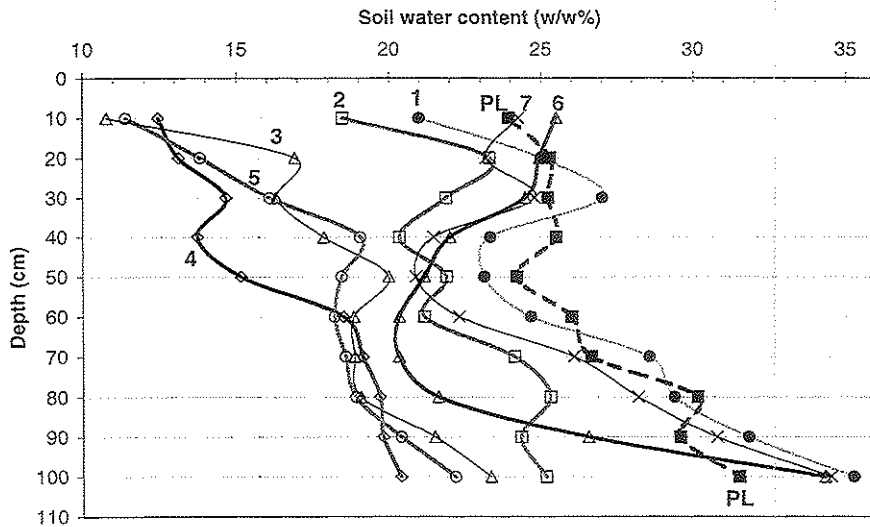
Fig. 2. Soil water content at seven wheeling occasions during 1999. In addition, the soil plastic limit (PL) is shown. 1=11 May, 2=8 June, 3=15 July, 4 =14 August, 5=10 September, 6=27 October, 7=1 December.

Table 3 . The measured contact area on a hard surface by different axle loads of the trailer used in the experiments, and the calculated average contact area stress. The tire was a Trelleborg TWIN 700-26.5.

Axle load (Mg)	Inflation pressure (kPa)	Contact area (m2)	Average ground contact stress (kPa)
4	140	0.156	128
6	140	0.197	152
8	140	0.293	137
10	140	0.343	146
14	240	0.285	246

3.3. Soil stress

Maximum soil stresses measured at 0.3 m, 0.5 m and 0.7 m depth are shown for all wheeling occasions and axle loads in fig 3. The measured soil stress was in general high. For example, with an axle load of 14 Mg the soil stress ranked from 300 to 650 kPa at 0. 3 m depth, from 100 to 225 kPa at 0.5 m depth, and from 75 to 270 kPa at 0.7 m depth. The stress varied considerably, but it generally increased with the axle load.
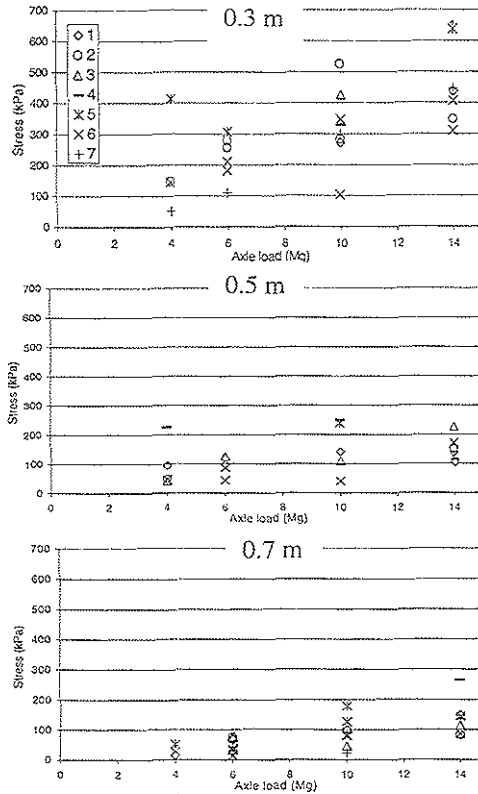
Fig 3. The soil stress at: 0.3 m, 0.5 m and 0.7 m depth at axle loads of 4, 6, 10 and 14 tonnes recorded at seven wheeling occasions: 1=11 May, 2=8 June, 3=15 July, 4=14 August, 5=10 September, 6=27 October, 7=1 December.

3.4. Soil vertical displacement

The soil vertical movement measured with four different axle loads at seven occasions are presented in Table 4 along with the soil precompression stress and water content.

In general, soil vertical displacement increased with increased axle load on each wheeling occasion. The load had a much larger effect on soil displacement than the water content or the precompression stress.

On the first wheeling occasion in May the soil precompression stress was approximately 100 kPa at all depths. The precompression stress increased during the summer, and decreased after September. In August, the precompression stress was above 580 kPa at all depths, and in September, the precompression stress at 0.7 m depth was nearly 1000 kPa and at 0.3m 1245 kPa. Fig. 4 shows an example of the relationship between bulk density and the applied stress. The soil sample was taken at 0.7 m depth, and the precompression stress was determined to approximately 1200 kPa.
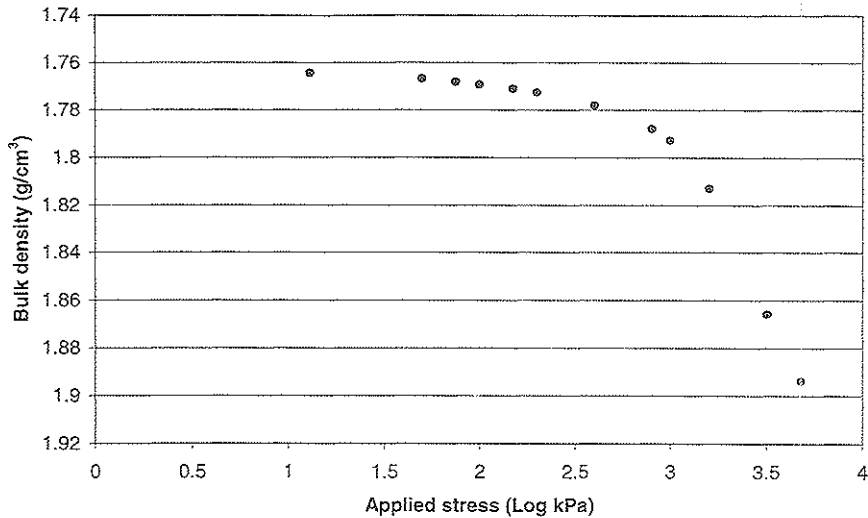
Fig, 4. An example of the relationship obtained between bulk density and applied uniaxial stress relationship. The undisturbed samples (25 mm in height, 72 mm in diameter) were sampled at 0.7 m depth on September 10. 1999. Each stress was applied on the soil for 30 minutes before the deformation was determined.

With an axle load of 14 Mg there was a tendency that the soil displacements at 0.5 and 0.7 m depth were larger when the soil was dry and the precompression stress high.

3.5. Modelling the soil compaction

The model calculation showed that on May 11, with axle loads of 4, 6, 10 and 14 Mg the soil strength was exceeded to 0.3m, 0.4m, 0.5m and 0.8m depth respectively. This corresponded relatively well with the measured soil displacement. However, on all other wheeling occasions, the model failed to predict any soil compaction by the wheeling, even at high axle loads.

4. Discussion

The precompression stress reflected the soil water content and the precipitation data well. After the determination of the soil precompression stress on August 14, it was clear that if the soil got any dryer, the stress range used was too limited to determine the virgin compression line, which is necessary to be able to determine the soil precompression stress. Therefore, on September 10 the stress range was increased up to 4800 kPa. Even when applying that very high stress, the virgin compression line was derived from only a few points, since the soil precompression stress was higher than 1000 kPa.

As expected, the recorded vertical displacement of the soil during wheeling with axle loads of 4, 6, 10 and 14 Mg increased with the axle load. Surprisingly, when the soil precompression stress was very high, wheeling with axle loads of 10 and 14 Mg resulted in soil displacement at 0.7m. At 0.5 and 0.7m depth the soil moisture content did not seem to be

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of importance for the amount of soil displacement. This was in contradiction to Arvidsson and Trautner (1998), who concluded after similar field measurements on a lighter soil that "the soil moisture content was the most decisive factor" for the soil deformation.

At most wheeling occasions, SOCOMO predicted that no soil compaction would occur. The reason for this was the failure criterion of the model that the calculated major stress should be higher than the precompression stress. However, field measurements showed that the soil was compacted below 0.7m when the precompression stress was well above 500 kPa at 0.3, 0.5 and 0.7m depth. The explanation is most likely to be found in the structure of the clay soil. As the soil dried out, fine cracks were observed between the soil aggregates and wide, desiccated cracks were formed. The displacement measured in the dry soil with high precompression stress was probably a result of soil aggregates being pushed together by closing cracks whereas the aggregates remained intact. This could explain the observed tendency that when wheeling with an axle load of 14 Mg caused the largest soil displacement at 0.5 and 0.7m was larger when the soil water content was very low and the precompression stress was high.

Arvidsson and Trautner (1998) reported from similar measurements in the southern part of Sweden that the measured soil stress was relatively close to the inflation pressure. In this experiment, however, the normal stress measured in the soil was often much larger than the calculated average ground pressure. A possible explanation could be that the stress distribution in a very dry and strongly structured soil is different from the stress distribution in more homogeneous soils. For example, it is possible that the vertical cracks can reduce or inhibit horizontal distribution of the stress. Thus, the stress may be concentrated around the load axis and propagate deeper into the soil.

An important question for further investigations is, whether this soil behaviour is common or is limited to a few specific soils only.

An implication of the results is that the precompression stress does not always provide a good indication of the risk for subsoil compaction. A practical consequence is that subsoil compaction in some soils may occur even when the soil is very dry.

5. Acknowledgements

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Changes of some physical properties of a clay soil following the passage of rubber tracked and wheeled tractors of medium power

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Abstract

Macroporosity, pore shape and size distribution, bulk density, penetration resistance and saturated hydraulic conductivity were analysed in a clay soil (Vertic Cambisol) following one and four passes on the same track of rubber tracked and wheeled tractors of medium power. The soil structure attributes were evaluated by characterising porosity by means of image analysis of soil thin sections prepared from undisturbed samples. Macroporosity decreased in the 0-10 cm layer of compacted areas of soil after the passage of the tractors. Such a behaviour was even more evident in the areas compacted by four passes, due to the strong reduction in the proportion of elongated pores and of their vertical continuity. The rubber tracked tractor showed a more pronounced compaction effect in the surface layer (0-10 cm) than the wheeled tractor both after one and four passes. In the latter, soil showed the lower values of porosity. The same trend was observed for hydraulic conductivity, which showed a highly significant correlation with elongated pores. In the 10-20 cm layer the porosity significantly decreased following traffic, apart from in the soil under one pass of rubber tracked tractor. Also in this layer the lower values of porosity was found in soil after four passes of rubber tracked tractor. Single and multiple passes made by the two tractors induced different effects also regarding soil penetration resistance and bulk density. Increment ratio of penetration resistance after tractor passes with respect to control was: 12.5 and 49.9% after one and four passes of the wheeled tractor and 34.4 and 39.8% after one and four passes of the rubber tracked tractor, respectively. Increment ratio of dry bulk density values after tractor passes with respect to control was 7.9 and 11.7% after one and four passes of the wheeled tractor and 7.5 and 8.3% after one and four passes of the rubber tracked tractor, respectively. The tractor passes transformed the subangular blocky structure of the control into a massive structure and sometime into platy structure just in the upper centimetres after soil compaction. These results indicated that the soil compaction following traffic of the rubber tracked tractor was generally more pronounced. However the compacting effect of this tractor after one pass seemed to be limitated to the surface layer.

Keywords: Rubber tracked tractors; Wheeled tractors; Soil compaction; Soil porosity; Soil pore system; Soil structure; Soil penetration resistance

1. Introduction

Soil compaction is one of the most important factors responsible for environmental degradation. It causes strong modifications to soil structure and reduces soil porosity. Soil compaction is caused by a combination of natural forces, which generally act internally, and by man-induced forces related to the consequences of soil management practices. The latter forces are mainly those related to vehicle wheel traffic and tillage implements and have a

much greater compactive effect than natural forces such as raindrop impact, soil swelling and shrinking, and root enlargement also because trends in agricultural engineering over the last few decades have resulted in machines of a greater size and weight and problems of finding tyres, inflation pressures, etc., able to reduce soil compaction are far from being solved.

In order to evaluate the impact of traffic on soil it is necessary to quantify the modifications of soil structure. Since porosity is the best indicator of soil structure conditions because it is the size, shape and continuity of pores that affect many of the important processes in soils, its characterization allows to quantify the soil structure quality. The use of image analysis on thin sections prepared from undisturbed soil samples allows the quantification of pores larger than 50 μm, i.e. macropores, which determine the type of soil structure (Pagliai et al., 1983, 1984; Moran and McBratney, 1992).

In a previous study, Marsili et al. (1998) investigated the changes of soil structure quality through the quantification of porosity, pore shape and size distribution, hydraulic conductivity, penetration resistance and bulk density following the traffic of large tractors with rubber and metal tracks. Results revealed that tractors with rubber tracks caused a more pronounced compaction effect than tractors with metal tracks. In this case the decrease of soil porosity after one pass was not significant compared to not compacted soil. However the use of metal track tractors is reducing due to the low travel speed and the less manoeuvrability with respect to rubber tracked or wheeled tractors and, overall, they are not allow to travel on public road. Further studies were considered worthwhile to compare the compacting effect of rubber tracked with that of wheeled tractors, especially of medium power largely diffuse in the Italian farmers.

2. Methods

2.1 Soils and treatments
The field tests were carried out using two tractors of medium power fitted with different types of mobility system, one with four drive wheels (Landini Globus 70/DBKL Techno) and the other with rubber tracks (New Holland 6985 FR). The main characteristics of these tractors and their mobility system are given in Tables 1 and 2. In February 1999, on a plain terrain 30 km north of Rome, compaction tests were carried out on a well drained clay soil, classified as Vertic Cambisol according to the Food and Agriculture Organization (FAO, 1988), making 1 and 4 passes on the same track for a total of four treatments, in a randomised block of 8 plots, each 420 m². The soil was ploughed to a depth of 40 cm and harrowed to a depth of 10 cm in November 1998. Measurements were also made on a control area with no traffic adjacent to every plot. The soil water content at the time of traffic tests was 30% on dry mass weight.

2.2 Soil porosity measurements
The pore system was characterized by the image analysis on thin sections from undisturbed soil samples. For this, six undisturbed samples were collected in the surface layer (0-10 cm) and in the 10-20 cm layer of control plots and in the areas compacted by one and four passes of each tractor.

Samples were dried by acetone replacement of water (Murphy, 1986), impregnated with a polyester resin and made into 6x7 cm, vertically oriented thin sections (Murphy, 1986). Such sections were analysed by means of image analysis techniques (Pagliai et al., 1984), using the IMAGE PRO-PLUS software produced by Media Cybernetics (Silver Spring - USA). The analysed image covered 4.5x5.5 cm² of the thin section, avoiding the edges where disruption can occur. Total porosity and pore distribution were measured according to their shape and size. In this experiment the instrument was set up to measure pores larger than 50 μm. Pores were measured by their shape, which is expressed by the shape factor

[perimeter^2/(4π·area)] and divided into regular (more or less rounded) pores (shape factor 1-2), irregular pores (shape factor 2-5) and elongated pores (shape factor >5). These classes correspond approximately to those used by Bouma et al. (1977). Pores of each shape group were further subdivided into size classes according to either the equivalent pore diameter, for regular and irregular pores, or the width, for elongated pores (Pagliai et al., 1983, 1984). Thin sections were also examined using a Zeiss "R POL" microscope at 25x magnification to observe soil structure.

Table 1 – Main technical characteristics of the wheeled tractor Landini Globus 70/DBKL Techno

Measured mass without ballast (kg)	2595	
Engine Power (kW)	48	
wheel tread (m)	1.45	
Overall width (m)	1.87	
Overall length (m)	3.60	
Cabin height max (m)	2.39	
Height above soil of implement hitch (m)	0.465	
Type of tyres	Front	Rear
	Good Year DT 810	Good Year DT 810
Identification initials	360/70 R20	420/70 R30
Open centre	yes	yes
wheel rim	W 11	W 13
Rim diameter (m)	0.508	0.735
Section of tyre (m)	0.359	0.422
Aspect ratio (height/width)	0.70	0.70
Rolling radius (m)	0.470	0.630
External diameter (m)	1.054	1.392
Lugs number (number)	30	38
Lugs height (m)	0.036	0.042
Lugs width (m)	0.032	0.040
Lugs angle (°)	45-50	45-50
Load on the two tyres (kN)	10.90	15.00
Total contact area of tyres on soft terrain (m^2)	0.18	0.30
Average ground contact pressure (kPa)	60.0	50.0
Inflation pressure (kPa)	120	140

2.3 Saturated hydraulic conductivity
To measure saturated hydraulic conductivity six undisturbed cores (5.68 cm diameter and 9.5 cm high) were collected from the 0-0.10 m layer of each plot in areas adjacent to those sampled for thin section preparation. The samples were slowly saturated and the saturated hydraulic conductivity was measured using the falling-head technique (Klute and Dirksen, 1986).

2.4 Penetration resistance and bulk density
Soil penetration resistance was measured in the tracks left by each tractor after 1 and 4 passes and on the control areas, using a penetrologger (electronical penetrometer) Eijkelkamp with 60° cone and base area of 100 mm^2 driven into the soil at a constant rate. For each plot, including control areas, 20 penetrometer readings were taken at depths of 0 to 40 cm each 1 cm.

Table 2 – Main technical characteristics of the rubber tracked tractor New Holland 60-85 FR

Measured mass with ballast (kg)	3080
Engine Power (kW)	44
Track tread (m)	1.0
Overall width (m)	1.30
Overall length (m)	2.90
Height max (m)	2.08
Height above soil of implement hitch (m)	0.30
Type of track	2 reinforced rubber tracks
Total track length (m)	5.00
Track thickness (m)	0.021
Lugs per track (number)	40
Lugs height (m)	0.035
Distance between centres of lugs (m)	0.125
Supporting wheels (number)	4
Diameter of driving wheel (m)	0.55
Diameter of support wheels (m)	0.30
Diameter of track wheel (m)	0.38
Ground contact length (m)	1.45
Track width (m)	0.30
Total area of support of the two tracks on soft terrain (m^2)	0.87
Average ground contact pressure (kPa)	35.4

Dry bulk density was measured by taking samples of soil below the tracks left by each tractor, after 1 and 4 passes and from control areas using a corer with 100 cm^3 volume sample ring (internal diameter 5 cm, lenght 5.1 cm and wall thickness of 0.15 cm) at depths of 0-5, 5-10, 10-15 and 15-20 cm. These samples were weighed and dried until they reached a constant weight.

In addition, the increment ratio of penetration resistance and dry bulk density (Γ_n) was used as a compaction criterion (Fujii, 1992) and is defined as:

$$\Gamma_n = (\gamma_n - \gamma_0)/\gamma_0 = (\gamma_n/\gamma_0) - 1$$

where γ_0 is the initial penetration resistance or bulk density (control) and γ_n is the penetration resistance or bulk density after the nth (1 and 4) tractor passes.

3. Results and Discussion

3.1 Soil Porosity

Total porosity, expressed as a percentage of area occupied by pores larger than 50 μm per thin section, in the control and compacted areas is showed in Fig. 1. Porosity significantly decreased in the surface layer (0-10 cm) just after a single pass. Such a decrease still increased after four passes, significantly when compared to single pass. The decrease of porosity in the surface layer was different after the passes of the two tractors. The compacting effect of rubber tracked tractor was more pronounced than that of wheeled tractor. The rubber tractor, after one pass, caused a significant reduction of porosity with respect to the four passes of wheeled tractor. Such a porosity reduction increased significantly after the four passes.

For a better interpretation of this data it could be stressed that according to the micromorphometric method, a soil is considered dense (compact) when the total macroporosity is less than 10%, moderately porous when the porosity ranges from 10 to 25%, porous when it ranges from 25 to 40% and extremely porous over 40% (Pagliai, 1988). The

soil of this study, in the surface layer, can be considered as porous. After the compaction due to wheeled tractor the soil became moderately porous (the porosity still remain over 10%) while after the compaction due to rubber tracked tractor became dense (compact) because the porosity decreased below 10%.

The compacting effect of traffic by the two tractors was also evident in the 10-20 cm layer, apart from the traffic by one pass of the rubber tracked tractor which caused a decrease of porosity not significant with respect to the control. On the contrary, after four passes of this tractor the porosity showed the lowest value (below 5%) and the soil appeared very dense.
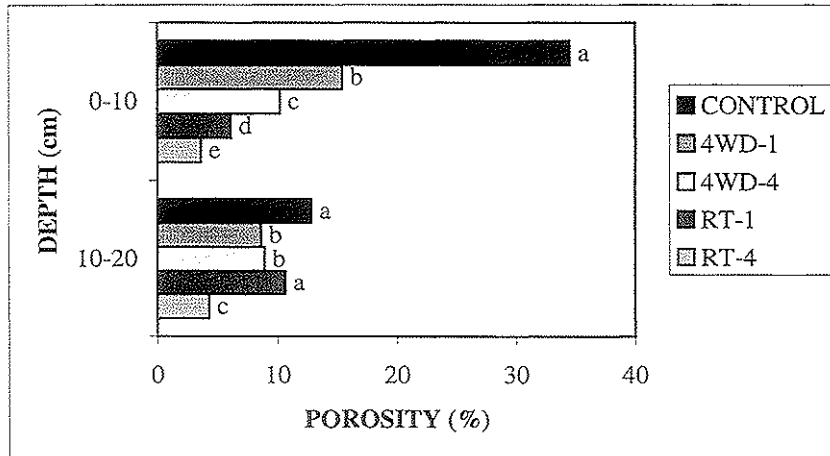
Fig. 1 — Effects of soil compaction, caused by one (1) and four (4) passes of the wheeled (4WD) and rubber tracked (RT) tractor, on soil porosity expressed as a percentage of area occupied by pores larger than 50 μm per thin section. Average of six replicates. Within each depth, values followed by lower case letter are not significantly different at 0.05 level.

3.2 Pore shape and size distribution

For a thorough characterisation of soil porosity, the main aspects to be considered are not only pore shape but also pore size distribution, especially of elongated continuous pores, because many of these pores directly affect plant growth by easing root penetration, storage and transmission of water and gases. For example, according to Russell (1978) and Tippkötter (1983), feeding roots need pores ranging from 100 to 200 μm to grow into. According to Greenland (1977), pores of equivalent pore diameter ranging from 0.5 to 50 μm are the storage pores, which function as a water reservoir for plants and microorganisms. Transmission pores (elongated and continuous pores), ranging from 50 to 500 μm, are important both in soil-water-plant relationships and in maintaining good soil structure conditions. Damage to soil structure can be recognised by a decrease in the proportion of transmission pores. Elongated pores larger than 500 μm are important for the drainage, especially in fine textured soils.

Fig. 2 clearly showed that the reduction of porosity after the traffic of the two tractors was due to a progressive reduction of elongated pores, following the same trend of total porosity. The decrease of elongated pores was associated to a progressive reduction of the size of these pores. Regular and irregular pores did not show particular changes following the traffic of one and four passes of the two tractors.
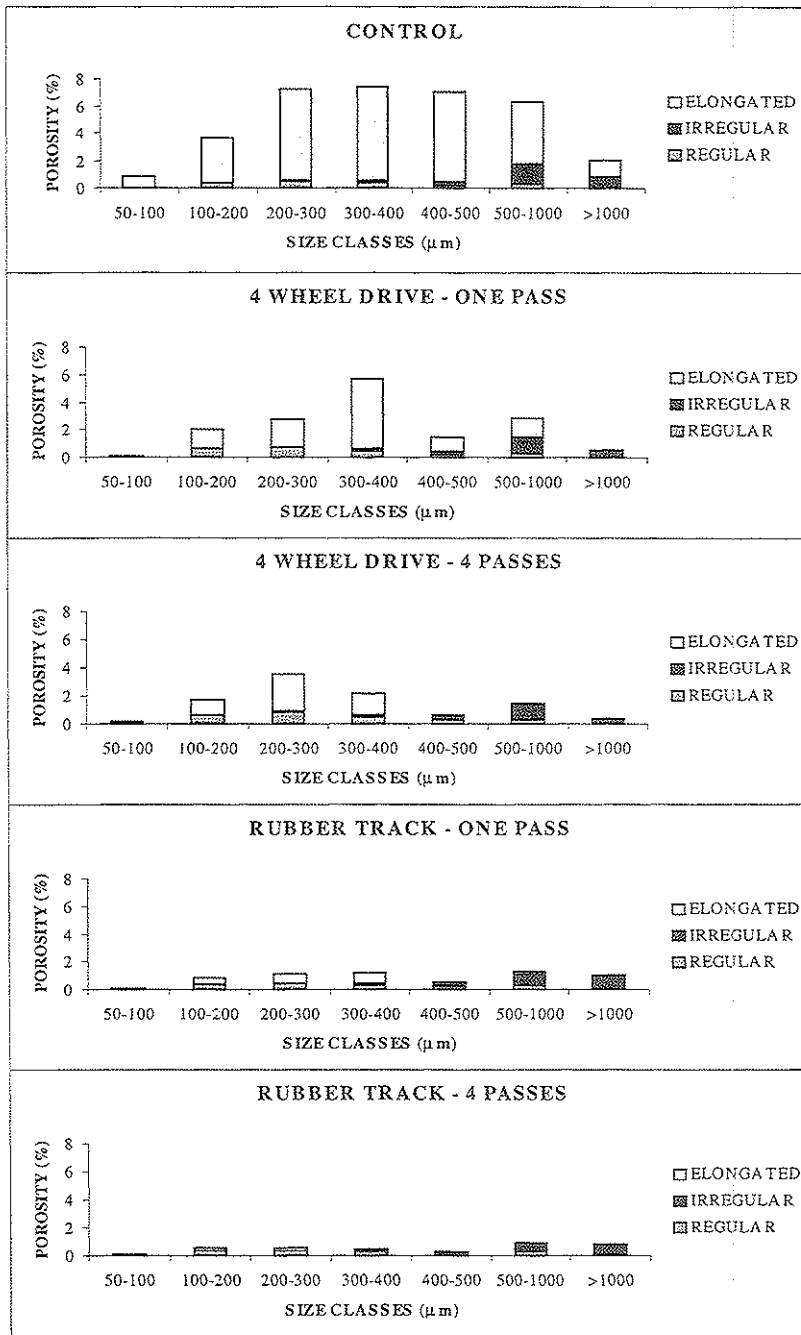
Fig. 2 – Pore size distribution, according to the equivalent pore diameter for regular and irregular pores, or the width for elongated pores, in the surface layer (0-10 cm).

According to the above mentioned classification of soil in terms of porosity (Pagliai, 1988), considering this parameter as the best indicator of soil physical quality, the effects of the traffic after one pass of wheeled tractor can be acceptable because the total porosity remained over 10% and the highest proportion of elongated pores (9.3%) was distributed in the range of transmission pores (50-500 µm) with the presence of these pores (1.2%) also in the size classes 500-1000 µm. In the control areas the transmission pores were 24.2% and those larger than 500 µm 5.8%. After four passes, on the contrary, the traffic caused a damage to soil structure because the large elongated pores (>500 µm) disappeared and the elongated transmission pores were strongly reduced (5.4%).

Such a situation was even more pronounced after the traffic of the rubber tracked tractor where the elongated transmission pores were reduced to a value of 2.2% after one pass and practically disappeared (0.4%) after four passes.

3.3 Soil structure

The changes in porosity, pore shape and size distribution following compaction by tractor traffic were reflected in the type of soil structure. Microscopic examination of thin sections showed that in the uncompacted areas a glomerular to subangular blocky structure was homogeneously present down the 0-20 cm layer (Fig. 3). Following the trend of porosity such a type of soil structure progressively changed into massive structure after the tractor traffic (Fig. 4). Obviously the more compact massive structure was observed in the soil after the four passes of the rubber tractor (Fig. 5). The few if any pores were completely isolated in the soil matrix. In the upper centimetres of the soil compacted by the four passes of wheeled tractor and also by one pass of the rubber tracked tractor the thin elongated pores were oriented parallel to the soil surface, thus originating a platy structure typical of compacted soils (Fig. 6). Therefore, the few elongated pores were not vertically continuous and practically useless for water infiltration, thus increasing the water stagnation or surface runoff and, as a consequence, the risk of soil erosion.
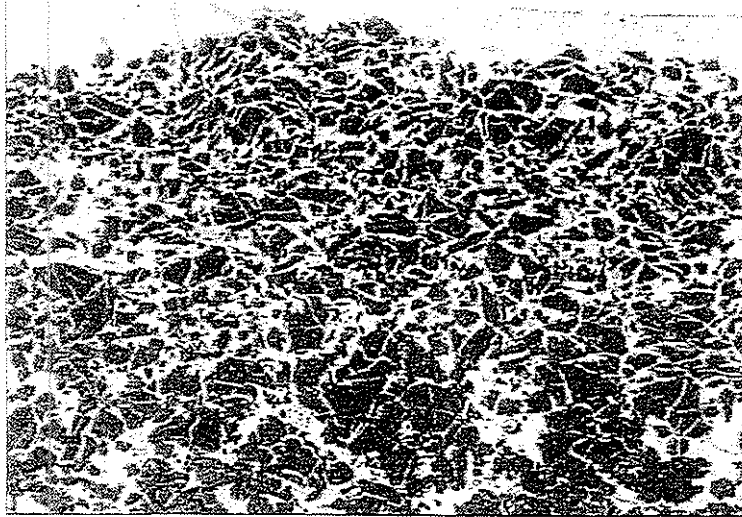
Fig. 3 – Macroporosity of vertically oriented thin section from the surface layer of the non compacted soil showing a glomerular structure. Plain Polarized light. Pores appear white. Frame length 3 cm.
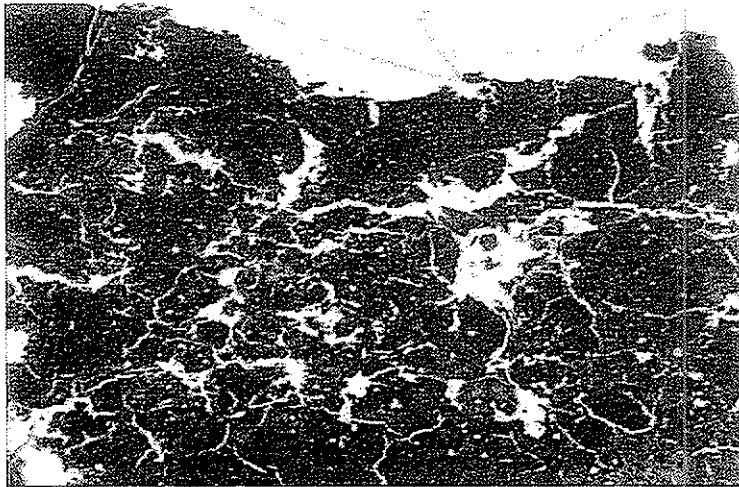
Fig. 4 – Macroporosity of vertically oriented thin section from the surface layer of the soil compacted by one pass of the wheeled tractor. The change of the previous structure (Fig .3) into a more compact structure is very evident. Plain Polarized light. Pores appear white. Frame length 3 cm.
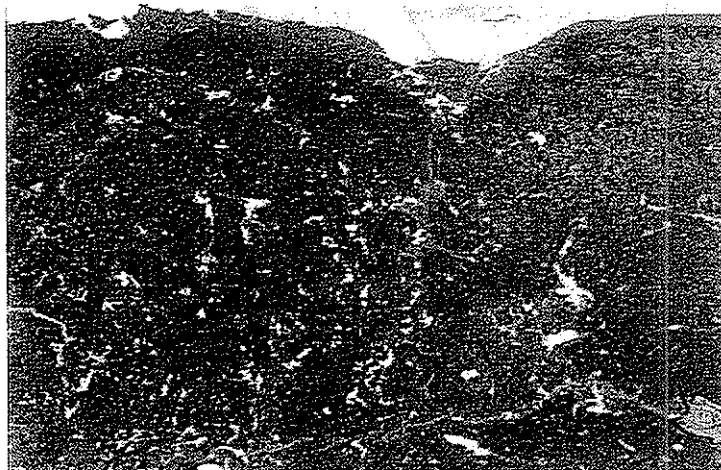
Fig. 5 – Macroporosity of vertically oriented thin section from the surface layer of the soil compacted by four passes of the rubber tracked tractor. A massive structure is very evident. Plain Polarized light. Pores appear white. Frame length 3 cm.

3.4 Saturated hydraulic conductivity
A highly significant correlation between hydraulic conductivity and elongated pores was found as shown in Fig. 7. The values are interpreted by a linear type regression namely:
$$y = ax + c$$
where y is saturated hydraulic conductivity in mm h^{-1}, x is elongated pores expressed in %; a = 2.93 is a coefficient and c = 0.036 is a know term.
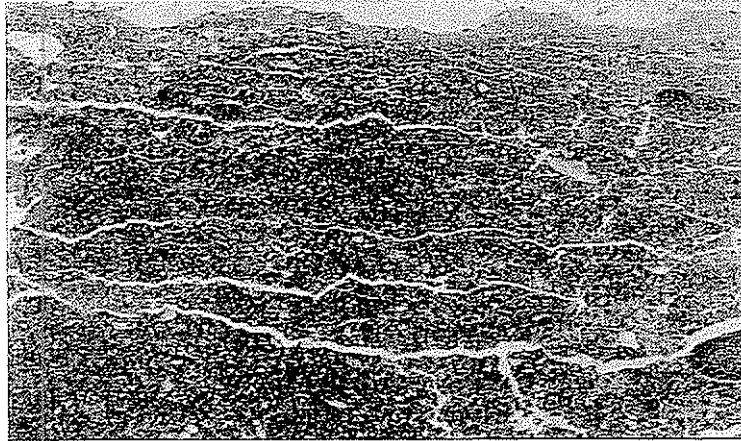
Fig. 6 – Macroporosity of vertically oriented thin section from the surface layer of the soil compacted by four passes of the wheeled tractor. In same areas a platy structure is very evident. Plain Polarized light. Pores appear white. Frame length 3 cm.

Since the elongated pores represented the highest proportion of total porosity in the control soils and the variation after compaction mainly caused a reduction of such pores, this result confirmed that hydraulic conductivity is directly correlated with elongated continuous pores. Saturated hydraulic conductivity of the 0-10 cm layer decreased following the traffic of the two tractors and the low values were found after the pass of the rubber tracked tractor. In the four passes of this tractor the hydraulic conductivity was drastically reduced in agreement with the presence of few if any elongated pores very thin and not continuous in a vertical sense. These results stressed that the compaction is one of the most dangerous aspect not only of soil degradation but also of environmental degradation, since the strong reduction of water infiltration may increase risks of soil erosion.
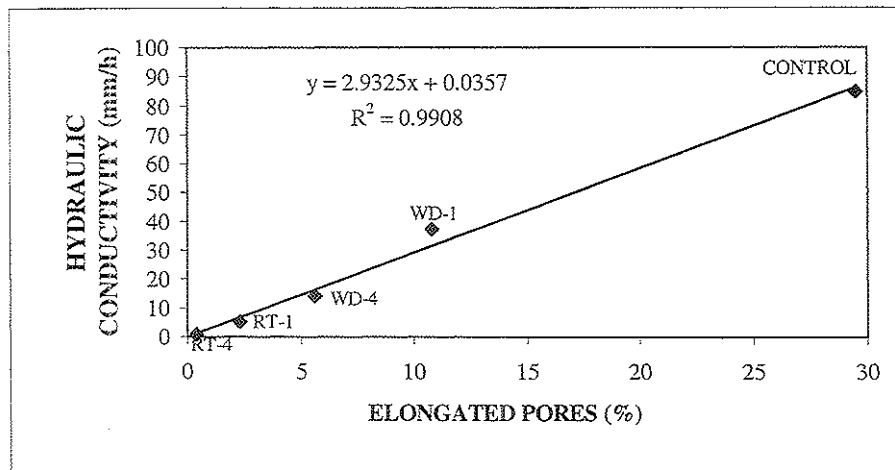
Fig. 7 – Correlation between hydraulic conductivity and elongated pores porosity after one (1) and four (4) passes of the wheeled (4WD) and rubber tracked (RT) tractor in the surface layer (0-10 cm).

3.5 Penetration resistance and dry bulk density

From results obtained, it is evident that the single and multiple passes of the two tractors induced an increase of soil penetration resistance, with some differences between the two tractors (Fig. 8). The increment ratio of penetration resistance after wheeled tractor traffic respect to the control was 12.5 and 49.6% after one and four passes, respectively. After one pass the mean values of soil penetration resistance with respect to the control increased significantly only in the surface layer (0-10 cm), while after four passes the increase of penetration resistance was significant in all layers.

Fig. 8 – Effects of soil compaction, caused by one (1) and four (4) passes of the wheeled (4WD) and rubber tracked (RT) tractor, on soil penetration resistance. Letters before the comma refer to the comparison for the tractor with the control at the same depth and letters after the comma refer to the comparison between the two tractors at the same depth and for the same number of passes.

The increment ratio of penetration resistance after rubber tracked tractor traffic respect to the control was 34.4 and 39.8% after one and four passes, respectively. In this case, the mean values of soil penetration resistance respect to the control increased significantly both after single and multiple tractor passes and in all layer considered from 0 to 20 cm depth.

The increment ratio in the deeper layers (20-40 cm depth) was 14.4 and 26.9% after one and four passes of the wheeled tractor and 29.8 and 32.5% after one and four passes of the rubber tracked tractor, respectively. In these layers all values of penetration resistance

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increased significantly after the tractor passes respect to the control, apart from the single pass of the wheeled tractor (4WD-1) in the 20-25 cm depth.

Comparing mean values of penetration resistance for one pass of the two tractors all differences were statistically significant in favour of the wheeled tractor from 0 to 35 cm depth, while for multiple passes, the differences were statistically significant in favour of the rubber tracked tractor but only in the upper layers (0-25 cm).

A highly significant correlation between penetration resistance and total porosity in the 0-10 cm layer was found, particularly for 4WD treatments (Fig. 9). The values are interpreted by a polinomial type regression for treatments 4WD, namely:

$$y = ax^2 - bx + c$$

where y is total porosity expressed in %, x is penetration resistance in MPa; a and b are coefficients, and c is a costant which for single and multiple passes amount to: a = 113.08; b= 281.31 and c = 184.06 and by an exponential type regression, for treatments RT namely:

$$P = ae^{-br}$$

where P is total porosity expressed in %, R is penetration resistance in MPa, a and b are coefficients which in this case amount to 1908 and 5.24. In the 10-20 cm layer there were not significant correlations between porosity and penetration resistance. These results confirmed previous findings (Pagliai et al., 1992; Marsili et al. 1998) in which it was demonstrated that the decrease of soil porosity and the increase of penetration resistance following traffic of agricultural machinery were strongly correlated.
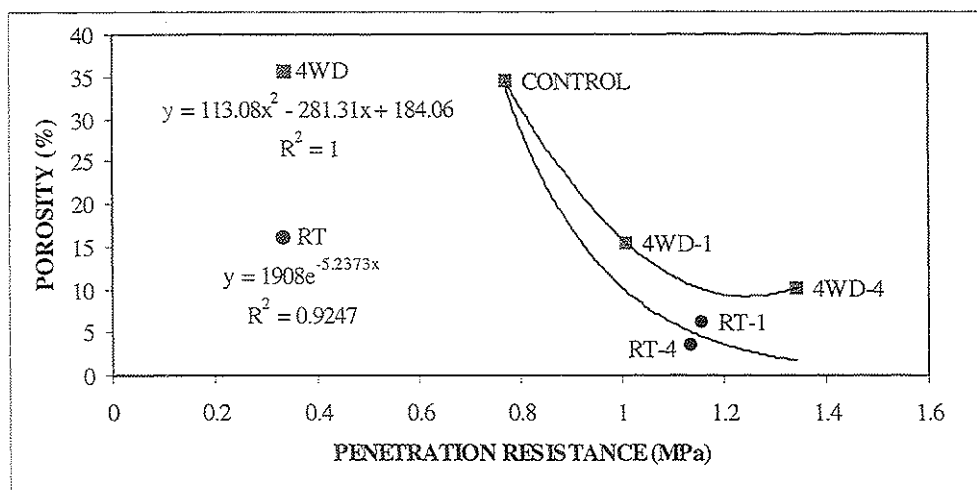
Fig. 9 – Correlation between soil penetration resistance and porosity after one (1) and four (4) passes of the wheeled (4WD) and rubber tracked (RT) tractor in the surface layer (0-10 cm).

Mean values of dry bulk density at various depths are reported in Fig. 10. In the surface layers (0-10 cm) it is evident that the traffic of the two tractors caused a significant increase of dry bulk density. The increment ratio of bulk density values after tractor passes with respect to control was 7.9 and 11.7% after one and four passes of the wheel drived tractor and 7.5 and 8.3% after one and four passes of the rubber tracked tractor, respectively.

If such an increment ratio is calculated separately for the 0-10 cm and for the 10-20 cm layer the results show that in the uppermost layers (0-10 cm) it was 13.6 and 19.3% after one and four passes of the wheeled tractor and was 15.3 and 12.3% after one and four passes of the rubber tracked tractor, respectively. Increment ratio in the deeper layer (10-20 cm depth)

was 2.4 and 4.3% after one and four passes of the wheeled tractor and 0.8 and 4.7% after one and four passes of the rubber tracked tractor, respectively.
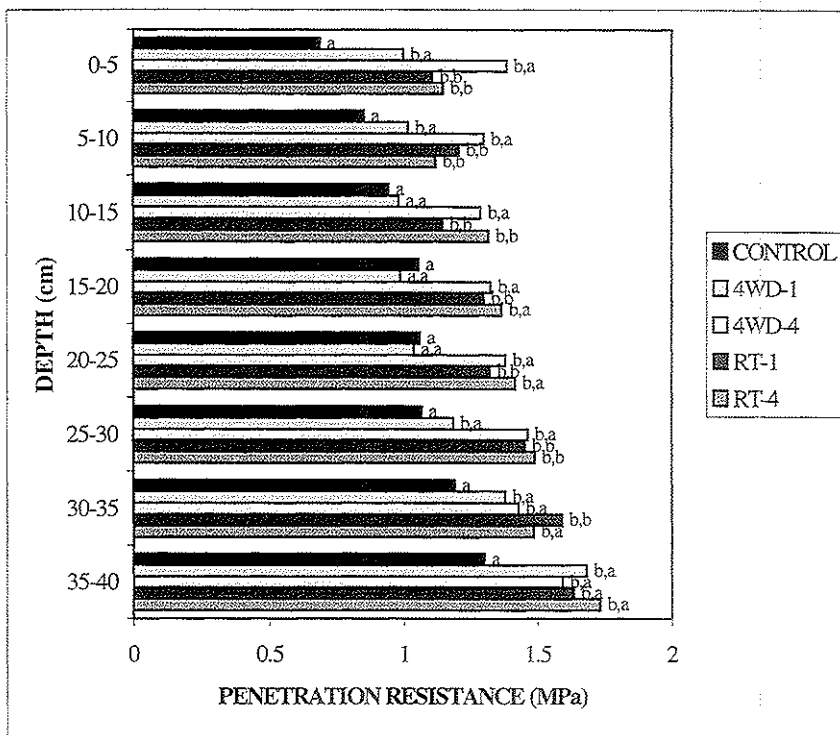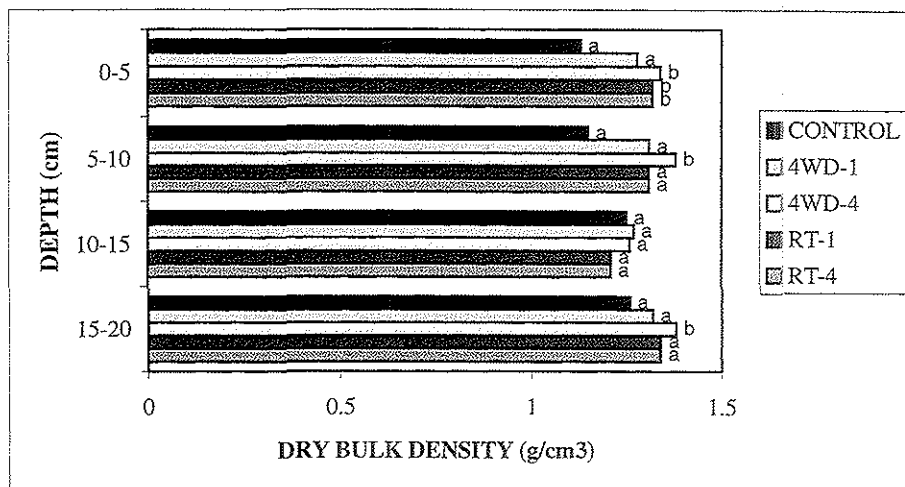

Fig.10 – Effects of soil compaction, caused by one (1) and four (4) passes of the wheeled (4WD) and rubber tracked (RT) tractor, on dry bulk density. Average of six replicates. Within each depth, values followed by lower case letter are not significantly different at 0.05 level.

4. Conclusions

From data found in this experiment it can be concluded that porosity significantly decreased in the surface layer (0-10 cm) just after a single pass of the tractors. Such a porosity reduction still increased after four passes. The decrease of porosity in the surface layer was different after the passes of the two tractors and the compacting effect of rubber tracked tractor was more pronounced than that of wheeled tractor.

The compacting effect of traffic by the two tractors was also evident in the 10-20 cm layer, apart from the traffic by one pass of the rubber tracked tractor which caused a decrease of porosity not significant with respect to the control. On the contrary, after four passes of this tractor the porosity showed the lowest value (below 5%) and the soil appeared very dense.

The reduction of porosity after the traffic of the two tractors was due to a progressive reduction of elongated pores, following the same trend of total porosity. The decrease of elongated pores was associated to a size reduction of these pores. Regular and irregular did not show particular changes following the traffic of one and four passed of the two tractors. After four passes, on the contrary, the traffic caused a damage to soil structure because the large elongated pores (>500 μm) disappeared and the elongated transmission pores were strongly reduced.

Such a situation was even more pronounced after the traffic of the rubber tracked tractor where the elongated transmission pores were reduced to a value of 2.2% after one pass and practically disappeared (0.4%) after four passes.

The changes in porosity, pore shape and size distribution following compaction by tractor traffic were reflected in the type of soil structure. Obviously the more compact massive structure was observed in the soil after the traffic of four passes of the rubber tractor.

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Saturated hydraulic conductivity of the 0-10 cm layer decreased following the traffic of the two tractors and the low values were found after the pass of the rubber tracked tractor. In the four passes of this tractor the hydraulic conductivity was drastically reduced in agreement with the presence of few if any elongated pores very thin and not continuous in a vertical sense. A highly significant linear correlation between hydraulic conductivity and elongated pores was found.

According to porosity results the passes of tractors increase significantly soil penetration resistance respect to the control; already after one pass, the differences were statistically significant in all layers for rubber tracked tractor and in the upper (0-10 cm) and deepest layers (30-40 cm) for wheeled tractor.

Comparing the two tractors the differences in penetration resistance were statistically significant in favour of wheeled tractor after one pass from 0 to 35 cm, and in favour of rubber tracked tractor after four passes from 0 to 15 cm. The same trend was found for dry bulk density results.

In conclusion, results obtained indicated that the soil compaction following traffic of the rubber tracked tractor was generally more pronounced than that of wheeled tractor.

5. Acknowledgements

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Setup of field experiments on the impact of subsoil compaction on soil properties, crop growth and environment - recommendations by Working Group 5 of the EU Concerted Action on Subsoil Compaction

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Abstract

Within an EU Concerted Action on Subsoil Compaction a working group was set up with the objective to make an inventory of present knowledge concerning the impact of machinery-induced subsoil compaction on crop production and the environment, to identify gaps in this knowledge and to recommend ways to set up new field experiments for susoil compaction studies. The results of the work are presented in this paper. The group stated that, in no region of the EU, present knowledge is sufficient to formulate site-specific guidelines for upper limits of mechanical stresses to protect subsoils from unacceptable compaction. The environmental effects of subsoil compaction are virtually unknown. Therefore, new field trials are required all over the EU. It is proposed that groups of trials be established on various types of soils in three regions of the EU, one northern, one central and one southern. To facilitate comparisons between individual trials and groups of trials some common treatments are proposed, comprising traffic by vehicles with axle loads up to 20 Mg. Desirable measurements in the trials are discussed and a minimum program of measurements to be carried out at all experimental sites is specified.

1. Introduction

Within the EU Concerted Action on Subsoil Compaction a working group (WG 5) was set up with the following tasks: "Determination of gaps in present data and knowledge; inventory and selection of methods and setup of field experiments resulting in recommendations; determination and dissemination of conclusions and results". The expected results of the work were "Recommended ways to set up field experiments to study the impact of subsoil compaction on crop production and environment". The members of the group are listed at the end of this paper.

During meetings in 1998-1999 the group has discussed previous research on machinery-induced subsoil compaction in the EU, established and potential consequences of such compaction for crop growth and environment and plausible consequences of the increasing machinery weights. The need of new research in various regions and design of possible new field experiments have also been discussed as well as the choice and methods of measurements in such experiments. The work of the group has been limited to subsoil compaction induced by machinery traffic. Dense or hard subsoil layers may also be the result of slow natural processes that cause movement of soil particles or cementation of soil layers, but problems in such soils have not been considered. This paper presents the result of the work.

2. Previous research

Within the EU, soil and crop responses to traffic by heavy machines with the potential to cause subsoil compaction have mainly been studied in northern Europe, particularly by the previous ISTRO Working Group on Subsoil Compaction by Vehicles with High Axle Load (Håkansson,

1994). This and other research was reviewed by Håkansson and Reeder (1994) and by Alakukku (1999). Most recent and ongoing research within the EU has been summarized in proceedings of three recent conferences (van den Akker et al., 1999; Horn et al., 2000; Arvidsson et al., 2000). Only a brief summary of previous research is provided here without any literature references.

2.1. Brief summary of results of previous research on subsoil compaction

Vehicular traffic causes mechanical stresses in the soil. Theoretical predictions and measurements show that, in shallow soil layers, the stresses caused by wheeled vehicles with normal weights and traditional wheel equipment mainly depend on the ground contact pressure. In deep subsoil layers, the stresses mainly depend on the axle load. (Axle load is used here rather than wheel load, since in this respect, two dual-mounted wheels act similarly to one single wheel.) In intermediate layers (i.e., in the upper part of the subsoil) the stresses depend on both ground pressure and axle load. Under circular ground contact areas with the same ground pressure, the depth to which a certain stress penetrates into a homogeneous soil increases with the diameter of the ground contact area. This also means that it increases with the square root of the wheel load.

Whether the stresses cause compaction in a certain soil layer also depends on the strength of the soil, and this is largely dependent on the moisture content. Many investigations have shown that traffic by vehicles with high axle loads on soils with high moisture contents actually causes deep subsoil compaction. For vehicles with traditional wheel equipment, an axle load of 10 Mg has typically caused compaction to a depth of at least 50 cm. With still higher loads, compaction to a depth of 1 m has been reported. The susceptibility of subsoils to compaction are generally regarded to increase with the water content. However, recent investigations (Trautner and Arvidsson, 2000) indicate that even dry soils may be susceptible. Repeated passes by heavy vehicles has been shown to cause cumulative compaction effects in the subsoil. Tractor wheels in the bottom of the open furrow when mouldboard ploughing is an important cause of subsoil compaction, and up to now probably the most important in many regions.

The persistence of soil compaction increases with depth. Whereas annual ploughing and natural factors may completely alleviate plough layer compaction within a few years, subsoil compaction is very persistent. At depth >40 cm it seems to be virtually permanent, even in clay soils in regions with annual freezing. In coarse-textured soils and in climates without freezing, the effects may be permanent already at shallower depths. Complete amelioration of subsoil compaction by mechanical loosening usually seems to be impossible and is definitely expensive.

Subsoil compaction causes persistent, possibly permanent, reduction of crop yields. In freeze/thaw areas of Europe and North America, compaction caused by four passes by vehicles with an axle load of 10 Mg resulted in great negative crop responses during the first 2-3 years. This was probably mainly caused by plough layer compaction. After this period, a mean yield reduction of 2.5 % persisted, probably caused by subsoil compaction alone, and during the rest of the experimental period (more than a decade) crop responses showed no tendency to further decrease. Crop yield reductions were proportional to the traffic intensity. When higher axle loads were used, compaction penetrated deeper and crop responses were more negative. No studies of environmental effects of subsoil compaction seem to have been carried out so far. However, it is likely that such effects occur, and that they are generally detrimental.

Because of the persistence and cumulative character of subsoil compaction, and because of the continuously increasing machinery weights, subsoil compaction is a serious long-term threat to soil quality. Therefore, limits for the machinery-induced mechanical stresses in subsoils are needed. These may be pure axle load limits or combined limits of axle loads and ground contact pressures, possibly adjusted with regard to the soil moisture conditions. It is assumed that the sensitivity to traffic by heavy vehicles varies considerably between soils, crops and climatic

regions, but existing experimental results do not enable an adaptation of stress limits to individual soils and regions. Such adaptation would require more detailed experimental work.

3. Gaps in present knowledge

Rational measures to avoid unacceptable machinery-induced subsoil compaction should be chosen both with regard to the risk of compaction in various soil layers when traffic is applied and to the consequences of such compaction once it occurs. The risk that subsoil compaction occurs as well as the consequences for the crops depend on soil type and climate. Therefore, they vary between soils and climatic regions. In no region of the EU, studies have been carried out on a sufficient number of sites to establish possible differences in soil and crop responses to heavy traffic between various types of soils. Since soil strength is generally higher the drier the soil, the risk that subsoil compaction occurs is probably lower in southern Europe than in northern. However, some part of the arable area in southern Europe is irrigated, which makes soils wet and susceptible to compaction. Crop responses to subsoil compaction once this occurs may well be as pronounced in southern Europe as in northern, perhaps even more pronounced, but because practically no studies have been carried out, this is unknown. In addition, subsoil compaction is probably more persistent in southern than in northern Europe, since the subsoils never freeze.

Subsoil compaction may not only cause negative crop responses, it may also negatively affect the environment. While compaction of the plough layer has been shown to cause considerable environmental effects, probably no studies of environmental effects of subsoil compaction have been carried out. Plough layer compaction has been shown to reduce water infiltration and increase surface runoff, soil erosion and associated phosphorus transport and to influence the biological activity in the soil thus affecting many biological processes, such as denitrification, carbon sequestration and release or uptake of greenhouse gases. Some of these effects have been quite significant. By inference from these studies it may be hypothesised that even subsoil compaction negatively influences the environment. Establishment and quantification of such influences would be an important objective of future research.

It is well known that ploughing loosens the topsoil too much. After ploughing, a moderate recompaction of the loosened layer generally improves crop growth and probably some other soil functions as well. The subsoil, on the other hand, is never or seldom mechanically loosened. Therefore, positive overall effects of subsoil compaction must be rare, and in European studies no effects of that kind seem to have been observed yet. However, individual soil properties, such as water retention or unsaturated hydraulic conductivity, can be positively affected, and therefore, it can not be excluded that positive overall effects appear in some cases. This should be observed in future studies.

4. Need of experiments

Because of the climatic differences, it is likely that at least some soils in southern and central Europe can resist higher mechanical stresses than the soils in northern Europe without being subject to unacceptable subsoil compaction. Nevertheless, there is a need for experiments in these regions, since the consequences of heavy traffic for soil properties, crop growth and environment are virtually unknown, and since recent measurements have indicated that compaction may occur in the subsoil of clay soils even when this layer is dried out to the wilting point.

If machinery weights and resulting mechanical stresses in the subsoil keep increasing, for each individual soil, sooner or later a point is reached when subsoil compaction becomes impermissible and counter-measures are required. However, to avoid undue technical limitations it is essential to establish the upper limits of acceptable stresses for various soils and moisture

conditions and the counter-measures required for individual soils and climatic regions. It may be equally important to investigate, whether there are soils or regions where such measures are not required. Even in northern Europe it is not yet known to what extent the counter-measures required differ between soils. Therefore, new experiments are needed all over the EU.

It is obvious that crop responses to subsoil compaction should be an important part of future research. However, the working group regards studies of various environmental effects as equally important. It may be assumed that the environmental impact of subsoil compaction is generally negative, but in different regions different effects may be the most important. The group identified some environmental effects to likely be significant and recommends studies of these effects. In southern Europe, effects on surface runoff and soil erosion are probably the most important, perhaps more important than the direct effects on crop growth. In northern Europe, various effects on nitrogen cycling, e.g., on denitrification and on leaching, are probably the most important. Effects on other plant nutrients may also be significant. Subsoil compaction also negatively affects the drainage of soils and it may affect the release or absorption of various greenhouse gases as well as the biodiversity of soil ecosystems.

5. Field experiments for crop response studies

5.1. Experiments on various soils in various climatic regions

It may be assumed that responses to heavy traffic differ considerably between soils, crops, climatic regions and individual years. Therefore, it is necessary to study the soil and crop responses over a series of years in various climatic regions and cropping systems and in soils of various types. So far, no models exist by which these responses can be predicted with due regard to all relevant factors. To be able to develop such models, series of field trials with similar treatments are required at many European sites.

In this context, it seems necessary to distinguish between at least three climatic regions within the EU, a northern (Baltic) region with a humid climate and deep soil freezing, a southern (Mediterranean) region with drier climate and no deep freezing and an intermediate (Central) region. In each of these it is recommended that trials be carried out in three soil groups. Tentatively it is recommended to distinguish between coarse-textured, intermediate and fine-textured soils, since both soil and crop responses probably differ between these groups. However, other factors than soil texture may also be considered. Since other working groups of the Concerted Action may point out other factors as equally or more important than soil texture, the exact basis for the grouping may be specified later. If a sufficiently comprehensive series of field trials can be spread over the EU, a good basis for practical conclusions and measures and for development of models will be obtained.

5.2. Statistical considerations, number of experimental sites

In previous trials in northern Europe carried out by the ISTRO working group (Håkansson and Reeder, 1994) the mean persistent crop yield reduction caused by four passes on one occasion by a vehicle with an axle load of 10 Mg was 2.5 %. This was below the typical standard error of the difference between two treatments in the individual field trials in individual years. Therefore, no conclusions could be drawn from the results of individual location-years, only from an extensive group of location-years. The same may be expected in a future trials, even though traffic by vehicles with higher axle loads than in the previous trials should be applied. Therefore, trials are required at a large number of locations, and each of them should be run for several years.

Statistical considerations were made on the basis of the results of the previous trials. They

gave the following results. If the "real" difference in mean crop response to a certain treatment between two groups of sites is 1-2 % (e.g., the yield reduction is 1.5 % in one of the groups and twice as much in the other, which is an important difference), the difference is likely to be established with statistical significance only if each mean value is based on 30-40 location-years, e.g., on trials at 8-10 locations, each harvested during a 4-year period.

This number of location-years is required in each region and soil group that we want to distinguish, provided we want to establish differences in crop response of 1-2 %, which seems to be a reasonable requirement. To be able to distinguish three soil groups in each of three regions of the EU, 30-40 location-years in 3 x 3 = 9 groups of locations will be needed. This means trials at a total number of about 80 locations with at least 4 harvest-years at each location. However, trials already carried out can be included when the results are compiled and this will reduce the need of new trials. Even then, such an experimental program will constitute a comprehensive project. Therefore, most trials must be simple, and more detailed studies may have to be limited to some of the sites. However, it is not necessary to start the whole program as one single project. It can be divided it into a few individually financed regional sub-projects.

5.3. Choice of experimental sites

Experimental sites typical for the region where the trials are carried out is the first priority. Comparisons between soils are facilitated, if locations with different soils (e.g., one coarse-textured, one intermediate and one fine-textured) are chosen close to each other. This will also reduce the costs. It is necessary to specify the position of each site and each plot in such a way (e.g., by GIS-technique) that measurements can be repeated even after decades. If it is possible to find sites where heavy traffic has never been applied previously, such sites should be chosen. However, in most European countries it will probably be impossible to find such sites with soils typical for large areas of arable land.

5.4. Crops

Cropping systems and individual crops typical for the individual regions should be chosen. To keep costs within reasonable limits and still be able to establish a sufficient number of trials, in most trials only one crop per year can be grown. However, at some locations two or more crops may be grown side by side each year to facilitate direct comparisons between crops.

5.5. Duration of experiments

Traffic by heavy vehicles on the soil surface causes compaction both in the subsoil and in the topsoil (plough layer). Therefore, subsequent crop responses depend on both subsoil and plough layer compaction, and during the first few years the responses to plough layer compaction may dominate. Since counter-measures required to avoid compaction in the plough layer and in the subsoil differ, it is necessary to make it possible to separate the compaction effects in these layers.

Swedish experiments (Arvidsson and Håkansson, 1996) reveal that compaction effects in the plough layer of annually ploughed soils persist up to four years. Consequently, if heavy traffic is applied on the soil surface, crop responses during the first four years are generally caused both by subsoil and plough layer compaction. Pure subsoil compaction effects can be obtained only after that time. Therefore, if experimental traffic is applied on the soil surface (point 5.6.2, method A), four years must proceed, before pure subsoil compaction effects are obtained, and in southern Europe, perhaps a still longer period, because the soils do not freeze. To obtain pure subsoil compaction effects already in the first succeeding year, the experimental traffic must be

applied directly onto the subsoil after removal of the plough layer (point 5.6.2., method B). In both cases the experimental traffic should be applied only on one occasion. Otherwise the experimental period must be further extended (when using method A) or the application of the experimental traffic would be too expensive (when using method B).

Previous experiments show that crop responses vary considerably between years. Whichever method be used to apply the experimental traffic, the pure subsoil compaction effects must be studied during at least four years, to obtain results from years with different weather. If method A is chosen, an initial period of about four years is required before pure subsoil compaction effects are obtained, and there will be considerable extra costs to run the trials during this period. The results will also be delayed. Furthermore, from most research funds it is difficult to obtain financiation for research that has to be continued for an eight year period. For these reasons, the working group recommends the use of method B for application of the experimental traffic, provided suitable equipment can be built to a reasonable cost.

5.6. Design of experiments for crop response studies

To be able to calculate mean values for groups of trials and to compare results from different sites, some common (standard) traffic treatments must be applied at all sites. However, since most trials must be simple, only a few standard treatments can be selected. Instead, at some sites, additional treatments may be applied for detailed studies of various factors or studies of interactions with other factors. This approach was used even by the previous ISTRO working group.

5.6.1. Standard treatments and additional treatments
It is an advantage to include the same standard treatments as those used by the previous ISTRO working group, which were as follows.

A. Control treatment with no experimental traffic. As light machines as possible were used for the annual field operations throughout the experimental period. Axle loads of all machines had to be <5 Mg.

B. The whole plot area covered four times track by track by a vehicle running on the soil surface and having a load of 10 Mg on a single axle or 16 Mg on a tandem axle unit and tyres with an inflation pressure of 250-300 kPa. This traffic was applied on one occasion and at field capacity soil moisture content.

In new experiments, it is necessary to include treatments with axle loads >10 Mg, since farm machines with much higher axle loads are now in use. Furthermore, during recent decades tyres have become available which can carry a high load at a relatively low inflation pressure. The working group recommends the following standard treatments to be used if the experimental traffic is applied on the soil surface (point 5.6.2., method A). If the experimental traffic is applied directly on the subsoil (point 5.6.2, method B), loads and tyre inflation pressures that result in similar stresses in the subsoil as the vehicles specified below should be chosen.

A. The same as treatment A above, but axle load during the experimental period <4 Mg.

B. The same as treatment B above, except that tyre inflation pressure and lateral displacement between two adjacent tracks should be the same as in treatment C.

C. The whole plot area covered four times track by track by a vehicle with a load of 20 Mg on each of two axles equipped with single wheels. The lateral displacement between two adjacent tracks should be 50 cm, but it may be necessary to slightly adjust this distance to achieve a uniform coverage of the plots with tracks. Speed should be about 5 km h^{-1}. The lowest tyre inflation pressure that can be used at all sites at this axle load should be chosen. With the tyres available at present this will probably mean a pressure of 200 kPa. Traffic should be applied at field capacity soil water content (a matric tension about 10 kPa). Subsequently, the whole site

must be uniformly treated during the entire experimental period in accordance with good local practice using machines with axle loads <4 Mg.

Additional treatments should be included whenever feasible. These treatments may be chosen depending on local interests and possibilities. Examples of such treatments are different number of passes, additional axle loads or ground pressures, traffic by a tracked vehicle, traffic under different moisture conditions, two or more crops at a time, different fertilization levels, subsoiling before or after experimental traffic or other measures that may enhance alleviation of compaction, such as growing of pioneer plants or measures that intensify soil freezing or drying.

An important problem is the choice of traffic intensity in B and C treatments. It is specified above that the same lateral displacement between the tracks be used in both treatments. This means that the traffic intensity in Mg km ha^{-1} (defined as the product of the weight of the vehicle in Mg and the travelling distance within the plots in km ha^{-1}) in treatment B is half of that in treatment C. In practical farming, for some field operations the working width of the machines is nearly proportional to their weight. In such cases, the number of Mg km ha^{-1} is about the same irrespective of the weight of the machines. For other operations the working width is nearly independent of the weight, and the number of Mg km ha^{-1} increases nearly proportionally to the weight. The working group selected the second possibility. However, since it is also of interest to compare the same number of Mg km ha^{-1} with lighter and heavier machines, it is strongly recommended that an additional treatment with the same axle load as in B, but with the same number of Mg km ha^{-1} as in C be included in some trials. This means that only half the lateral displacement between the tracks by used in this treatment.

5.6.2. Methods for application of experimental traffic

The following two possibilities to apply the experimental traffic were considered by the group.

Method A: traffic applied on the soil surface

This was the method used by the previous ISTRO working group. The traffic causes compaction both in the plough layer and in the subsoil. During the first four years it can be assumed that crop responses are caused by compaction in both of these layers. Therefore, each trial must be run for at least eight years (point 5.5).

Method B: traffic applied directly onto the subsoil

By this method the experimental traffic is applied directly onto the subsoil after removal of the plough layer. In this way, pure subsoil compaction effects can be obtained already during the first succeeding year, provided the plough layer is treated similarly in all plots, irrespective of the subsoil compaction treatment. This requires that special machines and procedures be used for the experimental traffic. A possible way is as follows. A wide, open furrow is made by a mouldboard plough with a single, widened plough body, traffic is applied in the bottom of this furrow by a loaded wheel, a new furrow is made, the loaded wheel is run in this furrow, etc. It was shown that equipment can be constructed by which this can be achieved. However, before this method can be used, considerable efforts are required to design and build the most suitable equipment.

When using this method, wheel loads and ground pressures in individual treatments should be chosen in such a way that the stresses in the subsoil as closely as possible resemble those exerted by the "standard vehicles" specified in point 5.6.1. An exact correspondence at all depths, however, is impossible. A simple one-dimensional calculation was carried out to estimate combinations of load and ground pressure resulting in stresses similar to those of the standard treatments B and C (point 5.6.1) at a ploughing depth of 25 cm. For treatment B (axle load 10 Mg, ground pressure 200 kPa, driving on the surface) the resulting wheel load was 2.7 Mg and ground pressure 120 kPa. For treatment C (axle load 20 Mg, ground pressure 200 kPa) the wheel load

was 5.3 Mg and ground pressure 160 kPa. A thorough, three-dimensional calculation should be made when influential factors such as the ploughing depth and the tyre widths have been chosen.

5.6.3. Soil water content at time of traffic

The experimental traffic should be applied when the water content makes the soil as susceptible to compaction as possible. This is usually the case when the matric water tension is about 10 kPa, i.e., close to the field capacity value for humid regions. Traffic at other soil water contents may be applied as additional treatments. E.g., in southern Europe soil water contents typical for traffic situations both under rainfed and under irrigated conditions may be chosen.

5.6.4. Experimental design, number of replicates

When only the standard treatments and possibly a few additional treatments are applied, a randomized block design with about 6 replicates is recommended. If the interaction with another factor is to be studied, e.g., if traffic treatments are applied at two soil moisture contents, or two crops are grown side by side each year, a split-plot design with at least 4 replicates may be used.

5.6.5. Plot sizes

The recommendable plot width depends on the method for application of experimental traffic. If method A is chosen, only an area twice as wide as the track gauge of the vehicle, or about 4 m, can be uniformly covered by tracks. Therefore, this width (or possibly a multiple of it) plus a protection strip of about 1 m, or totally about 5 m, is a suitable width of the gross plots. The harvest plots must be about 1 m narrower than the area covered by tracks, since only this area is uniformly compacted in the subsoil. Plots should be at least 20 m long, preferably considerably longer. If method B is used for application of the experimental traffic, the plot width may be chosen more freely, but even then, 4-5 m is usually a suitable width of the gross plots.

5.6.6. Treatments during subsequent years

After application of the experimental traffic, the whole experimental area should be uniformly treated throughout the experimental period in accordance with good praxis for field trials. If the experimental traffic is applied by method A, the site must be ploughed to a normal depth soon afterwards, possibly repeatedly, in order to alleviate as much as possible of the compaction effects in the plough layer. Ploughing should then be repeated annually during the first four years. After that, reduced tillage may be used if this is the normal practice in the region. In such regions, reduced tillage may be used immediately, if experimental traffic is applied by method B. Throughout the experimental period, axle loads of all machines should be <4 Mg and tyre inflation pressures <100 kPa. The traffic intensity should be the same in all plots. Soil and crop management (fertilizing, spraying, irrigation, tillage, etc.) should be typical for the region and in accordance with good agricultural practice for sustainable agriculture.

5.6.7. One or more crops at a time

To be able to establish sufficient number of trials, most of them must be simple with only one crop per year. Then, a crop rotation typical for the region should be chosen. Least trouble with pests, diseases and damages to the crops will generally be obtained if the crops in the trials are the same as in the surrounding fields. To be able to compare the response of different crops, it is desirable to grow two or more crops side by side in some of the trials. Of particular interest would be to compare crops expected to exhibit different susceptibility to subsoil compaction.

6. Experiments for studies of environmental effects

The working group discussed the goal and methods for such studies. Most environmental effects envisioned can be studied in field trials primarily established for crop response studies. Therefore, they should be studied in these experiments. However, this does not apply to all effects and some experiments may be required for such studies. Environmental effects of compaction may be substantially affected by soil type and should be studied in various types of soils.

6.1. Effects on water infiltration, inter-flow, surface runoff and soil erosion

The group recommends that saturated hydraulic conductivity and water infiltration rate is measured in as many of the crop response trials as possible. These data will be of interest in models to estimate possible effects of subsoil compaction on drainage, on lateral water flow on top of the subsoil (inter-flow) and on surface runoff and soil erosion. Direct measurements of the influences of compaction on drainage, inter-flow, surface runoff, soil erosion and phosphorus transport should also be made at some sites, but at least some of these seem to require special experiments. The group recommends that a few experiments of that kind be established.

6.2. Effects on nitrogen leaching and greenhouse gases and other effects

Among effects of subsoil compaction likely to be important are reduced nutrient use efficiency caused by impaired root growth or function. Therefore, more nitrogen may be left in the soil at the end of the growing season and exposed to leaching. Impaired aeration may affect the biological activity in the soil, thus affecting mineralisation of organic matter, carbon sequestration, release or uptake of greenhouse gases, decomposition of organic chemicals and nitrogen cycling and movement. The denitrification is probably increased. Such effects should be measured in as many of the crop response trials as possible and should be combined with as intensive studies as possible of the plant/soil interactions and root development. In the initial phase, no special experiments seem to be required. However, at a later stage, a need for special experiments may appear, e.g., experiments with plot-wise drainage to monitor nitrogen leaching or experiments to study effects on biological activity, carbon sequestration and greenhouse gases.

7. Who should be responsible for the field experiments?

The working group strongly stress that field trials for crop response studies must be of a long-term character (point 5.5). This was not sufficiently stressed by the previous ISTRO working group, which led to the termination of some trials before the main objective of the project was reached and to waste of resources. However, the handling of long-term field trials fit poorly to traditional university research. In the first hand, therefore, the trials should be placed at agricultural experiment stations with equipment and experience to handle them. However, once the establishment and annual handling of the trials are ensured, the specialized measurements are well suited to university research, such as Ph.D.-studies.

8. Measurements in the field trials

Various measurements necessary or desirable in the trials are specified below. However, some of the institutes involved in a future project will probably not have equipment or experience for all these measurements. In such cases, cooperation with other institutes involved is strongly

encouraged. The specifications in the workbook for the database of the present EU-project should be used as guidelines for many of the measurements and descriptions.

8.1. General characterization of experimental sites

A general characterization of each experimental site is necessary, including location, climate, recent land use and various soil profile characteristics such as texture, structure, description of individual horizons, water characteristic curves and shrinkage curves for individual layers. The instructions for the workbook of the database should be followed.

8.2. Soil mechanical properties

The soil mechanical properties at time of experimental traffic must be characterized. At least simple field measurements with penetrometer or shear vane should be carried out at all sites. To predict depth and intensity of compaction in various subsoil layers, or to develop or validate models for such predictions, more complete determinations of soil mechanical properties are needed. This may require participation of laboratories specialized in such measurements. Other working groups of the present project are requested to specify their demands on type of measurements and on number of sites for such measurements.

8.3. Soil water content and matric water tension at time of traffic

Soil water content as well as matric water tension in various soil layers must be measured at all sites at time of experimental traffic to the maximum possible depth of compaction, i.e., in most cases to a depth of at least 80 cm.

8.4. Description of the compacting vehicle and the experimental traffic

The type of compacting vehicle and its total weight, axle load and wheel load must be specified as well as types of individual tyres and their dimensions, inflation pressures and contact areas on a hard surface, and the speed. The traffic intensity in Mg km ha^{-1} in the plots should be calculated for all treatments. Subjectively assessed moisture conditions at the soil surface, as well as wheel slip and track depth must be recorded.

8.5. Stresses in the soil caused by the traffic

Whenever possible, the stresses, at least the vertical, normal stress, induced by the experimental traffic at various soil depths should be measured. This, however, requires the use of equipment that is not available everywhere. Cooperation between laboratories is encouraged so that this type of measurements can be made at most sites.

8.6. Depth and intensity of compaction

Maximum depth of compaction and the extent of compaction in various subsoil layers must be determined. Various methods may be used depending on local possibilities and interests.

Whenever feasible, soil displacement should be measured at several depths when the experimental traffic is applied to enable calculations of the incidence and extent of compaction in various layers. Direct determinations of changes in thickness of individual soil layers is an alternative. Equipment for such measurements, however, is only available at some laboratories, and therefore, cooperation between laboratories is encouraged.

After application of the experimental traffic, soil properties in various subsoil layers in control plots and trafficked plots should be compared by determining some of the following parameters: bulk density, total porosity, macro-porosity, air-filled porosity at a certain water tension, penetration resistance, vane shear strength, hydraulic conductivity, preferential flow or air permeability, and possibly some other parameters of local interest. When using traditional

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methods to determine such soil physical parameters, the effects of the treatments are generally small compared to the variability in the soil. The previous ISTRO project indicates that the number of replicates required to obtain statistically significant differences between treatments is very often underestimated. With traditional methods, such as core sampling, >30 replicates are usually required. Measurements of penetration resistance and vane shear strength are the least time-consuming, and are easiest to replicate as required. One of these, therefore, should generally be included in the measurement program. However, it is necessary either to determine soil water content at time of measurements and repeat them at different water contents, or to carry out the measurements when there are no differences in water content between treatments, e.g., when the whole site has a field capacity soil water content.

Most samplings and measurements may be made at any time during the first year after traffic, provided the soil moisture content is suitable and (particularly in swelling/shrinking soils) similar in all treatments. Measurements of penetration resistance or vane shear strength, however, should not be made during the first months after the traffic, since the disturbance often temporarily weakens the bonds between the soil particles. Some age-hardening is required (at least one drying/wetting cycle) before these parameters correctly reflect the compaction.

8.7. Persistence of compaction effects

Great efforts are justified to determine the persistence of the compaction effects at various depths. The only possibility seems to be to repeat some of the measurements of soil properties in various layers in control plots and trafficked plots according to point 8.6 periodically (e.g., every second year) during a 10-year period or more. Soil moisture content should be as similar as possible at all sampling occasions.

8.8. Weather and soil water content during subsequent years

The weather (air temperature, precipitation, potential evaporation, surface temperature, soil temperature and solar radiation) during the growing season in subsequent years influences the crop responses, and the depth of soil freezing influences the persistence of compaction in various layers. For interpretation of the crop yield results, appropriate weather records are needed. Unless weather records from an official meteorological station close to an experimental site are available, measurements should be made at the site. It is also recommended to determine soil water content and tension periodically during the growing season, particularly if data from the site is to be used for development or validation of crop response models.

8.9. Soil aeration, penetration resistance, hydraulic conductivity, ground water level

These factors influence crop growth, and if possible, they should be measured not only on one occasion or periodically to determine depth, intensity and persistence of compaction according to points 8.6 and 8.7 but at several occasions with different soil moisture contents during one or more growing seasons.

8.10. Root development

Possibilities for uptake of water and nutrients in various layers, and consequently, crop responses to subsoil compaction largely depend on the depth of the root zone and on root density and distribution in various layers. Detailed quantitative determinations of root systems in individual treatments, such as root length density, average half distance between nearest roots and heterogeneity of the root distribution in individual layers, should be made whenever possible. However, such determinations are labourious and can probably only be carried out at some of the sites. At the remaining sites, at least a qualitative description of normal rooting depth and root density and distribution in various soil layers should be made.

8.11. Crop growth and yield

Final crop yield, of course, should always be determined. Depending on the type of crop, determination of other crop characteristics such as time of emergence, number of plants, spikes and ears per m^2, plant height, leaf area index and lodging will increase the possibilities to interpret the final yield results and is recommended.

8.12. Plant nutrient uptake

Alakukku (1997) showed that subsoil compaction reduced nitrogen yield of cereals more than grain yield. This indicates that plant nutrient uptake by the crops should be studied in the new trials. It is recommended to always determine the nitrogen content in the harvested product. More detailed investigations of the effects of subsoil compaction on cycling, availability and uptake of nitrogen by the crops as well as on the uptake of other nutrients should be made at least in some trials. In this context, information about microbial activity, e.g., by determinations of some soil enzymes, may be helpful.

8.13. Pests, diseases and weeds

Observations should be made of possible effects of compaction on pests, diseases (particularly root diseases) and weeds (species, abundance). If effects are observed, they should be quantified.

8.14. Measurements of environmental effects

In the crop response trials, several measurements of environmental effects can be made and are strongly encouraged. However, other studies of environmental effects may require special experiments. In such case, special measurement programs not specified here may be required.

8.14.1. Infiltration, inter-flow, surface runoff, soil erosion

Measurements of water infiltration (e.g., by double ring or disc infiltrometer) and possibly also of inter-flow can be made in the crop response trials, and such measurements should be carried out at least at some sites. Direct measurements of surface runoff and erosion seem to require experiments specially designed for this purpose (point 6.1).

8.14.2. Nitrogen cycling, denitrification and leaching, leaching of chemicals

Determinations of the content of mineral nitrogen in various soil layers at various times of the year can be made in the crop response trials. They are useful tools to estimate the risk of nitrogen leaching and should be carried out at many sites. Suitable sampling depths are 0-30 cm, 30-60 cm and 60-90 cm. Since leaching of plant nutrients is generally greatest from soils with poor root development in the subsoil, these measurements should be combined with root investigations. More extensive determinations of various processes involved in the nitrogen cycling (e.g., studies by labelled fertilizer or studies of the denitrification by measuring gas emissions from the soil) should be made at least at some sites on various types of soils. It may also be of interest to study the transport of various organic chemicals at a few sites.

8.14.3. Effects on soil biological activity and organic matter

The group recommends that the influences of subsoil compaction on various soil biological processes be measured at some sites. Measurements may be chosen depending on local interest and possibilities, but processes influenced by soil aeration such as turnover of organic material, including carbon sequestration and CO_2 emission, plant nutrient mineralization, denitrification and uptake or release of methane seem to be the most interesting. Influences on soil fauna, e.g., on the earthworms, and on some soil enzymes should also be studied.

9. Minimum program of measurements in the trials

Some of the measurements specified may be carried out only at a limited number of sites, but the following minimum program of measurements to be carried out in all trials is recommended.

A. Measurements at the establishment of the trials.
1. General characterization of the experimental site (8.1)
2. Soil water content and matric water tension at time of experimental traffic (8.3)
3. Description of the compacting vehicle and the experimental traffic (8.4)
4. Some of the following soil physical measurements to determine maximum depth of compaction and intensity of compaction in various layers: penetration resistance, vane shear strength, bulk density, total porosity and macroporosity (8.6)

B. Measurements during the experimental period
4. Documentation of field operations, fertilization, spraying, etc. (date, method, time, quantity)
5. Periodically repeated measurements to determine the persistence of compaction (8.7)
6. Temperature, precipitation and potential evaporation throughout each growing season and maximum depth of soil freezing each winter (8.8)
7. Qualitative observations of the root system (8.10)
8. Crop yield and other relevant crop growth parameters (8.11)
9. Content of nitrogen in the harvested products (8.12)

10. Where to establish new experiments

Before a new project can be started a suitable group of experimental stations, universities, institutes or individual scientists interested in establishing new trials must be formed. Discussions in the working group have revealed that such an interest exists in many countries, but at present no list of organizations or individuals interested in a project can be presented.

11. Design, construction and use of special equipment

If the recommendation is followed to apply the experimental traffic directly on the subsoil (point 5.6.2, method B), some special equipment must be designed and built. This requires time and resources, but pure effects of subsoil compaction on crop growth will be obtained about three years earlier than if traffic is applied on the soil surface, which saves the overall costs. The special equipment must be designed and manufactured during the initial phase of a new project. Because of the costs, the same equipment must be used at many sites, and it must be built in such a way that it is easy to transport. Nevertheless, to be able to establish trials in most EU countries, more than one set of equipment may be required. When constructing the equipment, experience from previous special loading vehicles used in Braunschweig and Uppsala, may be valuable.

12. Subsoil loosening, pioneer plants or other methods to alleviate subsoil compaction

A problem with relevance both to the present project and to a possible new one is to what extent effects of compaction at various depths in various soils and climatic regions can be alleviated by mechanical loosening, by pioneer plants or other cultural practices or by natural factors. If most of the effects can be alleviated easily and quickly, subsoil compaction is not a serious problem. If this is not the case, however, the problem is urgent, since subsoil compaction increases rapidly as a consequence of the increasing weights of agricultural machinery.

Field trials with subsoiling have been carried out in most European countries. Trials with "biological subsoiling" by pioneer plants have also been established. The results seem to indicate that negative effects of machinery-induced subsoil compaction can, at the best, only be partly alleviated by subsoiling. Long-lasting positive effects seem to be limited to soils with genetically formed dense or hard subsoil layers. However, a critical review of all relevant research is missing, and is strongly recommended. It must be considered, however, that gradually heavier machines have made the subsoils more dense and in increased need of loosening. At the same time, soils may be more rapidly re-compacted and the loosening effects less persistent. A considerable part of relevant research on subsoil loosening has been carried out in eastern Europe, and therefore, a complete review would require contributions from somebody who can read Russian.

13. Experiments concerning the effects of non-agricultural traffic on agricultural as well as on non-agricultural land

Occasionally, heavy non-agricultural traffic (construction traffic, military traffic, etc.) occurs on arable land as well as on non-agricultural land and may be very intensive. Only a few studies of soil deterioration and ecological effects caused by such traffic have been made. The working group encourages the establishment of an international project for studies of various effects of heavy non-agricultural traffic on arable land and possibly also on other land. The first step should be to review existing data on areas exposed to such traffic and its consequences and to specify objectives of the project, treatments to be studied, measurements, etc. This would require a special working group.

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Assessing the vulnerability of subsoils in Europe to compaction

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Abstract

Identifying the vulnerability of subsoils to compaction damage is an increasingly important issue both in the planning and execution of farming operations and in planning environmental protection measures. Ideally, subsoil vulnerability to compaction should be assessed by direct measurement of soil bearing capacity but currently no direct practical tests are available. Similarly, soil mechanics principles are not suitably far enough advanced to allow extrapolation of likely compaction damage from experimental sites to situations in general. This paper, therefore, proposes a simple classification system for subsoil vulnerability to compaction based for field use on local soil and wetness data at the time of critical trafficking, and at European level on related soil and climatic information, readily available 'in Country' and/or within the European Soil Database and the agrometeorological database of the MARS Project. The vulnerability to compaction is assessed using a two-stage process. First the susceptibility of the soil to compaction is estimated on the basis of the relatively stable soil properties of texture and packing density. The susceptibility class is then converted into a vulnerability class through consideration of the likely soil moisture status at the time of critical loadings. For use at local level adjustments are suggested to take account of possible differences in the support strength of the topsoil and specific subsoil structural conditions. The vulnerability classes proposed are based on profile pit observations on a wide range of soils largely in intensively farmed areas employing large scale equipment. The system is, therefore, only the first step towards developing a more rigorous quantitative approach to assessing subsoil vulnerability to compaction. Nevertheless, it is hoped that the system will provide a valuable tool for immediate use to predict the areas in Europe most vulnerable to subsoil compaction and for use in local situations as an aid to the planning and selection of ground drive and support equipment to avoid subsoil damage.

1. Introduction

Knowledge concerning the vulnerability of subsoils in Europe to compaction is an increasing requirement within agriculture and in the planning of environmental protection measures. Once subsoil damage occurs, it can be extremely difficult and expensive to alleviate. Subsoil compaction risks are increasing with growth in farm size, increased mechanisation and equipment size, and the drive for greater productivity. The response of the engineering industry to the demands of agriculture has been impressive over the past 30 years. Larger and larger machines have been developed but, from the soil standpoint, the result has been a significant increase in axle loads not always matched by reductions

in ground contact pressures to prevent or minimise compaction. (Renius, 1994; Tijink *et al.*, 1995).

Research into the causes and effects of compaction in topsoils and subsoils in Europe has demonstrated the detrimental effects on the farming system (Hakansson, 1994). It is now clear, however, that the detrimental effects go far beyond agricultural concerns of a decrease in yield and increase in management costs. The overall deterioration in soil structure that may result from compaction can also:

1. increase lateral seepage of excess water over and through the soil, accelerating the potential pollution of surface waters by organic wastes (slurry and sludge), pesticides, herbicides and other applied agrochemicals;
2. decrease the volume of the soil system available to act as a buffer and a filter for pollutants;
3. increase the risk of soil erosion and associated phosphorus losses on sloping land through the concentration of excess water above compacted layers;
4. accelerate effective runoff from and within catchments.
5. increase green house gas production and nitrogen losses through denitrification under wetter conditions.

Recently, the Regions in Europe have been charged with the task of developing environmental protection plans and an integral component of these will be soil protection. Compaction, particularly in subsoils, has, therefore, ceased to be a problem only of productive agriculture; the environmental impacts that can ensue are now causing serious concern. Assessing the vulnerability of different subsoils to compaction is, therefore, an increasingly important issue. This is not only so that appropriate measures can be identified for its avoidance in different situations, but also to determine the extent of actual and potential problems within Europe.

Whilst the ideal method for assessing the vulnerability of a subsoil to compaction would be to make direct measurements of its support or bearing capacity, no reliable, easily usable direct tests are available to achieve this. Assessments have, therefore, to be made indirectly from more readily measured parameters and soil properties. From a research viewpoint, attention to the soil mechanical strength properties and stress/strain relationships is appropriate. The assessment of these properties is, however, particularly involved and to date there is insufficient information available to allow results to be extrapolated widely beyond the research locations themselves. Until such information becomes available, guidance on soil vulnerability to compaction must be based on more readily measurable and available information, supplemented by field experience of soil behaviour under load.

The most readily available information on soils in most countries is soil survey data and this can be supplemented with climatic and land use/cover data. The intention of this paper is to define a simple scheme using existing soil and climatic data for assessing the vulnerability of subsoils to compaction in different climatic situations. Adjustments are also suggested for application of the scheme in local areas but it should be emphasised that any such scheme can only provide general guidance for use on a local or national scale. Modification for local situations must take account particular of local characteristics that could alter any vulnerability class.

At European level, spatial soil data are held within the European Soil Database (Heineke *et al.*, 1998) and climatic data in the agrometeorological database of the MARS Project (Vossen and Meyer-Roux, 1995). Both these databases are located at the European Union's Joint Research Centre at Ispra, Italy. Using these data, maps, albeit at small scale, could be constructed showing areas most vulnerable to subsoil compaction. These would be of immediate value to policy makers. At local level, such vulnerability information could assist in the planning of field operations and is essential for any review of land use systems.

2. Methods

2.1. Soil resistance to deformation and compaction

The degree of soil movement and possible compaction consequences that occur when a soil is subjected to external loads, depend upon the magnitudes of the loads, the pressures applied and the soil sliding or shearing resistance developed during deformation. Soil shearing resistance comprises largely of two components whose magnitudes vary between soils and soil conditions. The two components are the frictional and cohesive resistances.

The magnitude of the frictional resistance component is dependent on soil particle type and size distribution, the shape, size and stability of structural units present, and the nature and tightness of their packing. Angular shaped particles and units tend to offer a greater resistance to sliding than rounded particles and the greater the degree of interlocking the greater the resistance.

The cohesive component is very dependent upon soil moisture status and the surface activity of the clay fraction. Cohesion increases at higher moisture tensions and with increases particularly in the active surface area of the soil particles and units. Chemical and organic bonding forces can be a significant component of cohesion in some soils and these can be influenced by cation type and soil pH. In rapid loading situations, in saturated soils or in cases with similar loadings on saturated structural/shrinkage units, viscosity effects can also influence deformation resistance.

Traffic loadings on subsoils tend to be largely vertical and hence air filled horizontal pores and cracks are much more susceptible to closure than their vertical counterparts thus decreasing horizontal permeability. Soil structural type and fissure/crack development are, therefore, important factors controlling the degree of compaction that may occur. The greater the number of vertical macropores for similar soil unit stability and strength, the greater the resistance to compaction. Vertical biopores formed by roots and soil organisms are also extremely resistant to collapse under the action of vertical compressive loads; they do, however, easily succumb to significant horizontal shearing loads. The exception to the normal largely vertical loadings arises through the operation of tractor wheels within the open furrow during ploughing operations. Large horizontal as well as vertical stresses can be induced through wheel slip in such situations.

In most field situations, subsoils have been previously stressed and hence have responded, through compaction and consolidation, to the stresses applied. These stresses have frequently originated from numerous in-furrow wheelings during ploughing operations.

In some situations, particularly on the coarse and medium textured soils, more compact zones of some type may be present at ploughing depth. These changes and conditions will influence the stress distribution in the subsoil during loading and the aim of subsoil protection measures in current loading situations, must be to ensure that new subsoil stresses do not exceed these pre-consolidation/compaction stresses.

During the application of surface loads, topsoil condition in terms of its looseness/firmness/strength will also influence the stresses transmitted to the subsoil. In weak topsoil situations considerable wheel or track sinkage can also occur increasing the magnitude of the stresses within the subsoil.

2.2. Soil physical properties related to soil shearing resistance

The soil physical properties that are most closely related to the factors controlling soil shearing resistance and hence the susceptibility of a subsoil to compaction are as follows:
1. Soil texture, estimated from the proportion of sand, silt and clay (% by weight), and expressed as a texture class.
2. Nature of clay fraction and associated ions
3. Bulk density, t m^{-3}
4. Organic matter content, often expressed as percentage organic carbon (by weight)
5. Structure, the type, size and degree of ped development which strongly influence porosity, permeability and nature of macro-pores
6. Soil moisture (water) content (% vol).
7. Soil moisture potential.

With the exception of information on clay mineral type and soil moisture content/potential, all the other properties are reported in or can be inferred from soil survey records and databases. In some situations, clay mineralogy can also be inferred from geology or soil parent material or soil structural properties.

The soil moisture content is the most variable of these parameters and, in the case of compaction, the water content at the time of deformation is critical to the amount and extent of the compaction that results. On a medium timescale, climate and weather govern the moisture status of soils except in highly receiving sites such as marshes, the lowest parts of river valleys and around lakes [wetlands]. The agrometeorological databases can, therefore, provide valuable information on moisture status for many large-scale situations. At a local level the moisture status at critical loading times is usually known or can be inferred.

2.3. Available soil data

A number of systems are used in different countries for recording soil information, but, in the European Soil Database, all the soils of Europe are classified according to the FAO-UNESCO (1974) system. Linkages are available for conversions between the different systems, including the revised FAO-UNESCO (1990), where required. In this paper, the FAO-UNESCO system is used as the standard. This system employs a simple scheme of soil texture classes and contains information that can be used to infer soil density and structure.

2.3.1. Soil texture

The soil texture classes are shown below in tabular (Table 1) and graphical form (Figure 1). Ideally, as more compactability data becomes available, a more complex scheme of soil texture classes would be advantageous for assessing vulnerability to compaction. Examples are those of the USDA (Schoeneberger *et al.*, 1998) and the UK (Hodgson, 1976).

Table 1. Texture and particle size grades used by the FAO soil classification system

Code	Class	Particle size grades
1	Coarse	Clay < 18% and sand > 65%
2	Medium	18% < clay < 35% and sand > 15% OR clay < 18% and 15% < sand < 65%
3	Medium Fine	Clay< 35% and sand < 15%
4	Fine	35% < clay < 60%
5	Very Fine	Clay > 60%
9	Organic	
0	No texture	

2.3.2. Bulk density

Bulk density measured on undisturbed samples (Hall *et al.*, 1977) for the different soil horizons (layers) in representative profiles provides the most useful density information for compaction assessment. Unfortunately such data are not readily available because of the time and expense required for making measurements of density. A pedotransfer rule (PTR) for estimating subsoil bulk density has, however, been developed by Van Ranst *et al.* (1995), for use where no direct measurements are available.
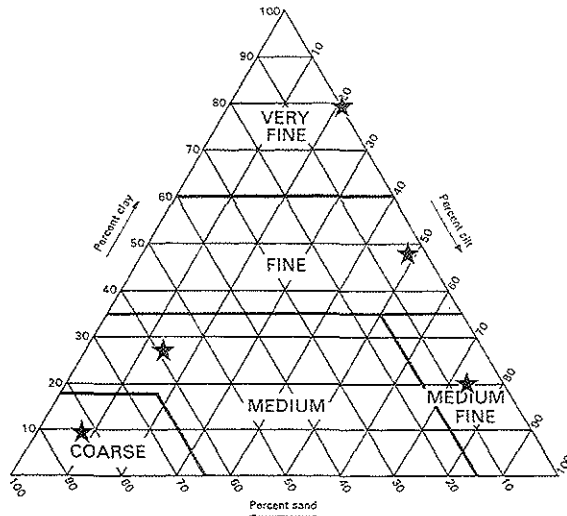
Figure 1   Texture classes of FAO used in the European Soil Database

This PTR integrates an estimate of subsoil structure and the FAO *soil name* to give *packing density* or *Lagerungsdichte* (Renger, 1970). Packing density (PD), which elsewhere in the literature is given the symbol Ld, effectively integrates the bulk density, structure, organic matter content of mineral fraction and clay content, to provide a single measure of the apparent compactness of the soil. It has proved to be a very useful parameter for spatial interpretations that require a measure of the compactive state of soils (Jones and Thomasson, 1993).

$$PD = Db + 0.009C \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(1)$$

Where Db is the bulk density in t m^{-3}
PD is the packing density in t m^{-3}
C is the clay content (%)

Three classes of packing density are recognised:

Class	PD (t m^{-3})
Low	< 1.40
Medium	1.40 – 1.75
High	> 1.75

Soils with high packing density (> 1.75 t m^{-3}) are generally not very susceptible to further compaction whereas those with medium and low PD (< 1.40 t m^{-3}) are vulnerable at critical moisture contents and loads. In situations where the actual bulk density is known, packing density can be readily determined through the incorporation of clay %.

2.3.3. Organic matter
Organic matter contents of mineral subsoils are usually very low and hence are unlikely to have a major influence on subsoil compatibility. The exceptions are some Fluvisols (CEC, 1985; FAO-UNESCO, 1974) that by definition are developed in materials recently laid down by river systems, in which organic carbon contents in the subsoils may exceed 2%. The packing densities of these soils are much lower than in non-fluvial soils of corresponding texture because they are naturally much less compact, and hence density assessments could require organic matter correction. In practice, the higher organic matter content in Fluvisols does not appear to significantly compensate, in terms of compactability, for the low density in the subsoil so it is not considered necessary to take organic matter into account in any *compactability* index.

2.3.4. Structure
International systems for assessing soil structure describe the size, shape and strength of ped development (Schoeneberger *et al.*, 1998; FAO-ISRIC, 1990; and Hodgson, 1976). Structure is an important aspect of the overall strength of the soil and hence its susceptibility to compaction. Generally, soils with single grain, granular and weakly developed blocky structures are susceptible to compaction. Strong blocky, prismatic and platy structured soils are not particularly susceptible at low moisture contents but generally the susceptibility of these structures is strongly interactive with moisture content. Another complicating factor is that fine and very-fine textured soils with angular blocky and prismatic structures often have high packing densities. In this respect, these

soils can be regarded as naturally compact and, therefore, are not usually susceptible to further compaction as a result of management.

The pedotransfer rule, defined at European level (Van Ranst *et al.*, 1995) for estimating packing density, uses an estimate of subsoil structure, assessed as poor, medium or good from pedological inputs such as texture and parent material. For local application, adjustments to vulnerability class may be necessary to take account of specific soil structure situations.

2.4. Soil moisture status/climate interaction

The previous section describes the soil physical properties important in assessing the susceptibility of a soil to compaction. The strength of any soil at a particular bulk density depends, crucially on its moisture status at the time of loading and deformation.

To translate soil susceptibility to compaction into vulnerability, soil moisture contents, topsoil condition and the magnitudes of likely loadings and pressures at critical times must be taken into account. This vulnerability, can be considered as a likelihood that compaction will occur. Considering the moisture component, to establish a scheme or system for classifying the vulnerability of soils to compaction, some direct measure or measure of climatic wetness is needed. A crucial question is: 'what is the likely moisture content of soils susceptible to compaction at the time of year when field operations such as seed bed preparation, fertilising, slurry spreading and harvesting, are taking place?' In machinery management terms, compaction risks are frequently greatest during the harvesting period, when the heaviest equipment is likely to be employed. However in climatic terms, risks may be greater in spring when moisture contents are higher than in autumn (Thomasson, 1982; Thomasson and Jones, 1989).

One measure of climatic wetness is to assess the excess of evapotranspiration over rainfall during a season. This can be a useful index in many situations, particularly with respect to likely moisture conditions during the harvesting period. In practical terms it is necessary to use the potential evapotranspiration and so the resulting parameter is called the potential soil moisture deficit (Smith, 1967; Jones and Thomasson, 1985).

For the period considered:
$$PSMD = \Sigma(R-PE) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(2)$$
When PE exceeds R
Where: PSMD is the maximum potential soil moisture deficit
R is the rainfall in mm
PE is the potential evapotranspiration in mm.

The PSMD, expressed in mm rainfall equivalent is a measure of the climatic dryness of a rainfed system. The actual soil moisture deficit is, however, not only dependent on weather conditions alone but is also affected by soil conditions, the crop ground cover, the proximity of a ground water table to the surface and certain management practices such as drainage and irrigation. Relatively high water tables during the growing season with associated capillary rise can significantly reduce soil moisture deficit when compared with the potential value, as can irrigation.

Despite its limitations PSMD has proved a useful wetness parameter in the wetter north of the European Continent, but its application needs to be tested further in the drier climates of the south. Other possible parameters for indicating potential soil wetness include the end and beginning of field capacity periods (Jones, 1985; Jones and Thomasson, 1985), the timing of likely rainfall following long dry periods and practical experience of water table measurements that indicate subsoil wetness at critical trafficking periods. In irrigated areas, information is usually available from irrigation scheduling data on likely moisture deficits at specific periods during the year.

In situations where the early spring period is the most critical for tillage or landwork, subsoil moisture contents then are usually at or very close to field capacity and hence moisture deficits can be assumed to be zero or very low. This of course may not be the case in southern Europe.

3. Results

In view of the general lack of quantitative data on the compactability of different types of subsoil, the following compactability classes have been drawn up on a basis of field experience, derived from profile pit observations on a wide range of soils, largely in intensively farmed areas employing large scale equipment.

3.1. Assessing vulnerability to subsoil compaction

A two-stage methodology is proposed to assess the vulnerability of subsoil to compaction:
1. Assessing the susceptibility on the basis of the relatively stable soil properties of texture and packing density.
2. Combining soil susceptibility and an index of climatic dryness/subsoil wetness to convert susceptibility to compaction into a vulnerability class.

3.1.2. Susceptibility classification
Table 2 classifies the susceptibility of subsoils to compaction on the basis of texture and packing density.

Table 2. Susceptibility to compaction according to texture and packing density

		Packing density t m^{-3}		
		Low	Medium	High
Texture		< 1.40	1.40 – 1.75	> 1.75
Code	Texture Class			
1	Coarse	VH	H	M[1]
2	Medium	H	M	M
3	Medium fine	M(H)	M	L[3]
4	Fine	M[2]	L	L[3]
5	Very fine	M[2]	L	L[3]

[1] *except for naturally compacted or cemented coarse (sandy) materials that have very low (L) susceptibility.*
[2] *these packing densities are usually found only in recent alluvial soils with bulk densities of 0.8 to 1.0 t m^{-3} or in topsoils with >5% organic carbon.*
[3] *these soils are already compact.*

Table 3 defines the level of susceptibility of the different classes.

Table 3. Classes of soil susceptibility to compaction

Class	Susceptibility
L	Low
M	Moderate
H	High
VH	Very High

The classification does not include a soil structure item directly, because in practice subsoil structure and its stability are often closely related to texture; packing density is also related to structure. Where this is not the case, due allowance will need to be made for the influence of structure. In the classification system proposed, it is considered that any structure within the texture code classes 1-3 is very weak in terms of its potential resistance to subsoil compaction. Strong and coarse structural units are frequently found in the fine and very fine texture classes playing an important role in resistance to compaction and this is taken into account in the susceptibility classes suggested.

3.1.3. Vulnerability classification

Table 4 classifies the vulnerability of subsoils to compaction on the basis of soil susceptibility, climate/wetness/moisture status and topsoil strength.. The influence of the topsoil condition is included, since this can have a significant effect on the degree of 'protection' provided to the subsoil. In situations where the topsoil is loose and weakly structured, or where it is very wet and the soil tends to flow on loading, the vulnerability rating in a number of situations will increase. Table 5 defines the degree of vulnerability of the different classes.

Table 4. Vulnerability to compaction according to susceptibility and climate

Class	Climate/wetness Moisture status	Perhumid: very wet Field capacity.	Humid wet	Moist PWP	Dry
Soil Susceptibility	PSMD mm	≤ 50	51 - 125	126 – 200	> 200
VH		E (E)	E (E)	V (E)	V (V)
H		V (E)	V (E)	M (V)	M (M)
M		V (E)	M (V)	N (M)	N (N)
L		M (V)	N (M)	N (N)	N (N)

Classes outside brackets refer to situations with firm topsoil conditions.
Classes within brackets refer to situations with loose/weak topsoil conditions.
PWP Permanent Wilting Point (=1500kPa).

Table 5. Classes of vulnerability to compaction

Class	Vulnerability
N	Not particularly vulnerable
M	Moderately vulnerable
V	Very vulnerable
E	Extremely vulnerable

Loads and pressures are not incorporated into the above classification, but the more vulnerable the subsoil the greater the attention that needs to be paid to loads and the pressures that are necessary to avoid subsoil compaction. There are some fine textured (codes 3,4,5 in Table 2) lower density, weakly structured subsoils with very limited macroporosity, where only a small reduction in this porosity would have a very significant adverse effect on their physical properties. In such cases whilst their vulnerability to compaction is unlikely to change, their sensitivity to the effects of compaction is greater than soils with greater macroporosity. In such situations, working on a higher vulnerability rating would provide a greater margin of safety against damage at high moisture contents. In converse situations, such as in dense strong coarsely structured soils, it may be possible to reduce the vulnerability rating.

3.2. Examples of subsoil compactability classes

The following examples identified in Table 6, are taken from a range of lowland British soils which, with the exception of Fladbury Series, are under continuous arable cropping and farmed using large scale equipment. The Susceptability and Vulnerability Classes identified follow closely field experience in terms of subsoil compaction problems. The average potential soil moisture deficits of these soils lie within the 126-200mm band.

The Naburn and Newport soils are very easily compacted, compaction pans form very readily and if broken allow compaction to extend to much greater depths in the subsoil. Subsoil compaction is, however, easily corrected and the subsoils rarely ever become anaerobic.

Wisbech, Wick, Romney and Agney series soils are less susceptible than the loamy sands to subsoil compaction. The Wisbech and Agney soils in particular have very firm subsoils full of vertical biopores. These biopores are the old root channels of the tidal zone vegetation growing during the period of soil formation. They constitute the main pathways for root, air and water movement and are extremely resistant to collapse under vertical loads. Shear forces disrupt them immediately and hence deep cultivation operations could have a disastrous effect on subsoil quality.

Table 6. Compactability classes of a range of British soils.

Soil Series	FAO Class	Texture Class	Bulk Density t/m³	Packing Density t/m³	Suscept. Class	Vulner. Class Field capacity (firm)	Vulner. Class PWP (firm)
Naburn	Haplic Arenosol	Coarse	1.23	1.32	VH	E	V
Newport	Haplic Arenosol	Coarse	1.43	1.47	H	V	M
Wisbech	Calcaric Fluvisol	Medium	1.35	1.40	M	V	N
Wick	Eutric Cambisol	Medium	1.36	1.46	M	V	N
Romney	Calcaric Phaeozem	Medium Fine	1.33	1.47	M	V	N
Agney	Fluvi-Eutric Gleysol	Medium Fine	1.32	1.59	M	V	N
Hanslope	Calcaric Pelosol	Fine	1.43	1.83	L	M	N
Fladbury	Eutric Fluvisol	Very Fine	1.04	1.67	L	M	N
Evesham	Calcaric Gleysol	Very Fine	1.41	1.92	L	M	N

Hanslope and Evesham series soils, largely in combinable crops, are naturally compact and hence very resistant to further subsoil compaction. Their subsoils comprise largely of coarse prismatic structural units which, due to the swelling and shrinking nature of the high clay fraction, remain largely saturated in themselves to moisture contents below permanent wilting point.

The Fladbury series clay soil is of low density and frequently extremely wet, but rarely in continuous arable cropping. Although the subsoil comprises of extremely stable micro-aggregates it is moderately vulnerable to compaction at high moisture contents. Under grassland with firm topsoil, the subsoil is well protected against damage. Risks of subsoil damage would only be likely if subjected to excessively high loads accompanied by considerable sinkage under wet conditions.

4. Discussion

The vulnerability classification proposed is intended for guidance only. Modifications to susceptibility and to vulnerability classes can be made in specific situations, taking account of local factors and management aspects, as illustrated in the previous section.

Particular attention needs to be given to soil wetness at the time of trafficking and to the particular loads and pressures being applied. Whilst the magnitude of axle loads is often emphasised, it is critical that the importance of ground pressures is given equal attention. Appropriate reductions in contact pressures can, within wide limits, mitigate the effects of high axle loads on the potential for subsoil compaction.

An estimation of the area in Europe covered by soils that are vulnerable to subsoil compaction is currently an urgent requirement. This estimation is necessary to ensure that compaction is considered together with erosion and pollution by policy makers as an ongoing process of soil degradation in the agricultural and environmental sectors. The only practical means whereby areas at risk can be identified at the European level is by building links between the scheme proposed here and the European Soil Database.

The computerised geometrical and attribute data in this database provide the necessary inputs to assess susceptibility to subsoil compaction. Climatic data suitable for computing an index such as potential soil moisture deficit, however, present an immediate problem. Nevertheless, the agrometeorological data held at JRC for the MARS Project should provide a good basis for an initial attempt. Summary data on temperature, evaporation and rainfall have been produced for 50km x 50km grid squares for the whole of Europe. These data should be used to generate potential soil moisture deficits.

5. Conclusion

It is essential that land use and generalised crop cover data are included in the final vulnerability assessments. There is much more work to be done to develop an accurate system for predicting the areas in Europe most vulnerable to subsoil compaction. This paper presents a simple system that is only the beginning of this process. It would be inappropriate in presenting the results of predictions based on the European Soil Database, at this stage in its evolution, to attempt to map the relative differences between the vulnerability classes. Any prediction map should only categorise soils as either *vulnerable* or *not vulnerable*. The simplified classification indicated in Table 7 is suggested as a basis for this.

Table 7. Simplied classification of vulnerability to subsoil compaction.

Broad Class for cartographic purposes	Vulnerability class on basis of soil and climate
Not vulnerable (N)	Not particularly vulnerable
Vulnerable (V)	Moderately vulnerable
Vulnerable (V)	Very vulnerable
Vulnerable (V)	Extremely vulnerable

The system as proposed is again only a beginning for use at local field level, but it offers possibilities for immediate use with modification as necessary, together with the opportunity for incorporating quantitative stress and deformation data as subsoil research develops and results come to hand.

6. Acknowledgements

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Management of the arable layer to avoid subsoil compaction

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Abstract

Subsoil compaction in crop production with negative effects on soil functions related to: soil physical properties, plant growth and crop yield, the soil as a buffer, filter and transformer, and behaviour of soil animals as well, is a site-specific and time-specific problem on arable land. Therefore, the subsoil compaction problem has to be defined carefully, and causes, consequences and solutions have to be analysed. In light of the aim of today's crop production to be profitable and sustainable, a concept to prevent subsoil compaction by managing the arable layer to avoid such compaction is proposed. It comprises four constituents: further development of technical possibilities, adaptation of production methods, improvement of soil trafficability, and limiting of mechanical loading.

Keywords: Subsoil compaction; Best practice management; Competitive crop production

1. Introduction

The goal of agricultural soil use is to develop production methods in such a way that the least amount of energy is used and the lowest costs maintained. At the same time high yields with good product quality should be achieved without affecting the stability of the ecosystem involved and/or neighbouring ecosystems. Resource conserving production methods are directed on the one hand to maintaining and caring for natural resources (soil, water, etc.) and on the other hand, to conserving as much of the technical, chemical and biological production means and energy as possible. Ultimately, the input-output relationship is useful for evaluating production methods, whereby in addition to economic considerations, the ecological and social aspects must particularly be taken into account today. Resource conserving soil use and management is a significant principle in sustainable agriculture.

Farmers are afraid -- rightly or wrongly -- of a conflict of interests between the current quality goals of production methods in crop production: resource conserving soil use and management on the one hand, and the ability to remain commutative (meaning the reduction of production costs wherever possible) on the other.

Preventing such possible goal conflicts is a significant aspect of Best Practice Management (BPM). Guiding principles for BPM must be:
- scientifically regarded as safe
- appropriate, applicable and recognised as necessary on the basis of practical experience
- economically viable
- accessible to the user

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[1] supported by the other members of the working group 6

Best Practice Management is targeted at:
- making a significant contribution to high performance, environmentally conserving and quality assuring production methods through cost saving, soil structure preserving reduction of the mechanical disruptions of the soil;
- securing the soil fertility and performance capability of the soil as a natural resource through measures to protect the production-, control- and living space function of the soil.

Soil compaction with negative effects on these soil functions is a problem connected directly to the location, soil moisture content and techniques used in crop production. Preventative measures require – in addition to research on important details – the future development of strategies and concepts on the basis of main principles for avoidance of subsoil compaction (Chamen et al., 2000): no repeated loosening as a routine cultivation technique, increased soil stability and reduced soil stress, and selection of machines with a low risk potential.

2. Problem and definition of subsoil compaction

With the increase in performance over the past decades, the size of vehicles including tractors, loading and tank vehicles, trailers as well as combines and self driving harvesting combines for potatoes and sugar beets has increased. This powerful technology makes implementation possible in time, and allows a reduction in tracks due to increased working width. It can, however, particularly during harvesting under moist conditions, introduce more stress on the soil. The danger then exists that the soil could be compacted at a deep level.

Subsoil compaction is a special problem in crop production because no normal tillage operation loosens the soil at such depths. In this paper, the definition of subsoil compaction is used which was defined by Chamen et al. (2000):

„To achieve a universal definition, it was considered necessary to divide the subsoil into two distinct layers, namely:
Pan layer. This is the layer below the annually cultivated layer. It will vary in thickness depending on the type and severity of compaction created by either implements or wheels or both. In many instances it is loosened on a regular basis.
Unloosened subsoil. This is the layer which normally remains undisturbed by tillage operations. It is also at a depth where tillage operations would be considered to be undesirable and often uneconomic, and if carried out, would create the potential for damage. This layer may however be disturbed during drainage operations, such as mole ploughing, or may need some careful treatment if already in a severely damaged state.“

3. Principles of best practice management to avoid subsoil compaction

For soil conserving agricultural practices, four possible solution approaches can be further explored in combination with location- and farm-specific requirements toward a concept for soil conserving wheeling on arable land:
- the further development of technical possibilities
- adaptation of production
- improvement of the trafficability of the soil
- limitation of the mechanical stress on the soil

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3.1. Further development of technical possibilities

Recently, a reduction of the contact surface pressure (in the contact area between machine and soil) was given a great deal of attention. In addition to the long-known cage-wheels and twin wheels, wide and terra-wheels were introduced. The increasing contact area caused a reduction in the contact ground pressure at the same level of wheel load. This led to less soil pressure. Large volume tires can support a wheel-load of up to 5 tonnes by a contact surface pressure of 100 kPa. Newer developments are three track vehicles which distribute the total load on three or five terra-wheels across the entire width of the vehicle.

Further technical possibilities can help to lessen the problem. Included here are the regulated adaptation of inflation pressure on the condition of the passage (soil, road), the use of semi-mounted implements instead of mounted implements to reduce the rear axle stress of the tractor (for example, pulled sprayers) as well as four-wheel drive and low wheel slip. Rubber band drives should be further developed and offered at low cost. For ploughing, plough robots with fewer plough bodies (meaning lower wheel load) must be developed that can be used without a tractor driver and allow longer usage times (high use with positive soil conditions).

3.2. Adaptation of production methods

The following summarises the known and developing possibilities:
- combination of work processes
- on-land ploughing
- „track free" work practices (basic soil tillage and seeding in one work process)
- to lead striking force (passing over fields when the soil is dry)
- use of hydraulic drives instead of pulled implements (reduced traction)
- summer furrow instead of winter furrows (soil conditions)

New approaches could range from controlled traffic better concepts, as used in horticulture, through to controlled-traffic systems for which the newest global positioning systems (GPS) are available. Tram line systems can be used in other areas and not only in cereal cropping, and pit ploughing as well as mechanical alternatives (plough robots, etc.) can be implemented.

3.3. Improvement of the soil traffickability

Field tests have shown, that conserving soil loosening at the topsoil depth is possible (with a Para-plough or chisel plough) without yield losses as in comparison to conventional ploughing. The lesser disturbance to the soil makes a re-compaction unnecessary and succeeds with a non-turning crop sequence specific soil-loosening (principle of conversation tillage). If a cover crop is cultivated between two main crops, the best time for sowing is under dry conditions. This practice makes increased demands on the farm management.

Conserving soil-loosening helps to prevent compaction damage – particularly in subsoil – and results in better traffickability. This is illustrated with the example of calculated pressure bulbs. This reaches its deepest point in ploughing with high wheel load and a significantly lower depth, if the tractor tires are running on the soil surface and the soil can carry more load as a consequence of non-turning, crop-sequence specific (about once every three years) soil loosening. This helps to save costs of expensive soil tillage and investments (the use of high performance and tractors on several farms).

3.4. Limiting the mechanical load

The truly critical point for soil-conserving traffic rests with the increasing wheel load in plant production. Limits must be set in the case of compaction-sensitive soil conditions. It is difficult to set a reliable limit for the mechanical stress resistance of soil because of the regularly changing soil moisture in the topsoil as well as in the subsoil. Compaction damage can be expected with higher moisture levels, and can be recognised by the farmer only through the track depth. A contact free measurement technique to evaluate soil changes under the wheel during trafficing must be developed.

The technical possibility of changing from narrow tires to broad tires helps from the perspective of soil conservation only when the wheel load is not simultaneously increased. Indeed, the tendency to increase wheel load is not in the interest of a preventative soil protection, especially in the subsoil, if compaction-sensitive conditions prevail during driving with high wheel loads. In the interests of soil protection, in addition to consideration of wheel load, tire choice and inflation pressure, more consideration must be given to the current traffickability of the soil.

The total amount of today's sugar beet technology of harvesting up to 50 tonnes, combined with poor soil and weather conditions, as well as frequent passage of the harvesting machines and transport vehicles, raises a serious question of subsoil compaction. For this reason, special studies of practical equivalents have been carried out in this area over the past five years. The results to date provide the following additional solution approaches to the already mentioned principles:

- Five wheel or rather buckling hinge machinery used together with terra tires.
- Modern head systems make possible the harvesting of sugar beets from one side
- Planting of the following crop (i.e., winter wheat) directly next to the harvester without any soil tillage.

4. Conclusion

In order to prevent subsoil compaction damage in the interest of an environment-conserving land use, and to reduce costs in the interests of competitive agriculture, the four recommended solution approaches build a practical overall concept (s. Figure).

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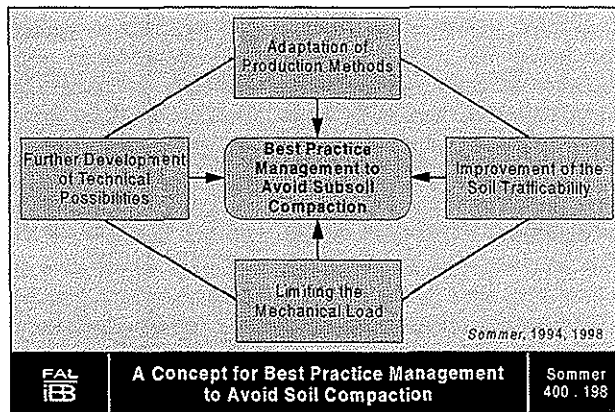
This concept can provide a significant contribution for an environment-conserving use of the soil in agriculture when the individual principles are put together in accordance with the individual location, crop sequence and farm needs. The use of these principles can ensure a cost-saving plant production while at the same time avoiding subsoil compaction damaging side-effects of agricultural production practices.

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Prevention of field traffic induced subsoil compaction

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Abstract

Field traffic induced subsoil compaction is discussed to determine the variables important to the prevention of the compaction capability of running gear. Likewise, technical choices to minimize the risk of subsoil compaction are reviewed. The risk of subsoil compaction is high when moist to wet soils are loaded with high wheel load traffic or with moderate to high ground contact pressure respectively. The most serious source of subsoil compaction is tractor wheels running in the open furrow during mouldboard ploughing. To prevent subsoil compaction, recommendations for wheel load-ground pressure combinations in different soil conditions based on quantitative guidelines for machinery-soil interactions should be available.

Keywords: average ground pressure, axle load, inflation pressure, subsoil bearing capacity, wheel load

1. Introduction

The effects of subsoil compaction have been documented to be long-lasting (more than 5 years, Blake et al. 1976, Pollard and Webster 1978, Etana and Håkansson 1994, Alakukku 1995) and difficult to correct (Kooistra and Boersma 1994). It is better to avoid subsoil compaction than to rely on alleviating the compacted structure afterwards. The subsoil-machinery –system includes several variables and processes (Fig. 1). Before recommendations to avoid subsoil compaction can be given, the key variables and processes involved in the system must be known and understood. In the present paper the prevention of field traffic induced subsoil compaction is discussed with the following objectives:
(1) to determine the variables controlling the risk for subsoil compaction induced by field traffic
(2) to identify those field operations that have a high risk for subsoil compaction
(3) to discuss the existing technical recommendations to avoid subsoil compaction
(4) to evaluate the need for further development of machines to reduce or avoid subsoil compaction

In the present paper, we concentrate on the soil/running gear interaction and technical solutions to control the risk of subsoil compaction. Chamen et al. (2000a,b) discuss more detailed equipment and field practices to avoid subsoil compaction. Likewise, Spoor et al. (2000) examine subsoil vulnerability and Sommer et al. (2000) asses the benefits that might be achieved by topsoil management. This paper is a part of the activities of the Working Group 'Equipment selection and field practices for the control of subsoil compaction' set up within a European Union Concerted Action 'Experiences with the impact of subsoil compaction on soil, crop growth and environment and ways to prevent subsoil compaction' (contract N°FAIR 5 CT97 3589).
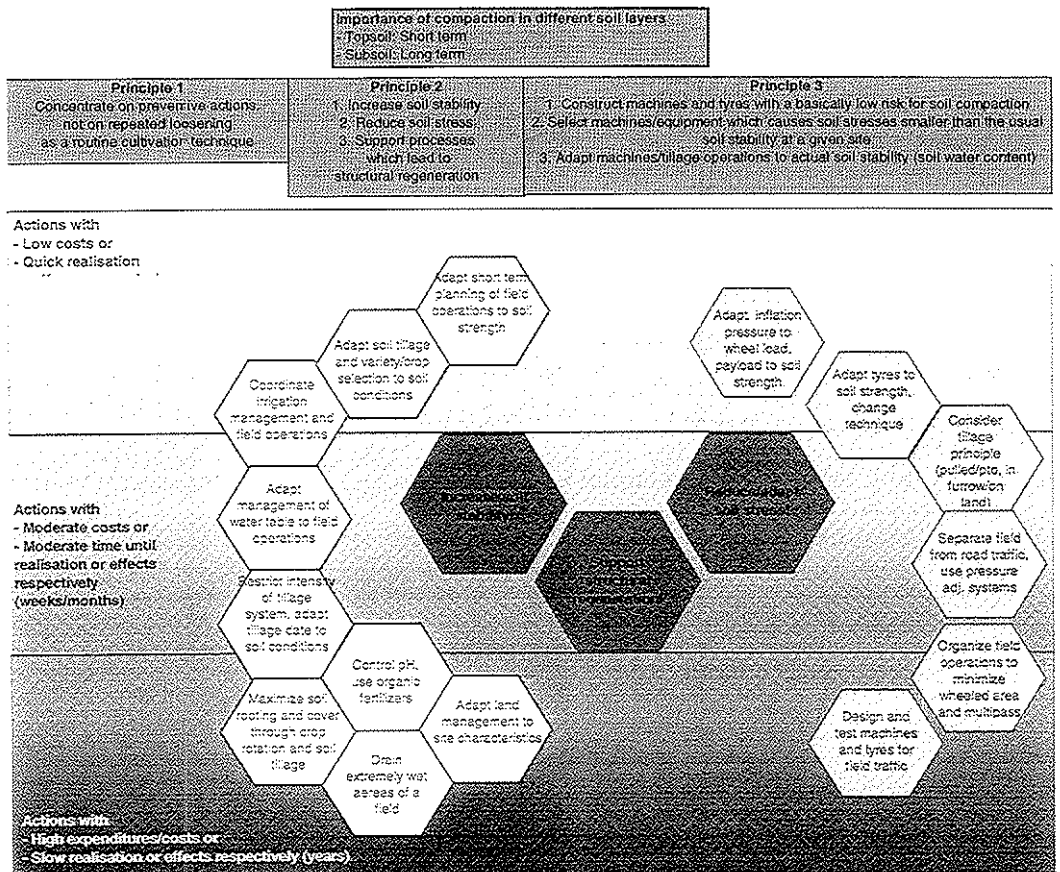
Fig. 1. A framework of soil-machinery –system in connection with subsoil compaction.

2. Subsoil-field traffic –system

Subsoil-field traffic –system may be divided into two main variables: soil bearing capacity and soil stress caused by field traffic (Fig. 1). Subsoil bearing capacity means the capability of a soil structure to withstand stresses induced by field traffic without changes in the three-dimensional arrangement of its constituting soil particles. The existing research work on the effects of different variables on subsoil compaction is reviewed. Variables changing during the growing season and variables which are affected by the choices of the farmer are focused.

2.1. Subsoil bearing capacity

Different parameters have been used to assess soil bearing capacity and the susceptibility of soil for plastic deformation. Constitutive soil properties like texture, organic substance, structure, bulk density as well as soil moisture status, which are indirectly related to soil strength, have been used as classifying parameters to qualitatively predict soil stability (e.g. Anonymous 1997, Spoor et al. 2000). To quantify bearing capacity as trafficability directly in the field, cone penetrometer technique has been used (Paul and DeVries 1979). Also soil consistency (the Atterberg parameter "plastic limit" and "liquid limit") as well as parameters of the Proctor test ("critical moisture content") have been used to predict the susceptibility of soils for compaction (Mapfumo and Chanasyk 1998). In order to get direct measurements of soil strength and to model the interactions between vehicles and soil

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quantitatively, parameters have been adapted from geotechnical engineering. Of special interest were parameters of compaction and shear testing, as precompression stress, angle of internal friction, cohesion. Based on data sets of arable soils with different properties, quantitative prediction of subsoil bearing capacity (expressed as precompression stress) became feasible by using pedotransfer-functions for calculating precompression stress from constitutive soil properties (DVWK 1995). Data sets of field measurements on arable soils in Central Europe (e.g. Horn et al. 1989b, Nissen and Horn 1996) showed considerable differences (factor 5 and more) between preconsolidation stresses of different soils. Accordingly DVKW (1995) divided soils (or soil horizons respectively) into 6 classes from <30 kPa up to > 150 kPa, depending on their precompaction stress. Additional to this effect of soil type and soil constituents, also soil moisture status influences the precompaction stress.

Taking into account the process of stress distribution in a layered soil profile, compacted layers such as plough pans can – by their high mechanical stability – influence the stress distribution so that subsoil layers beneath them are protected from high stresses by a strong compensation of stresses (Wiermann et al. 2000).

Because the strength of soils as a measure for soil bearing capacity depends also on aggregation and because development of soil structure is influenced by natural and anthropogenic factors, values for precompaction stress and therefore also for bearing capacity are the result of individual stress histories of a soil and have therefore to be deducted for clearly defined situations consisting of site characteristics and cultivation practices.

2.2. Characteristics of machines

2.2.1. Total load, axle load, wheel load

The changes in agricultural production techniques in industrialized countries over the past few decades have been dramatic. The increased cost of labour and the need to maintain farm income at a stable level have encouraged the formation of larger farms and more intensive and specialized production on a wide range of soils. This has led to the continuous increase of machinery power and weight and implement size. For instance, in Germany, the proportion of newly registered tractors larger than 44 kW increased from 33% to 77% between 1976 and 1992 (Renius 1994), and the average tractor weight increased from 1.4 Mg to 3.3 Mg between 1958 and 1981 (Bolling and Söhne 1982). In Finland, the proportion of newly sold tractors larger than 61 kW increased from 8% to 66% between 1976 and 1996. In the same period the proportion of tractors weighing more than 4 Mg increased from 2% to 43%. In recent years, the number of large tracked tractors which weigh more than 10 Mg have increased in Western Europe. Even the total weight of power units has increased, the power/weight –ratio has decreased. During the last decades, 4-wheel drive tractors have replaced 2-wheel drive tractors. Thus, the static axle and wheel loads have probably not increased in proportion to total loads.

The heaviest loaded combine harvesters may be more than 25 Mg and slurry tankers may weigh more than 30 Mg (Håkansson and Petelkau 1994). Likewise, six-row self-propelled sugar beet harvesters are increasingly used. Fully loaded the weight of two axle harvesters is about 35-40 Mg and three axle harvesters up to 50 Mg or even more. The weight distribution between axles and wheels depends clearly on the construction of the machine.

Above static axle/wheel loads were discussed. During the field operations, the weigh distribution may, however, vary clearly between axles and wheels on the same axle depending even on the degree of the loading of tank or weight transfer during ploughing. Thus, the dynamic wheel loads are more important when the effects of load on subsoil compaction are discussed.

2.2.2. Contact area and average ground contact pressure

Running wheel/track represents the link between machine and soil. The tyre/track contact area is the portion of the tyre/track in contact with the supporting surface. The average ground contact pressure (wheel load divided by ground contact area between tyre and surface) estimates the average value of the vertical stress in the tyre/track- soil contact area. Measurements of contact area stress distribution in the contact area are, however, complicated which is one reason for the need of simplistic approaches. Contact area estimations based on wheel parameters have been given. For instance, McKyes (1985) proposed to estimate tyre contact area on rigid surface by multiplying the tyre section width by overall tyre diameter and dividing the product by 4. On a deformable surface, the wheel contact area is, however, always larger than on a rigid surface. Burt et al. (1992) and Tijink (1994) offer a detailed examination of the determination of contact pressure.

The ground contact pressure is often evaluated from the tyre inflation pressure. The relationship between the average ground contact pressure and the inflation pressure of a tyre depends, however, on tyre stiffness and soil conditions. For stiff agricultural tyres, tyre walls carry a considerable proportion of the total load, and on rigid surfaces stress in the contact area, especially peak values of profiled tyres are considered higher than the inflation pressure (Plackett 1984). Burt et al. (1992) found that the dynamic average ground contact pressure below an 18.4R-38 tractor tyre on rigid soils was closely approximated by the inflation pressure, whereas on non-compacted soils the contact pressure was clearly lower than the inflation pressure. The average contact pressure on a rigid surface is a measure for the deformability of the tyre, while average ground pressure on soil is a measure for the deformability of the soil (Tijink 1994).

The average ground contact pressure denotes the calculated average value of the vertical stress in the tyre/track –soil contact area. The pressure is not, however, uniformly distributed over the contact area. Pressure distribution beneath the wheel is complex because of the tyre lug patterns and of tyre construction (stiffness of the carcass, etc.). Thus, the maximum ground contact pressure under lugs or stiff tyre walls may be several times (four to ten) the estimated average ground pressure (Smith 1985, Burt et al. 1992, Gysi et al. 2000). Likewise, the ground contact pressure under a track will concentrate under the jockey wheels (Wong 1986). It is believed that the effect of the unevenness is limited to the upper part of the soil profile. Measurements of Gysi et al. (2000) showed that at a depth of 0.30 m, the influences of stress-distribution in the contact area due to the tyre profile have changed to a generally recognizable stress distribution, with high pressures concentrated around the vertical on the loaded area. Likewise, the uneven pressure distribution below a tyre running in the furrow during ploughing may introduce high peak pressures into the subsoil. Rüdiger (1989) calculated the vertical stress below tyre contact areas while driving in the plough furrow. He found that the stress was clearly less in the upper part of subsoil when the ground pressure was uniformly distributed over the contact area compared to the situation when the tyre lugs carried the load.

2.3. Stresses applied to soil by running gear

Under practical field conditions stresses in soil caused by trafficking are not constant, but – depending on properties of soil, topography, machinery and tyres – are changing in their extent and direction. Static loading with constant vertical normal stress is a simplified idealization of a much more complex process.

2.3.1. Stress components

During field trafficking, vertical and horizontal stress components as well as shear forces in the soil are caused by the profiled, moving and deflecting tyre. Under the rolling tyre wheel load and stress distribution in the contact area are permanently changing due to accelerating/braking of the tyre, and changing payload and uneven soil surface. Even the direction of horizontal stresses changes

depending on whether a wheel is approaching or leaving (e.g. Bakker et al. 1995, Weisskopf et al. 2000). The resulting stress path is decisive for the effects of loading on soil structure. Stress paths with strong changes in the direction of stresses will lead – depending on the stability of soil – to kneading and shearing of soil, as can be shown by tracing the displacement of soil particles (Wiermann et al. 2000). The shear effect is expected to vanish rapidly with depth (Koolen et al. 1992). The shear stress can, however, damage the subsoil markedly, especially during ploughing, owing to furrow wheel slipping. Davies et al. (1973) suggest a slip maximum of 10% to avoid topsoil damage owing to shear. The same limit is probably appropriate for subsoils.

Additionally to these stresses with changing periods of tenth of seconds to seconds, stresses with very short loading/unloading cycles ("vibrations") can be transferred to soil. The contribution of vibration effects to the soil compaction below running gear has seldom been documented for arable soils (Soane et al. 1981). Vibration is, however, evaluated to be unimportant in relation to subsoil compaction. With stress distributions normally occurring in soil, intense detrimental effects on soil structure caused by high frequency loading changes, or the reversal of stress direction will be restricted to topsoil layers. An exception is the extreme combinations of mechanical loading and soil stability, which can even influence subsoil layers (Weisskopf et al. 1998), e.g. large and highly loaded contact areas on the surface of weak soils (as for heavy harvesters or transport vehicles on wet soils), or highly loaded contact areas acting directly on deeper layers of weak soils (as for conventional in furrow ploughing).

When the velocity of a machine is increased, the duration of the loading is reduced. Bolling (1987) measured the effects of velocity on the maximum soil stress below a wheel centre with two wheel loads (0.82 Mg, tyre inflation pressure 160 kPa and 1.5 Mg, 170 kPa) on sandy loam soil and found that an increase in velocity from 2 km h^{-1} to 10 km h^{-1} decreased stress at 0.30 m depth below the wheel centre. The effect of velocity was greater on loose than on dense soil. Similar results were reported by Horn et al. (1989a). An increase in velocity seems to reduce the stress transmitted to upper subsoil layers. The effects of velocity on the stress in deeper layers and the practical importance of velocity to subsoil compaction have seldom been documented, however. The highest velocity tested has been 8-12 km h^{-1}, which is the normal speed in field operations.

2.3.2. Extent of stresses

In unsaturated soil, stresses are transmitted three-dimensionally via solid, liquid and gaseous phases. The analytical models for the propagation and distribution of stresses in the soil still mostly describe the stress distribution under a point load or a loaded area acting on a homogenous, isotropic, semi-infinite, ideal elastic medium. The theoretical solution was proposed by Boussinesq in 1885 (cited by Söhne 1953). Fröhlich (1934) later modified the original solution by introducing an empirical concentration factor to account for the increase in Young's modulus with soil depth due to overburden stress. Söhne (1953, 1958) and Koolen and Kuipers (1983) review the equations that describe stresses on a soil element.

By changing the value of concentration coefficient, the stress distribution in the model body is changed from confining stresses to the upper part of so called „hard soils" (with rather spherical isobars) to a stress distribution concentrated along the stress axis and reaching deeper into „soft soils" (with rather longish isobars). Horn et al. (1987) reported that the concentration factor depends on the moisture content, density, load history, structure and texture of the soil. Unfortunately, this coefficient cannot directly be related to real-soil properties; based on direct measurements of normal stress in soil it can be calculated with the procedure of Newmark (DVWK 1995).
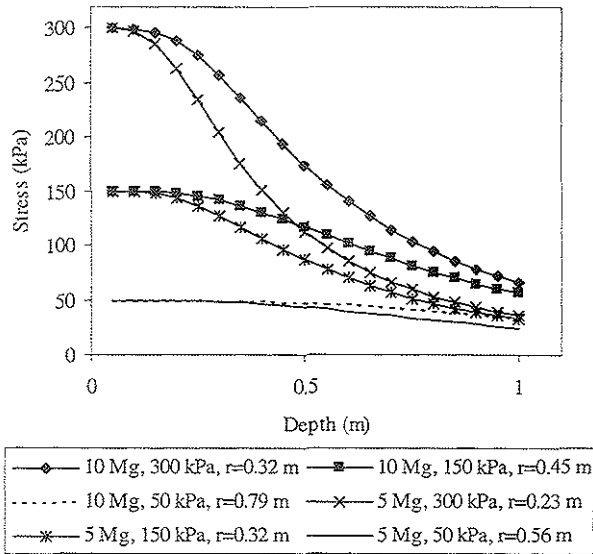
Fig. 2. Calculated vertical normal stress (σ_z) as a function of depth (z) beneath the centre of a circular and uniformaly loaded ground area. Equation (Söhne 1953, 1958): $\sigma_z = p(1-\cos^\gamma\alpha)$; p, average ground contact pressure acting on the tyre-soil contact area; γ, concentration factor (here 5); α, half aperture angle between the point at depth z and the contact area's edge; Mg, wheel load, kPa, average ground pressure; r, radius of the circular contact area.

The analytical solution shows that the stress in the soil under a loaded wheel decreases with depth (Fig. 2). From this, a highly simplified conclusion can be drawn: the stress in the topsoil depends on the average ground contact pressure, but the stress in the subsoil is determined mostly by the wheel load (Söhne 1958, Carpenter et al. 1985). Hadas (1994) and Olsen (1994) criticize this generalization, however. On the basis of analytical calculations, Olsen (1994) concludes that the decrease of induced vertical normal stress with depth in the upper subsoil (0.10-0.30 m to 1 m depth) depends on both ground contact pressure and wheel load, and below 1 m solely on wheel load. Based on the equation used in the Figure 2, the wheel load determines the normal stress level deep in the soil profile, but the stress level will never exceed the maximum ground contact pressure level.

From the analytical solution and experimental results the following conclusion can be drawn on the effects of wheel load and contact pressure on the soil stress:
1) As the same tyre and contact area is loaded with a higher wheel load, the stress at a specific depth increases and a given stress is transmitted (Danfors 1974).
2) When the wheel load is increased, even though the contact pressure is kept unchanged by increasing tyre dimensions or the number of tyres (dual, triple), a given isostress is transmitted deeper into the soil and a greater soil volume is stressed, as long as there is an interaction between the stress distribution below the contact areas of the additional wheels (Fig. 2, Lebert et al. 1989, Hadas 1994). Olsen (1994) pointed out that the extent of a given isostress may, however, be reduced by spacing the tyres widely apart to avoid any interaction between them. In this case the contact areas of the additional wheels will act as separate – smaller - contact areas with improved stress compensation.

According to *in situ* stress transmission measurements by Lebert et al. (1989) vertical stresses can be reduced in the topsoil by using larger tyres (lower inflation pressure, larger contact area) with constant wheel load. In the subsoil the reductions due to decreased ground pressure are, however, less

significant (Lebert et al. 1989). Likewise, Danfors (1994) reported that a reduction in inflation pressure from 150 to 50 kPa (axle load > 8 Mg) reduced the compaction of moist clay soils only down to a depth of 0.30-0.40m, not in the deeper layers. In summary it can be stated that risk of subsoil compaction exists whenever a moist/weak soil is loaded by moderate to high ground contact pressure on a large contact area, i.e. with a high wheel load.

2.4. Number of passes and cumulative effects of stresses

The number of passes affects the number of loading events and the coverage, intensity and distribution of wheel traffic. When a vehicle has been converted to low wheel load and ground pressure by increasing the number of wheels that follow the same track, average ground pressure is lower, but the number of wheel passes higher. Because of the multi-pass effect, this wheel arrangement would be less efficient in avoiding high levels of compactness in the topsoil than wide tyres and dual wheel arrangement. The repeated number of wheel passes may also increase the risk of subsoil compaction. Wilde (1998) measured soil stress at 0.10, 0.15, 0.25 and 0.40 m depth in marshy soil. He found that when the number of passes was increased in the same track soil stress at 0.40 m depth increased. During the first pass the stress was 60 kPa and during the fourth pass 200 kPa. Likewise, the compactness of mineral subsoils (Gameda et al. 1987, Schjønning and Rasmussen 1994, Alakukku and Elonen 1995) and the depth of the compacted layer (Sommer and Altemüller 1982, Alakukku 1996) were found to increase as the number of passes in the same track increased.

The alleviation of the effects of severe subsoil compaction takes many years, if it occurs at all. The annually repeated traffic may cause cumulative effects when the effects of earlier subsoil compaction have not disappeared before new loading. The area of compacted subsoil may increase year by year due to random field traffic. The effects of subsoil compaction may thus become more harmful as time goes on even though the effect of a single pass by a heavy vehicle tends to be rather small (Håkansson 1994).

2.5. Stress/strain equations

Boussinesq's half-space model for homogeneous isotropic elastic media as well as its extension by Fröhlich for elasto-plastic behaviour of a media did not principally allow for estimations of soil strain. This restricts it's use to a semi-quantitative assessment of stress distribution in soil without the possibility to get quantitative information about effects on soil structure.

With the coupling of a purely statistical model to predict the precompression stress of soils and the analytical model of Boussinesq/Fröhlich to estimate the stress distribution in soil, DVWK (1995) offered a quantitative decision tool for assessing the risk of deformation of a given soil structure as a consequence of field traffic. Later work extended this tool with the possibility to assess the effect of soil stress on soil structure by assuming relationships between predicted plastic deformations in the load range of virgin compression behaviour and associated changes in physical properties of soils (DVWK 1997). O'Sullivan et al. (1999) presented a simplified model to explore the stress/strain-relations between machinery and soil factors governing compaction processes. On the stress distribution side they used the same fundamentals as DVWK, whereas soil strength was described with the empirical concentration factors, and the consequences for soil structure were expressed by specific volume as an indicator for the compactness of soil.

With critical state theory it has become possible to interconnect stress and strain as a process directly in (even layered) soils by using finite element models (Horn et al. 1998). Based on soil mechanical properties from compression, shear or triaxial tests respectively (Kirby 1994; O'Sullivan and Robertson 1996, Kirby et al. 1998), these models allow calculation of stress distribution and the

Table 1. High risk operations for subsoil compaction categorised under crops and summarised for returns from Finland, Germany, Portugal, Switzerland and the United Kingdom (Chamen et al. 2000b). The separate tables of each country are given in Chamen et al. (2000a).

Ploughing (in furrow) or Cultivating	Subsoiling	Bed-forming	Harvesting		Organic fertiliser application
			Harvesters	Trailers	
Ploughing <Sugar beet> <Potatoes> <Grain maize <Spring cereals <Onions> *Cultivating* <Sugar beet <Potatoes <Spring cereals <Onions	Sugar beet> Potatoes>	<Vegetables	Roots Fresh peas Early cutting for silage or fresh fodder crops Combinable crops, e.g. wheat, barley, oats, grain maize, oilseed rape, linseed, beans, peas	Roots Tree fruits	All crops

<just before crop sowing
>just after crop harvesting

resulting strain (as void ratio or total porosity) in 2D layered soil profiles (corresponding to an infinite loading area in x-direction). They may also be used in 3D-space (providing the loading area is defined in y- and in x-direction). In contrast to fully elastic or analytical elasto-plastic models critical state theory makes it possible to take elasto-plastic reactions of soils (volume decrease, compaction or volume increase, softening) into account. Additionally it allows for calculations of the influence of defined loading events on soils with defined mechanical properties, i.e. quantitative predictions of the risk of damage to soil structure as durable, plastic deformations. Although originally developed for saturated soils, efforts have been taken to extend its use also to unsaturated soil conditions (Horn et al. 1998).

With the intention of extending the possibilities of describing the three-phase soil medium, complete multiphase models have been developed. These couple the state and characteristics of the three phases fully, i.e. any change in water content will affect not only the mechanical, but also the hydraulic properties of a soil structure, for example (Klubertanz 1999). Considering both dynamic and hydraulic loading, soil deformation caused by wheel load as well as by weather-induced changes in soil moisture content can be simulated. In this way, effects such as strength increase parallel to suction increase, structural collapse as a consequence of wetting the soil or increasing brittleness of a drying soil structure can be considered.

3. Critical field operations

Table 1 shows the summary of the critical operations listed by Chamen et al. (2000a,b). Chamen et al. (2000a) provide the definitions necessary for the Table 1 and the separate tables for each country. There are clear differences between countries in the high risk operations depending on the main crops grown and weather conditions. In Finland, for instance, the seedbed preparation of spring sown crops is classified as moderate to high risk operation since at the time of sowing the subsoils are often wet after the frost has thawed in spring.

The risk of subsoil compaction is high when moist to wet (i.e. weak) soils are loaded with high wheel load traffic with moderate to high ground contact pressure (Table 1). The most serious source of subsoil compaction is the tractor wheel running in the open furrow during mouldboard ploughing. The tractor wheel runs directly on the upper part of the subsoil. Tijink (1994) calculated vertical

Table 2. Recommendations for maximum average ground contact pressure and vertical soil stress at 0.50 m depth in different soil conditions to prevent soil compaction in arable fields, meadows and pastures (Rusanov 1994).

	Ground contact stress (kPa)		Stress at 0.50 m depth (kPa)	
Soil	Spring	Summer/ Autumn	Spring	Summer/ Autumn
Clay				
MC > 90% of FC[1]	80	100	25	30
MC 70-90% of FC	100	120	25	30
MC 60-70% of FC	120	140	30	35
MC 50-60% of FC	150	180	35	45
MC < 50% of FC	180	210	35	50
Sand, Sandy loam				
MC > 90% of FC	95	120	25	30
MC 70-90% of FC	120	145	25	30
MC 60-70% of FC	145	170	30	35
MC 50-60% of FC	180	215	35	45
MC < 50% of FC	215	250	35	50

1) moisture content (MC) of field capacity (FC)

soil stress under low ground pressure tyres. According to his calculations, the stress caused by a wheel carrying 2 Mg load and having an average ground pressure of 80 kPa in the plough furrow was greater in the layer of 0.30-0.70 m than a tyre on soil surface with 5 Mg wheel load and 60 kPa ground pressure. Also, subsoiling is found to be a critical operation as discussed by Chamen et al. (2000a). Deep loosening reduces soil strength clearly, and loosened subsoil may be recompact easily.

4. Stress and wheel load recommendations

With the aim of avoiding soil compaction, recommendations have been given for maximum values of average ground contact pressure (Rusanov 1994, cf. Table 2). These are combined with soil conditions by giving separate recommendations for spring (soil moist/weak) and summer/autumn (soil stronger than in spring, Table 2). Petelkau (1984) recommended that on sand, loam and clay soil the ground pressure should not exceed 50, 80 or 150 kPa respectively, in spring. In autumn (soil moisture content < 70% of field capacity), the ground pressure recommendations were 80 (sand), 150 (loam) and 200 (clay) kPa (Petelkau 1984). Vermeulen and Klooster (1992) propose a maximum level of 50 kPa in spring and 100 kPa in autumn for ground pressure. When the moisture content of mineral soils was higher than at field capacity, ground pressures not exceeding 40-50 kPa have been recommended (Bondarev et al. 1988, cited by Lipiec and Simota 1994).

The ground pressure recommendations above are given to avoid soil compaction in the topsoil. Carpenter and Fausey (1983) suggest that the maximum ground contact pressure with high wheel loads should not exceed the stress allowed in the subsoil. Rusanov (1994) reported official standard values of maximum permissible normal stress at a depth of 0.5 m (Table 2). He gave also maximum ground pressure levels which were clearly higher than the allowable stress in subsoil (Table 2). Few data exist, however, to allow assessment of the maximum allowable subsoil stress in different conditions, and this area should be addressed in future studies. However, the allowable subsoil stress may be evaluated by looking at the stress history of subsoil.

From a practical point of view it is relevant that the recommendations for ground contact pressure are close to the recommendations for the maximum tyre inflation pressures, as given by Dwyer (1983, 50

kPa for moist soil, 100 kPa for dry soil) and Perdok and Tijink (1990, 50 kPa for moist soil, 250 kPa for dry soil). Relevant to this, Söhne (1953) already recommended a maximum inflation pressure of 80 kPa in the early 1950's.

To avoid soil compaction below normal primary tillage depth (0.2-0.3 m), single axle loads not exceeding 4 to 6 Mg have been recommended for moist mineral soils (Danfors 1974, 1994, Voorhees and Lindstrom 1983, Petelkau 1984) even when the tyre inflation pressure is 50 kPa (Danfors 1994). For tandem axle loads on moist soils Danfors (1974, 1994) proposes a limit of 8-10 Mg (total load).

We criticize the use of axle load recommendations in connection with the prevention of subsoil compaction. Recommendations need to be set with a view to the most critical conditions prevailing during the normal use of a machine. At least gross/axle weight recommendations should be related to soil conditions prevalent during wheel operation. Otherwise the recommendations could be too theoretical and not adapted to real situations. Likewise, the weight distribution may vary markedly between wheels on the same axle. Thus, we prefer to use wheel load instead of axle load and to combine wheel load and ground pressure recommendations. The ground pressure is combined with wheel load, since the wheel load alone does not give any information about the stress level transferred to the soil and the corresponding stress distribution in the soil. To prevent subsoil compaction, recommendations for wheel load-ground pressure combinations in different soil conditions and for different field operations (wheels running on surface vs. in open furrow) should be available. True regulations which account for the interactions between machinery and soil (e.g.DVWK 1995) would, however, be better than general recommendations.

5. Technical solutions to prevent subsoil compaction

The fundamental principle of subsoil protection is to prevent structural deformation and not to alleviate existing compaction. The basic idea of prevention is to avoid irreversible plastic deformation; this is often interpreted as a general conservative attitude against change of the existing soil structure. Quantitative models to describe the interaction of tyre and soil over a broad spectrum of different conditions are sparse. With the DVWK-model (DVWK 1995) a comparison between soil stability (expressed as precompression stress) and soil stress (expressed as vertical stress under the center line of the contact area) was proposed. A differing approach was chosen by Matthies (1998), who presented a computer-based information system as decision-making tool for the use of forest harvesters. This system gives values for soil moisture which allow the use of vehicles with known specifications (wheel loads, tyres) on given soils without a high risk of soil compaction.

Based on the data reviewed we conclude that limitations of the average ground pressure and wheel load can be considered to be the major engineering tools for the control of subsoil compaction. In the following sections we suggest ways of choosing machines and of adapting them to low subsoil strength, as just one part of the process of the prevention of subsoil compaction. Besides that the general planning of cultivation practices and the organization of field operations are important (Fig. 1). Chamen et al. (2000b) discuss the equipment and field practices to avoid subsoil compaction.

5.1. Wheel/track load

The weight of a tractor is largely associated with the draught force which it must develop to pull an implement. Similarly, the draught load and tractor traction control system will effect the dynamic loading on the front and rear axles. In theory, the control system should maximise the tractive efficiency of the combination of tractor and implement by transferring load from the implement onto the tractor. As this weight transfer also includes an element of draught load, the loading on the axles will be constantly changing and difficult to predict. Setting minimum tyre pressures in this situation cannot therefore be very precise and new monitoring and control systems that average dynamic loads and adjust inflation pressures on the move should be encouraged.

In critical conditions, wheel loads can be temporarily reduced by using only a proportion of the loading capacity of a combine harvester or trailer. Load distribution between axles may also be shared by using weight transfer facility (Tijink 1994). Likewise, wheel load can be reduced by dividing the total load between two or more axles instead of one. The axles/wheels should be spaced apart to avoid any interaction between them as described by Olsen (1994). Multi-pass effects may, however, reduce the advantage of several axles as discussed in 2.4. To avoid multi-pass effect, sugar beet harvesters and slurry spreaders having hydraulically extending axles should place one pair of wheels out of line with the wheels on another axle. The multi-pass effect can be avoided by using this management but the wheel tracks cover a larger area. The first pass of a wheel/track has been found to compact topsoil relatively more than the following passes in the same track. If one pass with a wheel already causes harmful subsoil compaction effects the advantages of the extending axle may be questionable.

To control the wheel loads of heavy machinery, the fly weighing possibility would be useful. Likewise, the testing procedure of a machine should include information about dynamic wheel loads and their changes during the pulling or filling process. The procedure would also determine the properties of the standard tyres used on the machine (e.g. width, inflation pressure with different loads and speeds, tyre deflection on rigid surface with different loads), standard ground pressures and standard soil stresses in different depths.

5.2. Tyre inflation pressure

When the tyres are selected, the technical solution will depend on the demands of the given/designed machine, the wheel load and the field operation in which a machine is used. The tyre inflation pressure should always be the lowest allowable in the prevailing situation (tyre loading capacity, velocity, traction). Ground pressure distribution in the tyre-soil contact area should be uniform. Thus, the tyre should adapt to soil properties without high peak stresses due to stiff carcass construction. Ground contact pressure prediction based on easily measurable parameters should be available. Likewise, a European testing station for tyres would provide information on contact pressure in relation to tyre inflation pressure in different soil conditions.

Low tyre inflation pressure usually provides low ground pressure and allows even ground pressure distribution. These are advantageous to both soil compaction caused by wheel traffic and to wheel tractive efficiency. When wheel load can be measured, the right tyre inflation pressure can be determined easily by using specifications given by tyre manufactures. If a weighbridge is not available the right inflation pressure can be determined simply by using the specifications and measuring the loaded radius of a wheel as described by Chamen et al. (2000b). Tyres have different requirements for field traffic and road travel: driving on the road requires high inflation pressure but in the field, the inflation pressure should be low. Usually the inflation pressure is a compromise between the road and field requirements. With a central tyre inflation system it is possible to control ground pressure in the field and on the move, so this system should be used more extensively, especially on vehicles with highly loaded large contact areas.

The inflation pressure may be reduced by increasing the size of a single tyre (width or height or both), or by dividing the load among several tyres (dual, triple) or several axles. Radial tyres, which are now generally fitted as standard, are flexible and their deflection increases the contact area, especially on a firm surface, in that way reducing the average contact stress. Low profile tyres with radial carcass construction are now available. These tyres allow low inflation pressure (below 50 kPa) without high contact pressure below the tyre side walls. On the other hand, Koolen (1994) pointed out that increasing use of low tyre inflation pressures gives farmers easier access to soft terrains, so that in future plastic flow type soil behaviour may occur more frequently. For detailed discussion of tyre factors see among others Tijink (1994) and Tijink et al. (1995).

5.3. Tracks

Tracks can give a large ground contact area. Rubber-belt tracks remove many of the disadvantages of steel tracks (Erbach 1994). However, Marsili and Servadio (1996) reported that steel tracks compacted the soil less than rubber tracks (tractor weight 3.8 Mg). Below the rubber tracks the distribution of contact pressure was more uneven than below steel tracks. The edges of the rubber track were flexible and stress concentrated below the centre of the track (below the jockey wheels). A track consists of a number of rigid jockey wheels running over a moving surface. Each track jockey axle creates a pronounced stress pulse (Blunden et al. 1994). Without an implement, the pulses are relatively uniform from front to rear. When pulling an implement the stress pulses increase clearly from the front idler to the rear driven wheel on the track system.

Bashford et al. (1988) and Rusanov (1991) found that track tractors compacted the soil less than similar wheel tractors. On the other hand, Brown et al. (1992) found that rubber-belt tractors (average ground contact stress 40 kPa) compacted the soil at 0.13 m depth as much as wheel tractors with 125 kPa ground contact stress. Similar results were reported by Wolf and Hadas (1984) and Evans and Goven (1986). Blunden et al. (1994) loaded sand soil with a track tractor (weight 15 Mg, average ground contact stress 58 kPa) and a wheel tractor (18 Mg, 74-81 kPa). They found that even though the track tractor exerted less normal stress on the soil than the wheel tractor at 0.40 and 0.50 m depth, the penetrometer resistance of a sand soil at 0.40 m depth was 1.51 and 1.48 MPa when track and wheel tractor were used, respectively. There were no differences in resistance at 0.50 m depth.

Based on the results discussed above, it is difficult to draw any conclusions about the advantages of tracks compared to tyres to avoid subsoil compaction. Olsen (1994) calculated the stress distribution below circular (tyre) and rectangular (track) contact areas. He found that the vertical normal stress decrease started at a somewhat shallower depth for the rectangular area than the circular. Olsen (1994) concluded that if the stress due to track load spread over a large contact area is unacceptable in the subsoil, it is advantageous to divide the load between wheels having the same contact pressure as the track, but spaced to avoid interaction. Under normal agricultural conditions, tracks seem to be less efficient in preventing soil compaction than in improving the tractive efficiency and the trafficking of wet or loose soils.

5.4. Development of machines and field systems to avoid subsoil compaction

In the future, subsoil damage due to field traffic should be avoided by modifying the present machines. The machines and equipment used in the field should be adjusted to actual strength of the subsoil by controlling wheel/track loads and using low tyre inflation pressures. Weisskopf et al. (2000) found that on-land ploughing reduced the risk of subsoil compaction compared to in furrow plough. Likewise, new technical solutions to reduce loads carried in the field are now available. For instance, to reduce compaction during wet conditions, Godwin et al. (1990) distributed slurry with umbilical injection equipment, not requiring a heavily laden tanker.

In the long term, the development of lighter loading practices should be continued. The automated information and decision aid systems in machines should be developed further. For instance, the testing data (5.1), dynamic weighing and central tyre inflation systems, slip sensors and rut depth sensors may be integrated in the information and decision aid systems of the machines. Machine weight may be reduced by using new, lighter materials. In Norway, a prototype tractor made of aluminium was introduced. Automation may also allow lighter machines. In Finland, a light, self-navigating tractor for agricultural applications (Nieminen et al. 1994) has been developed. The idea has been that with the help of a self-guiding system, a single operator could control more than one tractor at a time, enabling field operations to be done with two to three small units as fast as with one

large unit. Chamen et al. (2000b) offer a more detailed discussion of visions to develop machines and practices to avoid subsoil compaction.

5.5. Predicting subsoil moisture content from cropping and weather data

In much the same way as irrigation scheduling is based on crop and weather data, it may be possible to determine the local vulnerability of subsoils in a similar way. This is particularly relevant to in-furrow ploughing, which might be abandoned if subsoil moisture levels were predicted to be high, or for the operation of subsoiling, which would only be considered if conditions seemed favourable. The procedure would involve an element of modelling and on-farm records of rainfall, evapotranspiration and days following cessation of drain-flow, if available. In many instances our observations and decisions are based on the topsoil and can be quite misleading as far as the subsoil is concerned. Sampling the subsoil is more arduous and time consuming however and a semi-automated system coupled to on-farm cropping practices and weather data could provide a useful predictive measure.

6. Conclusions

The risk of subsoil compaction is high when moist to wet soils are loaded with high wheel load traffic or moderate to high ground contact pressure. The most serious source of subsoil compaction is tractor wheels running in the open furrow during mouldboard ploughing. To prevent subsoil compaction, recommendations for wheel load-ground pressure combinations in different soil conditions or regulations based on quantitative guidelines for machinery-soil interactions should be established. The machines and equipment used on field in critical conditions should be adjusted to actual strength of the subsoil by controlling wheel/track loads and using low tyre inflation pressures.

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Equipment and field practices to avoid subsoil compaction

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Abstract

Although the financial implications of subsoil compaction are as yet uncertain, it is clear that the loads imposed by modern farm machinery have considerable potential to increase subsoil stress. The greatest potential for damage centres on fragile or loosened subsoils combined with high wheel or track loads and contact pressures that create noticeable ruts in the topsoil. In-furrow ploughing increases this potential considerably by placing loads nearer the subsoil. Measures to avoid this potential involve a whole farm approach and an understanding of the many interactions between cropping systems and machinery. Alternatives to in-furrow ploughing that involve working from the surface and building a protective topsoil are discussed. Key measures to reduce the risk to subsoils involve a clear understanding of tyre load and inflation data. Simple and low cost on-farm methods are proposed which involve only a tyre data book, a calibrated pressure gauge and a tape measure. Although avoidance has the potential to reduce the risk, confinement of damage to specific strips in the field is seen as a realistic alternative. Controlled traffic operations, together with precision guidance, offer an economic means by which compaction on the cropped area can be avoided. Care is needed in planning these systems where artificial drainage systems are employed.

Keywords: subsoil compaction; wheel load; ground pressure; in-furrow ploughing; controlled traffic; tramlines; precision guidance

1. Introduction

Avoiding a level of compaction in the subsoil which impairs crop growth or causes environmental damage, is an ideal that should, and due to legislation in some countries, must be aimed for in crop production operations. Unfortunately this ideal is often compromised by financial constraints, for example the timeliness costs of harvesting with a small vehicle are too high, or ploughing with a small tractor takes too long and is labour intensive. These costs tend to be obvious, they are easily calculated from known data and are easily demonstrated. There are however contrasting penalties in terms of soil damage that are equally costly, but much less obvious, considerably more difficult to quantify and often very expensive to demonstrate.

Håkansson & Petelkau (1994) attributed subsoil compaction to an average yield depression of around 2% in the 4 - 8 years following four passes on one occasion of 10 Mg on a single axle. Although this depression is modest, the trend towards larger vehicles remains and once subsoil compaction has been created on a field scale, it is difficult and extremely costly to repair. Avoidance must therefore be the primary means by which the

problem is addressed, and any measures recommended must be both practical and cost-effective. Unfortunately the whole farm economics are difficult to quantify until more data are available, but there are tools (Audsley, 1981) that will allow us to make calculations once subsoil compaction effects can be predicted.

Recommendations for avoidance need to be made against a background of a thorough understanding of the mechanisms involved, knowledge of the operations that have the highest potential risk and the likely vulnerability of different soils. Gaining this knowledge within a European framework has been made possible under the auspices of the European Union Concerted Action contract N° FAIR 5 CT97 3589 "Experiences with the impact of subsoil compaction on soil, crop growth and environment and ways to prevent subsoil compaction". More particularly, a working group set up within the Concerted Action has specifically addressed the topic of equipment selection and field practices to avoid subsoil compaction (Chamen et al., 2000). As a result, the group has produced a number of papers as the foundation for a knowledge base. Alakukku et al (2000) in their paper concentrate on the mechanisms and interactions involved in creating subsoil compaction. Sommer et al. (2000) assess the benefits that might be achieved by managing the topsoil more appropriately to protect the subsoil, while Spoor et al. (2000) provide an overview of European subsoils and propose a means by which their vulnerability to compaction might be predicted.

The aim of this paper is to put forward and discuss ideas about selection of equipment and how it should be used in the field to minimise the risk of subsoil compaction. The information is divided between specific equipment and its use, and field practices that can be applied to a number of machines or operations. However, there is some blurring of boundaries between these two aspects, and some subjects are discussed under both headings.

2. Definition of the subsoil

Before we discuss this subject extensively, we need to be quite clear about what we mean by the subsoil within existing agricultural production systems. Firstly, it is convenient to divide the subsoil into two distinct layers, the pan layer, which might be cultivated periodically, and the unloosened subsoil as defined below:

Pan layer. This is the layer below the annually cultivated layer. It will vary in thickness depending on the type and severity of compaction created by either implements or wheels or both. In some instances it is loosened on a regular basis.

Unloosened subsoil. This is the layer which normally remains undisturbed by tillage operations. It is also at a depth where tillage operations would be considered to be undesirable and often uneconomic, and if carried out, would create the potential for damage. This layer may however be disturbed during drainage operations, such as mole ploughing, or may need some careful treatment if already in a severely damaged state.

It should be noted that although these definitions are universal, they will occur at different depths depending upon the production system in use.

3. Aspects of field machinery associated with subsoil compaction

Initially it is helpful if we can identify those aspects of field machines that have the potential to create or avoid subsoil compaction. Although this might appear simple, there are a number of interactions that immediately show that planning to minimise the risk of subsoil compaction is complex. It is a complete farming system issue, as we can demonstrate from the factors that effect subsoil compaction on a given farm, namely:

- Cropping practices (crops and crop rotations)
- Depth and timing of cultivation
- Time available and the cost of labour in relation to machinery costs
- Strength of the arable layer
- Draught required by implements (self-propelled, power take-off (pto) driven or purely draught)
- Vehicle mass and the ground pressure of its supporting elements (eg. tyres, tracks)
- Number of passes and speed of vehicles across the field

3.1. Cropping practices

Growing potatoes and sugar beet, for example, will mean that the depth of tillage is generally greater than for crops such as cereals. This greater depth of tillage exposes the subsoil to increased risk of damage because the soil above it is less able to resist loads, or the tillage itself may involve ploughing in the furrow. Similarly, growing crops that are harvested during wet periods of the year on fragile subsoils may not be sustainable. Depending upon the perceived cost of this damage, either in reduced yield, soil erosion or repair, a review of cultivation practices and/or crop rotation may need to be undertaken. This highlights the need for a whole farm and system approach to ensure that profitability is not compromised by focussing on only one aspect of the problem.

3.2. Depth and timing of cultivation

These two factors are highly significant in terms of the potential for damage. The deeper the cultivation, the greater is the vulnerability of the subsoil during subsequent operations and the greater is the likelihood that a heavy vehicle is used to pull the cultivator. This problem is particularly extreme if deep in-furrow ploughing is practised. Although timing of cultivation will be closely associated with cropping, there may be some flexibility that can be linked to the predicted subsoil water content. Alternatively, different tillage techniques might be adopted if risk of subsoil damage were considered to be too high.

3.3. Timeliness, labour and machinery costs

All of these issues are interactive and must therefore be addressed with care. In simple terms we are looking for a minimum cost solution that provides sustainable profit, which in soil terms is probably of the order of 25 years. The interactions lie in matching the time available, size of machine and the labour cost. Of the three, probably timeliness costs are

the most difficult to quantify, but nationally there may be yield loss prediction data that relate to timing of crop establishment, crop protection and harvesting. Labour and machinery costs are closely linked, with larger machines requiring a lower labour input per hectare. However, these heavier machines generally (but not exclusively) run over less ground per hectare in a given season because they operate with wider equipment.

3.4. Strength of the arable layer

It may actually be advantageous for the subsoil if the topsoil has a high degree of natural strength. If this increased strength can be combined with a stable and well aerated soil structure, the topsoil can act like the bonding of bricks in a wall, spreading concentrated loads at the surface across a large area of the subsoil. Unfortunately it is difficult to achieve these conditions in practice, except perhaps under a well managed direct drilling regime where ruts in the soil are largely avoided by using low ground pressure equipment. Rut depth is a good indicator of the amount of damage that is being imposed.

3.5. Implement draught requirement

In most instances, the weight of tractors is largely associated with the draught loads which they have been designed to pull, and the greater this is, the heavier the tractor needs to be. More recently, tractor weight has also been associated with balancing the load from heavy rear-mounted equipment. In this situation, significant additional mass may be required on the front axle. However, where draught is the main factor involved, cultivation equipment which uses the tractor power take-off (pto) to deliver engine power to the soil, may be an attractive alternative. Thus, rotary spading or digging machines with integral deeper working tines may replace draught implements and the mouldboard plough. These pto machines have two significant advantages:

a) a lighter tractor can be used and there is little wheel slip associated with the operation.
b) the tractor is working on the soil surface rather than in the furrow, as still happens with mouldboard ploughing in many countries.

Although there are these advantages with pto driven machines, there are also a number of risks. These include the possibility of applying excessive power to the soil, either when it is too dry or when it is too wet and having to add counterbalance weights to the tractor front axle. Most, if not all of these problems can be significantly reduced by well designed machines. Uneven loading on the tractor, for example, might be avoided by using a self-propelled machine. The most important thing with these and all machines is to consider how the load is distributed and to minimise the contact pressure across the whole vehicle. In this respect, trailed implements have the advantage that they don't add additional weight to the tractor when turning on the headland. These implements should be equipped with the largest wheels that are practical and some benefit can be gained by using a weight transfer system to the tractor, as may be used for trailers.

3.6. Vehicle mass and soil contact pressure

As far as the subsoil is concerned, vehicle mass and soil contact pressure are the dominating factors in terms of potential for damage. The starting point for a decision about these is either the present state of the subsoil, if known, or the predicted vulnerability. We need to know whether any damage has, or is likely to have occurred already, and more importantly, whether it is restricting the function of the subsoil. This function needs to be considered in terms of the crop, either directly through poor rooting and water availability or indirectly as a result of increased soil erosion from poor drainage. Guidance for this can be obtained from the paper by Spoor et al. (2000) which identifies vulnerability classes for subsoils. These, together with cropping and weather data, should allow some prediction of subsoil condition on a particular soil and at a particular time of year. Thus, for example if in the wettest condition it is predicted that a subsoil at 400 mm depth will have a strength of 100 kPa, we need to ensure that our operations at the surface do not lead to a subsoil stress greater than this. Some indication of subsoil strength may be obtainable in the future by reference to the historic pressure imposed by vehicles and its transmission to the subsoil. Presently however, and **most importantly**, it is essential to have the tyre manufacturer's book of load/inflation tables - these should be available free from suppliers. All that is needed then is a <u>calibrated</u> pressure gauge and a tape measure, as illustrated below (Fig 1).

A simpler approach is: (1) choose tyres that can carry the highest possible load at what you have decided is your safe tyre inflation pressure (this will vary according to soil conditions, but could be decided by rut depth) and (2) control the laden radius. An added advantage would be a central tyre inflation/deflation system that is sensitive to forward speed. This would allow pressures to be adjusted to a safe minimum at all times when in the field.

Tyre 540/65 R 38
Laden radius = 759 mm
30 km/h road use involved

With the wheel standing on a hard surface and supporting the load that it will carry in the field, lower the inflation pressure until the laden radius is 759 mm, but no less. Now check that the pressure is not below the minimum listed in the load/inflation tables for this tyre. If it is, reflate to this minimum pressure. If the laden radius is always less than 759 mm over the whole pressure range, the load is excessive and needs to be reduced, the tyre changed or lower speeds used.
(Consult tyre dealer for advice on the latter)

Straight edge across rim, with pin protruding both sides

Laden radius
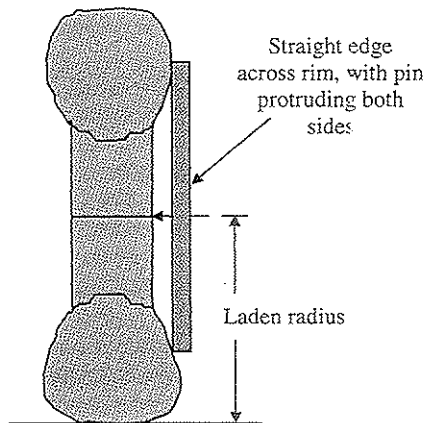
Fig. 1. Example of using pressure gauge and tape measure to check the correct tyre load and inflation pressure

3.7. Vehicle speed

Although the speed effect is of much lesser consequence than that of other factors, it is useful to note that compaction of the soil is time dependent, i.e. it takes a finite time to occur. Thus, although there are dynamic effects such bouncing and acceleration which might increase stress with speed, on average, the faster one goes over the soil, the less effect it will have. This is particularly true for waterlogged subsoils of low permeability, because water must move before compaction can take place. Again, the paper by Spoor et al. (2000) will provide information on this aspect of the problem.

4. Equipment selection and method of use to reduce subsoil compaction

As part of the Working Group methodology, (Chamen et al., 2000) operations which were considered to present a high risk of subsoil compaction, were tabulated. These data have been used as a means of identifying the most critical operations and the equipment involved. Table 1 provides a summary of the high risk operations.

Table 1. High risk operations for subsoil compaction categorised under crops and summarised for returns from Finland, Germany, Portugal, Switzerland and the United Kingdom.

Ploughing (in furrow) or Cultivating	Subsoiling	Bed-forming	Harvesting		Organic fertiliser application
			Harvesters	Trailers	
Ploughing	Sugar beet>	<Vegetables	Roots	Roots	All crops
<Sugar beet>	Potatoes>		Fresh peas	Tree fruits	
<Potatoes>					
<Grain maize					
<Spring cereals			Early cutting for silage or		
<Onions>			fresh fodder crops		
Cultivating			Combinable crops, e.g.		
<Sugar beet			wheat, barley, oats, grain		
<Potatoes			maize, oilseed rape,		
<Spring cereals			linseed, beans, peas		
<Onions					

<just before crop sowing
>just after crop harvesting

In all cases, the risks were considered to be higher in moist conditions, often associated with late autumn or early spring ploughing, or where late maturing crops were harvested. Similarly, cultivation for spring sowing on soils that are dry on top but moist below. Rut depth is a good indicator of the amount of damage that is being imposed, and this must be minimised or the operation delayed.
We can also note from this table that the principal damage is caused by tractors, harvesters, trailers and tankers. Equally the subsoiler is identified as a potentially damaging implement, and this is dealt with in section 4.2 below.

4.1. Ploughing

In very few cases was on-land ploughing identified as a high risk operation, and moving the tractor onto the surface is the obvious first course of action to reduce the risk of damage to the subsoil. However, with a wheeled tractor, traction out of the furrow is often perceived to be a problem, but this could be considered as a safety valve. If slip at the surface is excessive, this probably means that the wrong wheel equipment is being used (singles rather than duals) or that it really is too wet. Similarly, matching plough, tractor and load on the driving wheels is crucial to ensure an acceptable level of wheel slip. Aiming for around 10% slip will ensure high efficiency while limiting damage to an acceptable level. (Alakukku, 1997 & Scarlett, personal communication, 2000) Always minimise the depth of ploughing conducive to the desired result, as this will bring the wheel closer to the soil surface. As with most soil protection measures, it will also reduce the cost of the operation and increase yield potential.

With a tracked vehicle, on-land working is the normal mode of operation, as it should be with wheeled tractors. If however there is resistance to moving a wheeled tractor onto the land, some improvement can be achieved by fitting tyres up to 650 mm wide - these can still effectively be used "in the furrow". Many modern ploughs are designed to work in or out of the furrow. Similarly, if the plough design allows, it may be preferable in some circumstances to reduce the plough width by one body so that forward speed can be increased and slip reduced. Ploughing at low speed with a high level of slip should be avoided.

A second option is to introduce a loosening tine behind the tractor wheel. This can often take out a pan layer very effectively and is to be preferred compared with a conventional subsoiler. However, avoidance will always be better than cure!

4.2. Subsoiling

Subsoiling is introduced in this paper to highlight its potential for increasing the vulnerability of subsoils, rather than as a curative measure. Subsoil strength will have been substantially reduced by this operation, so rather than being able to resist stresses of perhaps 100 kPa, as we predicted above, it may now only have a strength of 50 kPa. The danger is that we will re-compact the subsoil very easily, and possibly to a greater depth, if we don't take account of this reduced strength, particularly in the first six months after loosening and particularly if no crop is present.

There are instances when subsoiling can be beneficial, but these are the exception rather than the rule and involve close definition and careful management of the problem. Any subsoil loosening where necessary, should be minimal and just sufficient to restore pore continuity through the compacted zone. This minimises loss of subsoil strength and hence the risk of re-compaction.

4.3. Bed formers

The danger in using bed formers is from the power unit, which often has to create significant draught on a cultivated soil. There is also little flexibility in timing for this operation, which is generally carried out in the spring when the subsoil can be very wet.

First advice would be to re-time the operation for when the subsoil might be dryer, but if this is not possible, care and attention to tyres and tractor are essential. If only two beds are being formed, adding dual wheels may not be possible, but large tyres at low inflation pressure should be considered. Where four or more beds are being formed, dual wheels can be introduced, but in both cases, attending to tyre pressures and wheel loads is the key to reducing the potential for damage. This is also true for following operations, when the tractor is now working at a level effectively below the original soil surface. Particular care should be taken following high rainfall, when this may have been concentrated into the furrows.

4.4. Harvesting

Damage from harvesting operations is all about high loads and high contact pressures at the surface. As far as the machinery is concerned, it will almost certainly be uneconomic to reduce its size, but it is worth scrutinising the harvesting operation to determine exactly what limits the work rate. The work rate is not that of the harvester alone, it is the complete system that delivers crop to the store. It's of no value to have a cereal harvester with a capacity of 30 t/h , when the operating system only allows 25 t/h. Such scrutiny will almost certainly lead to an improvement in the operating system, rather than a reduction in harvester size, but this may not always be the case.

If we accept that vehicle weight is unlikely to decrease, the main thrust of improvement must be in ground pressure. With recent improvements in tyres and tracks, there is considerable potential for improvement from both of these technologies with appropriate knowledge and application. The recent introduction of articulated vehicles with a half-track design is encouraging, but as yet there are few data on their performance. There is no reason why such designs, with tracks or wheels (the latter with an element of crab-steer), should not be incorporated into harvesters and into power-assisted trailers. Similarly, the use of the hovercraft principle, hitherto perhaps uneconomic, may be a useful system of taking at least some of the load from the wheels. At a wet harvest, when surface dust would be less of a problem, both trailers and harvesters could be equipped with a system of this nature that takes a proportion of the load while the vehicle is in the field. In the same way, the introduction of "on the move" tyre inflation/deflation systems are well overdue on a wide scale as are weight transfer systems. Central inflation /deflation systems offer the opportunity of lowering tyre pressures during field operations (where speeds are less than on the road) and raising them quickly for road use. The ideal is a system that responds to actual forward speed. This is of particular relevance to trailers and tankers.

Although much of this equipment is widely available, adoption has varied considerably across the Union. The simple approach of specifying the largest tyres, or adding dual wheels to both front and rear of harvesters should be a first priority. Again, we are looking for pressures that when transmitted through the soil have little potential to damage the function of the subsoil.

4.5 Organic fertiliser application

In almost all cases, problems are associated with slurry application using large tankers in moist conditions on grassland, but the dangers may be even greater on other less well structured soils. The most effective method of overcoming this problem is to use an umbilical hose connecting a tanker at the field headland with the tractor applying the material in the field. This equipment is readily available and can be used effectively over almost any distance providing the correct operating procedures are used. Modern telemetry systems can be employed to ensure that the hose always remains charged, which is essential for effective operation.

Other means of reducing risk revolve around the running gear of the tractor and tanker, and which have already been covered under harvesting systems. However, other approaches, such as alternative road and field running gear combined with containerisation might also be worth consideration.

5. Field practices to reduce subsoil compaction

In this section we look at methods that are not confined to the machines themselves, but rather those that are associated with how they are used on a field or farm scale. There are a number of strategies that might be adopted, namely:

- Management to avoid wet conditions
- Pro-active field management of operations and route planning
- Confining damage to specific and manageable strips within a field
- Managing the topsoil to increase its strength
- Adopting new or existing technologies that allow a fundamental change in the equipment used or the manner in which it is used.

The above strategies can be divided into avoidance or confinement. Confinement accepts that damage occurs, but is confined to sacrificial strips or strips that are annually repaired.

5.1. Methodologies for avoidance

5.1.1. Minimising wet conditions
Soils are considered to be too wet when they are at or above the plastic limit moisture content. (Soil will just form into a sausage when rolled between the fingers and palm of the hands)

Drainage and cropping practices are the key areas of management that can be used effectively to reduce wet conditions. On poor draining soils, a well-designed artificial drainage system should be installed and properly maintained. On these and other soils, ditch maintenance is essential together with a good local infrastructure to take excess water away.

If climate and soil act together to make wet conditions common at certain times of the year, crops should be chosen that require little work on the land at these times. Conversely, inappropriate crop management can create wet conditions. Set-aside land depleted of green cover can lead to a situation of high potential risk. This management

allows very high moisture levels to build up below a surface dried out by summer sunshine. Ploughing in this situation can be particularly damaging. Sowing weed suppressing but non-invasive cover crops can reduce this problem by lowering moisture levels and by generating organic matter and hence an improved soil structure.

Similarly, inappropriate timing of irrigation can have disastrous effects, particularly furrow irrigation, where some of the furrows will be used as wheel tracks. Careful planning is needed to ensure that natural rainfall does not add to a potential problem.

5.1.2. Pro-active management of operations and route planning

If wet conditions cannot be avoided, an option might be to part fill harvesters and trailers to reduce loads. Care must be taken however that topsoil compaction is not increased due to covering a larger area. Route planning is a useful means by which this problem can be avoided, or where crops can be grown with the addition of transport lanes within the body of the field. However, the two following general rules apply in all conditions and should be noted by equipment manufacturers:

1. If rut depth is likely to be minimal (contact pressure below 50 kPa), cover as large an area as possible with the wheel arrangement

2. Where ruts are being formed, confine the wheels to the minimum area possible.

The latter is similar to the technique of confinement, as described below, where damage is confined to a small and annually repaired area. Route planning in this situation takes account of crop yield and harvester and trailer capacity as well as the drains. These should be crossed at right angles and this should also ensure near-parallel running to mole channels, which could all become damaged if run over at right angles.

5.1.3. Increasing topsoil strength

This technique, as we have seen, protects the subsoil by creating a strong layer above it, but precludes both ploughing and subsoiling as part of the cultivation programme. Techniques can include direct drilling of the crop, or minimum tillage, both of which should be used with low ground pressure equipment to avoid rutting and maintain vertical pores. These techniques also tend to improve soil structure and stability in the surface layers by concentrating organic matter in this region. Maintaining soil pH at the correct level is also important, as this improves organic and chemical bonds within the soil and optimises the conditions for most soil organisms.

An artificial strengthening of the topsoil layer occurs when the surface crust is frozen, and other than with in-furrow ploughing, can be a useful means of carrying out operations with little danger of damage to the subsoil. Increased night-time working could be beneficial in making maximum use of these occasions.

5.1.4. New technologies

Techniques that reduce stresses at the soil surface are the primary area in which advances are anticipated. This can be brought about by using lighter materials for the machines, improved running gear or by introducing automation. Tyres have improved considerably over the past 20 years, and further advances are likely. Track technology also continues to develop, and particularly with its recent introduction on an articulated tractor. Automation can allow smaller machines to be used for longer periods. An example might be a winch and sprag system that currently has far too low a work rate, but could be used

for ploughing if the operation were maintained for 24 hours a day. Alternatively a number of smaller tractor units could be used simultaneously but operated by only one person (Nieminen et al., 1994).

5.2. Methodologies for confinement

Probably the most common method of achieving confinement is with "controlled traffic". The wheels or tracks of vehicles run in either permanent or temporary sacrificial strips across the field. This leaves the cropped area either free of all traffic or limits its impact to certain periods in the crop production cycle. Many farmers create the latter in the form of "tramlines" during crop sowing but mainly as a means of improving the accuracy with which they can subsequently apply chemicals. However, more extensive use can be made of this technique by using it for a wider range of operations. Unfortunately its extended use in Europe is limited by the need to transport equipment along the road. Cultivators of 8 m width, for example, which although they can be folded, are still not wide enough to make the loss of land to tractor wheel tracks acceptable. An alternative is to use a wide-span vehicle system, as illustrated in Fig. 2.
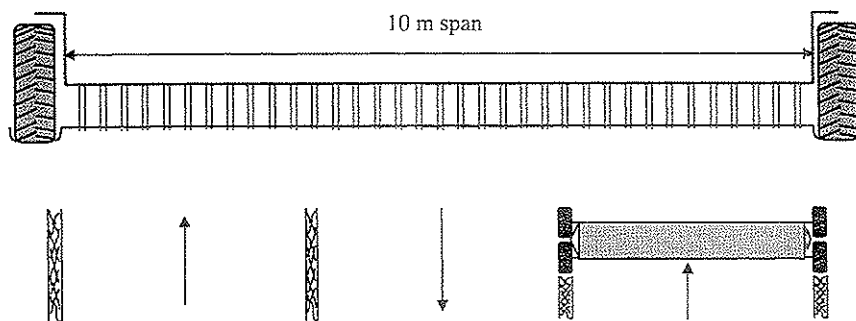
Fig. 2. Illustration of a wide span vehicle system and the way it is used in the field. Advantages include its minimum loss of land to wheel tracks and automatic method of field marking.

These create only one new wheel track for every pass across the field, rather than two. On the road, they travel lengthways where their width, including appropriately designed implements, may be no more than 3 m. If a complete system of farming using this equipment were devised, the need for tillage as a remedial operation would largely be avoided. Wide track vehicles also provide a more stable mounting for implements, and together with new precision and control technology, can work with high efficiency in most field shapes and sizes. As with tramlines, the position of the wheel tracks should be planned in relation to the field drainage system. Ideally, they should run parallel to but offset from shallow drains, and particularly those without backfill and where no mole ploughing is used. With deeper drains and where moles have been drawn, the wheel tracks should be parallel to the mole drains. In this way, only isolated moles may be damaged, whereas, crossing them with wheel tracks has the potential to seal the large majority.

The argument that larger tractors with high pressure tyres and wider implements can reduce the number of wheel tracks on a field has little value unless a controlled traffic system is employed. Limited but random trafficking by these vehicles simply means that the damage takes longer to build up on the whole area, but it will occur if pressures are not reduced, and also to a greater depth than with smaller equipment.

6. Conclusions

Subsoil compaction will only become an issue on farms if it becomes a legislative issue or it can be clearly demonstrated that it has a negative effect on farm profit. This is likely to occur as a result of additional expenses for subsequent crops, the labour component of which can rarely be compensated. Currently presented evidence to suggest a reduction in crop yields is tenuous, but the outcome of the Concerted Action may reinforce the data available. This should allow the cost of avoidance or remediation to be calculated in relation to yield loss.

The greatest potential for subsoil compaction comes from tractors, harvesters and trailers and from ill conceived subsoil loosening. The wheel load and its contact pressure are the primary means by which compaction is transmitted, and the subsoil is at highest risk when tractors run in the furrow while ploughing in moist conditions.

The most effective avoidance measures are those based on a complete system approach, attention to detail and knowledge of the soil upon which one is working. Understanding the mechanisms involved and the benefits that can be gained are the only means by which an improvement can be sustained. Avoidance and confinement are the main tools for this improvement. Primary measures for avoidance include working at the most appropriate soil moisture content, out of furrow ploughing, reduced loosening of both topsoil and subsoil and the use of low ground pressure equipment. Cropping and mechanisation should also be adapted to the site, rather than the other way around. Confinement can eliminate wheel compaction on the cropped area completely, but new systems and technologies need to be introduced. Information in a readily available and understandable form and customised to the end user is the key means by which negative impacts on the subsoil can be lessened.

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Equipment selection and field practices for the control of subsoil compaction - Working Group methodologies and data acquisition

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Abstract

A summary is provided of the activities of one of a number of Working Groups set up within a European Union Concerted Action dealing with subsoil compaction (contract no. FAIR 5 CT97 3589). The aim of this Working Group was to provide a framework and knowledge base that would allow farmers, growers and manufacturers to better understand and avoid the situations that could lead to subsoil compaction. The Group activities included definition of the subsoil, the principles used for developing the framework and aspects of machines and field systems that have the potential to impact on the subsoil. The susceptibility and vulnerability of subsoils were also surveyed, critical operations identified and recommendations made. The potential negative impact on farm profit was seen to be the main driving force that would bring about change if operations and vulnerability suggested that subsoil damage would occur. Training at farm level was considered to be the key means by which the industry would be better able to respond positively to the needs identified.

1. Introduction

On the 1st January 1998, a European Union Concerted Action, contract N° FAIR 5 CT97 3589, "Experiences with the impact of subsoil compaction on soil, crop growth and environment and ways to prevent subsoil compaction", was started under the management of Jan van den Akker of ALTERRA Green World Research, the Netherlands. At the first meeting of the 34 members of the Concerted Action, six working groups were set up to address the particular issues raised by the subject of subsoil compaction. This paper reports the activities of one of these groups whose objective was:

To provide a best practice framework within which growers, farmers, manufacturers and
advisors can work to achieve some control over subsoil compaction.

The authors of this paper constitute the membership of the group. This has met on four
occasions, twice during workshops of the CA, and twice in the UK for meetings of 2-3
days duration.

The first task of the group was to provide a basis for the framework. This required a
universally applicable definition of the subsoil and identification of the aspects of
agricultural production systems that would have an impact upon it. In addition, principles
for the best practice framework were needed and most importantly, a means by which
subsoils might be classified to identify their potential for damage. Within this
classification it was hoped that some information might be available about the likely level
of existing stress within subsoils of a particular origin and region. It was also important
that the group could identify those operations that were the most sensitive in terms of
potential impact on the subsoil. To do this, tables of critical operations within each of the
countries represented were drawn up. These were supported by similar information from
experts about cropping and machinery practices and national or other guidelines designed
to reduce the risk of subsoil compaction.

2. Definition of the subsoil

To achieve a universal definition, it was considered necessary to divide the subsoil into
two distinct layers, namely:

Pan layer. This is the layer below the annually cultivated layer. It will vary in thickness
depending on the type and severity of compaction created by either implements or
wheels or both. In many instances it is loosened on a regular basis using the
practice termed "subsoiling".

Unloosened subsoil. This is the layer which normally remains undisturbed by tillage
operations. It is also at a depth where tillage operations would be considered to be
undesirable and often uneconomic, and if carried out, would create the potential for
damage. This layer may however be disturbed during drainage operations, such as
mole ploughing, or may need some careful treatment if already in a severely
damaged state.

Although these definitions are universal, their depth will vary depending upon the crop
production system in use.

3. Principles of the best practice framework

It was agreed that the framework should, in general, be non-prescriptive. It should provide
basic and easily assimilated information about what is going on in the soil so that the
recipients of the data can make their own informed decision about the most appropriate
course of action.

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Consideration was also given to a "red light" concept - identification of conditions beyond which operations would be suspended. However, this was seen to be contrary to a non-prescriptive approach.

Knowledge about tyres and their interaction with the subsoil was seen to be of particular importance. A means of predicting ground contact pressures from readily measurable parameters was also considered vital as a starting point for a decision structure. In this respect, the projected area technique for predicting ground contact area of a tyre was considered to be very limited and required revision. A European testing station for tyres was suggested to provide information on contact pressure in relation to tyre inflation pressure in different soil conditions. It was also observed that "precision farming without compaction control is a contradiction".

Local weather data would be a significant benefit in decision making on any specific farm. This coupled with crop water extraction models could provide a more robust prediction of the actual state of the subsoil.

Three main principles for avoidance of subsoil compaction were identified:

No repeated subsoil loosening as a routine cultivation technique	Increase soil stability and reduce soil stress	Select machines that have a low risk potential
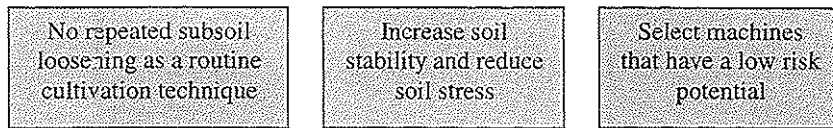
Alongside these principles, the measures required to achieve improvements were presented graphically in ascending order of cost and the time required for their realisation as shown in Fig. 1.

4. Aspects of agricultural production systems that impact on the subsoil

The following aspects were identified:

- Crop, crop rotation and water management
    - crop restructuring of the soil - amelioration and regeneration
    - adjusting rotation to reduce the potential for damage
    - increasing soil strength by improving drainage
    - complying with legislation
- Timing of operations
    - seasonal and short term
    - assessing cost and other risks associated with delay
- Equipment
    - Tillage machinery
        - depth of work
        - inversion versus non-inversion
        - powered or non-powered
        - tractor mounted or trailed
        - pan forming - beneficial or detrimental?
- Ground support

Fig. 1. Management structure of measures to avoid subsoil compaction categorised in ascending order of cost and time (Weisskopf, personal communication, 1999)

Principle 1
Preventative actions; no repeated loosening as a routine technique

Principle 2
1. Increase soil stability
2. Reduce soil stress
3. Support processes which lead to structural regeneration

Importance of compaction in different soil layers
- Topsoil: short term
- Subsoil: long term

Principle 3
1. Construction of machines and tyres with low risk of soil compaction
2. Selection of equipment that promotes stresses lower than those existing a particular site
3. Adaptation of machines to actual working conditions (soil water content)

Selection/operation of machines T1

Adaptation of machines T1,T2

Soil tillage T1,T2

Organisation of field operations T1,T2

Information on design of machines T1,T2

Organisation of field operation T3

Soil stress (quantification=2)

Irrigation T1

Planning of land management T1

Soil/tillage management T1,T2

Soil stability (quantification: soil compactibility classes)

Wheelings T1,T2

Drainage T2

Soil/tillage management T2

Planning of land management T1

Fertilisation T3

Drainage T3

Crop rotation, crop variety T3

- Tyres
  - selection, loads and inflation pressures
- Tracks
  - rubber, metal
- Field operating systems
  - soil water regimes - structure strength in relation to field capacity water content
  - traffic intensity
  - artificial headlands matched to harvesting needs
  - controlled traffic
- Soil vulnerability class and climate
  - initial state of compaction - under or over consolidated
  - structural stability, clay content and type, organic matter content
  - work days available, yield response to timeliness
  - soil workability - particularly when drying from below
  - soil temperature, rainfall patterns and evapotranspiration
  - rotational adjustments

Most of these topics are covered in other papers prepared by the working group (Alakkuku et al., 2000, Spoor et al., 2000, Sommer et al., 2000, Chamen et al., 2000), but a number of important points were raised during discussion of these topics.

4.1. Water management

Where a drainage system was installed, it was suggested that the water table should be designed to be at 0.5 m depth minimum at mid drain position. Where irrigation was applied, the crucial question was timing of application in relation to subsequent trafficking. Advice should be based on the drainage system and the nature of the drainage problem. It was accepted however that in certain circumstances, little useful advice could be given.

4.2. Timing of operations

In some circumstances, it was accepted that influences from outside the farm would determine when operations were carried out, for example, the sugar or pea canning industry. The point was made that factories, once started, could not stop, or that the quality of the product came before any other considerations. In the case of sugar beet, and on farms with vulnerable soils, it may be possible to provide premiums to cover the cost of on-farm storage following early harvesting.

4.3. Cultivation practices

"On land" ploughing should be recommended where possible, or wide wheels working in the furrow or in the presence of a "furrow widener". Shallower ploughing should be

encouraged, or perhaps the introduction of a stepped plough, where the full depth is only reached after the wheel has passed over a shallower furrow. Non-plough techniques should be favoured. Power take-off driven low draught cultivators would allow lighter tractors to be used. The structure of the topsoil should be improved so that it can better carry the loads imposed upon it and protect the subsoil. Pan layers, providing they are porous to roots, water and gases, may actually be beneficial in protecting the soil below them.

4.4. Ground support

This was an area which received particular attention. Although a great deal of information was already available on the subject of ground pressures, axle loads and pressure distribution in the soil, further information on this aspect would always be welcomed. Trailer designs were considered to be an area where improvements were needed, and particularly load transfer onto the tractor.

Contrary to the topsoil, subsoils may actually be at relatively little at risk in spring, or when soils were in a drying out phase. In this situation, equipment is lighter and wheel sinkage would limit the loads being applied. However, it was crucial that we understand how large, low inflation tyres transmitted their loads, particularly with a very vulnerable subsoil. Rut depth is a particularly simple indicator of the potential for damage and should always be minimised.

4.5. Field operating systems

Although reducing traffic intensity (larger tractors pulling wider machines) might at first seem a practical means of reducing potential impacts on the subsoil, wheel loads and ground pressure are the dominating factors in a random trafficking regime. Eventually, the whole field will be subjected to these higher loads. Controlled traffic operations are to be preferred, whether they are designed simply to confine harvest trailers to particular sections of a field, or to be extended to all operations. Again, greatest advantage would be gained by adopting wide track tractors (> 6 m) as these minimise the land used for wheelways.

5. Assessing the vulnerability of subsoils across Europe

This is a key area that has been recognised by the CA. Without information about the present state of subsoils, it is difficult to make recommendations about the level of protection that might be needed. Data presently being collected by the database managers within the CA, should provide information on this and many other aspects. However, it has also been possible within this group to anticipate additional information about subsoils based on land use, climate and soil survey data. Such a risk analysis is particularly prudent at this juncture, when climate change and the environmental impact of cropping systems makes soil protection of increasing importance. Spoor, working closely with Jones and Thomasson (2000) have identified the major factors influencing the susceptibility of subsoils to compaction, the majority of which are available from survey records and databases. Soil moisture and bulk density measurements, crucial for assessing the

vulnerability of a subsoil to damage, are unfortunately often absent from these data. This information can however be inferred from other data, enabling susceptibility classes to be converted into levels of vulnerability. Use of inferred data is not accurate enough for use at a local scale, but offers a practical means by which areas at risk can be identified at a European level. Substituting actual moisture data and incorporating the influence of topsoil condition allows vulnerability estimates to be made at a local level.

6. Critical operations and their significance in different countries

Table 1 provides the definitions necessary for the summary of the critical operations listed in Table 2. It is perhaps of some surprise to see that the actual operation of subsoil loosening is listed amongst the critical operations. This emphasises two things: firstly that subsoiling at any depth in the soil is often detrimental and should only be considered as a last resort. Loosening of the subsoil reduces its strength, increases its vulnerability and requires careful aftercare. Secondly, any subsoil loosening where necessary, should be minimal and just sufficient to restore pore continuity through the compacted zone. This minimises loss of subsoil strength and hence the risk of re-compaction.

The table also confirms that in most respects, the potential for damage to the subsoil comes from similar operations carried out in similar circumstances. These centre on high wheel loads applied when the subsoil is likely to be moist or wet. This potential for damage is considerably increased when tractors operate in plough furrows with high levels of wheel slip (>10%). Avoidance largely relies on finding cost-effective alternatives to the plough. Rotary spading or digging machines, if correctly selected and set up, can achieve greater work-rates than ploughs and can be used on high power but lighter tractors.

Harvesting operations are particularly critical and it is with these that there is considerable potential for new ideas and machinery. Planning of field movements, confinement and new designs for running gear, perhaps integrated with hovercraft-type principles, all provide opportunities for research and development.

7. National cropping and machinery practices

The following list of questions was developed during meetings of the Working Group. The questions were designed to gain information from national experts about potential problem areas within different countries and to determine what measures, if any, were in place to reduce the potential for subsoil compaction. Each question is followed by a résumé of the responses from national experts.

Questions for national experts:

Q. 1. What are the critical field operations in terms of subsoil compaction? For example, what are the heaviest machines on the farm and under what soil water status would they normally be used, dry, wet or normal?

R. The responses to this question have already been summarised in Table 2.

Q. 2. Are there any national guidelines for wheel equipment, inflation pressures and axle loads?

R. National guidelines were largely absent, but in two countries, "Codes of Practice" suggest that advice should be sought with respect to tyres, inflation pressures and axle loads.

Table 1. Definitions of the different parameters used in Table 2 to determine the potential risk of damage to the subsoil

Parameter	Level	Definition
Bout width	Low (L)	Up to 3 m
	Medium (M)	3 - 10 m
	High (H)	10 m and above
Forward speed	Low (L)	Up to 5 km h^{-1}
	Medium (M)	5 - 10 km h^{-1}
	High (H)	10 km h^{-1} and above
Soil moisture	Low (L)	pF 2.8 or above
	Medium (M)	pF 1.8 - 2.8
	High (H)	pF < 1.8
Mass on wheels	Low (L)	One or more wheels with up to 1t wheel^{-1}
	Medium (M)	One or more wheels with 1 - 3t wheel^{-1}
	High (H)	One or more wheels with over 3t wheel^{-1}
Potential for damage	High (H)	Subjective combined assessment of levels
to the subsoil	Medium (M)	of previous parameters
	Low (L)	

Qs 3. & 4. What proportion of the cropped area has the potential to be irrigated, and what proportion of the cropped area is under-drained?
R. 3 & 4. Proportion of cropped area irrigated and under-drained:

	Irrigated	Under-drained
Portugal	18%	No data
Finland	2%	54%
Netherlands	19%	75%
Switzerland	1%	<10%
England	3%	90%
Germany	3%	30%

Q. 5. What range of crops is grown and what proportion of the cropped area does each of them cover?
R. Table 3 provides a summary of the principal crops grown

Q. 6. What is the dominant cultivation system? eg plough, disc, tine etc. and at what depth are these operations carried out? Approximately what percentage of the total area is cultivated with the different implement types?
R. In all the countries represented by the Group, the mouldboard plough accounts for

Table 2. Operations with a medium to high risk of damage to the subsoil. (See Table 1 for column definitions)

Country & critical operation	Crop	Critical machinery[1]	Bout width	Forward speed	Soil moisture	Mass on wheels	Potential for damage in the subsoil
Netherlands							
Subsoiling	Potatoes & cereals>	Subsoiler	Low	Low	M/L	M/H	H
Ploughing in late autumn	<s. beet & potatoes	Tractor - in furrow	Low	Low	M/H	H	H
Harvesting	Cereals	Combine harvester	M	L/M	M/L	M/H	M/H
		Trailers	M	M	M/L	M/H	M/H
	Root crops	Harvesters	L	L/M	M/H	M/H	H
		Trailers	L	L	M/H	M/H	H
	Fresh peas	Harvesters	L/M	M	M	M/H	M
		Trailers	L/M	M	M	M/H	M/H
	1st cut intensive silage	Harvesters	L	M/H	M	M	M
		Trailers	L	M/H	M	M	M
Finland							
Ploughing in late autumn	<Spring cereals, s. beet, potatoes; cover crop, grass>	Tractor - in furrow	L	L	M/H	L - H	H
Seedbed preparation	<Spring cereals, s. beet	Tractor	L/M	L/M	M/H	M	M/H
Harvesting	Cereals	Harvester	M	L/M	L - H	M	M/H
		Trailers	M	L/M	L - H	M/H	M/H
	Root crops	Harvesters	L	L/M	M/H	M/H	M/H
		Trailers	L	L - H	M/H	M/H	M/H
	1st cuts of silage	Tractor & Trailers	M	M	M/H	M/H	M/H
Fertilisation: Mineral	All	Lime spreader	M	M	L/M	M/H	M
Organic		Tractor/spreader/tankers	L - H	L/M	M/H	M/H	M/H
Switzerland							
Ploughing over winter	Maize, beet & others	Tractor - in furrow	L	L	M/H	L/M	H
Harvesting	Grain & silage maize, cereals, s. beet, peas	Harvesters	L - M	L - M	M/H	M/H	H
		Trailers	L	L	M/H	M/H	H
	Potatoes	Harvesters	L	L	M/H	M	H
		Trailers	L	L - M	M/H	M/H	H
Fertilisation: Organic	All	Tractor/tankers	M	L - M	M/H	M/H	H

[1]In all instances, the risks are increased as soil moisture content rises <just before crop sowing; >just after crop harvesting

Table 2, continued. Operations with a medium to high risk of damage to the subsoil (See Table 1 for column definitions)

Country & critical operation	Crop	Critical machinery[1]	Bout width	Forward speed	Soil moisture	Mass on wheels	Potential for damage to the subsoil
Germany							
Ploughing	<winter wheat, maize, s. beet & potatoes	Tractor - in furrow	L	M	M/H	L/M	H
	Grain maize, s. beet, potatoes, & fodder crops>	Tractor - in furrow	L	M	M/H	L/M	M/H
Harvesting	Cereals, grain maize and oilseeds	Harvesters/trailers/tractors	M	L	M/H	M/H	H
	S. beet, legumes, potatoes & fodder crops	Harvesters/trailers/tractors	L/M	L/M	M/H	M/H	M/H
Fertilisation: Organic	All grains, s. beet, cover	Tractors and tankers	M/H	M	M/H	M/Hf	M/H
UK							
Deep cultivations after subsoiling	All	Tractor	L/M	L/M	L/M	M	H
Ploughing	<s. beet & potatoes>	Tractor - in furrow	L	L	M/H	M	H
	Cereals>	Tractor - in furrow	L	L/M	M/L	M	M
Harvesting	Cereals	Harvesters/trailers	M	M	L/M	H	H
	Root crops	Harvesters/trailers	L	L/M	M/H	M	H
	Fresh peas	Harvesters/trailers	L/M	M	M	M/H	H
	1st cuts of silage	Harvesters/trailers	L	M	M/L	M	M
Fertilisation: Mineral	All	Lime spreaders	M	H	M/L	M/H	M
Organic	All	Tractors/tankers	L/M	L/M	M/H	M/H	H
Bed forming/cultivation	Vegetables	Tractor	L/M	M	M/H	M	H
Portugal							
Deep cultivations after subsoiling	All	Tractor/Heavy discs	L/M	L/M	L/M	L - H	H
Ploughing	s. beet & potatoes>	Tractor - in/out of furrow	L	L	M/H	L - H	H
Harvesting	Cereals	Harvesters/trailers	M	M	L - H	M/H	M/H
	Root crops	Harvesters/trailers	L	L/M	M/H	M/H	M/H
	Fresh peas	Harvesters/trailers	L/M	M	M	M/H	M
	1st cuts of silage	Harvesters/trailers	L	M	M/H	M	M
	Olives, nuts & citrus	Trailers	L	L	M/H	M	M

[1] In all instances, the risks are increased as soil moisture content rises < just before crop sowing; > just after crop harvesting

between 80% and 95% of primary cultivation practice, and generally in the depth range 20 - 40 cm. Only in the Netherlands is there any evidence of a significant use of powered diggers. However, recent financial constraints are pushing farmers towards lower input systems, often including discing or direct drilling in place of ploughing and particularly on clay soils.

Subsoiling is widely practised, but particularly in the Netherlands and England, where depths of between 30 cm and 50 cm are the norm.

Q. 7. Are there any recommendations for field operating systems designed to minimise subsoil compaction? If not, are there any that you would recommend? For example, are sugar beet or potato fields divided in their length to allow unloading on centre headlands? Are combine harvesters driven parallel to tramline systems, or is any thought given to matching tramlines to combines unloading on the move into trailers?

R. There seems to be few recommendations in any of the countries that relate specifically to the protection of the subsoil. Where recommendations do exist, these largely relate to the topsoil but will also give some protection to the subsoil. The most developed guidelines may be found in Switzerland, where in-furrow ploughing is actively discouraged, and guidance for soil protection is given in terms of maintaining farm profit. Recommendations by members of this Group for field operating systems are covered in a parallel paper (Chamen et al., 2000).

Table 3. Summary of the principal crops grown (by area) in a number of European countries

| Crop | Area of crops grown (ha x 1000) in different countries | | | | | |
	Germany	Portugal	Finland	Netherlands	Switzerland	England
Grasses	1772		682	949	740	6675
Wheat ⎫		137	137	103	97	1847
Barley ⎬	7042	20	578	59	51	1179
Oats ⎪		45[1]	387	2	8	92
Rye ⎭			36	3	7	8
Maize[2]	464	315		256	175	
Oilseeds	959		65	5	14	626
Paddy rice		29				
Sugar beet	503	4	33	119	16	183
Potatoes	297	85	33	183	17	178
Peas				8 (dry)	2[3]	89 (dry)
Onions				20		
Citrus		27				
Olives		323			8[4]	
Vines		263			13	
Vegetables				43	8	126
Other crops	5224	169	30	23	115	159
Area in production	17373	1829		1773	1073	11416

[1] Including rye: [2] Includes grain and silage maize: [3] For fodder: [4] Intensive fruit

Q. 8. Are there any incentives for avoiding subsoil compaction? For example, government initiatives, company (sugar, supermarket) or other organisation's recommendations. In particular, are there any monetary incentives for avoiding compaction?

R. No monetary incentives were identified. However, in Switzerland, the "Soil Protection Index" provides an indirect means by which subsidies can be deducted if, for example, erosion damage can be linked to poor protection of the soil.

Q. 9. Future. What do the experts consider should be the way forward in terms of dealing with subsoil compaction?

R. These responses are largely covered in other papers by this Group (Alakukku et al., 2000, Sommer et al., 2000 Spoor et al., 2000, Chamen et al., 2000). However, the principal recommendations centred on:

- Demonstration of an improvement in farm profit as a result of avoiding or reducing subsoil compaction.
- Training, and particularly on-farm training, designed to show graphically the dangers of deep cultivation and subsoiling and the vulnerability of soils once they are loosened. Aspects of deeper working should include the increased cost of fuel, wear and tyres and the negative effects on water availability.
- Machinery design and operation. Lighter machines, better management of operations, automation and the general embracing of new technologies. Attention to detail in all aspects of the farming business.
- Further research to a) determine pre-consolidation stress from undisturbed subsoils and b) investigation of the approach of tabulating historical tyre inflation pressures to identify the stress history on different farms. Further, to integrate these data with those determined from the approach of Spoor et al. (2000).

8. Conclusions

The Group has identified a range of operations within a number of countries that have the potential to create subsoil compaction. In parallel, a member of the Group has pursued with other researchers, the possibility of identifying those subsoils in Europe that are susceptible, and through climatic factors, are actually vulnerable to the stresses that might be imposed by critical operations. These two approaches need close integration to determine whether, by inspection and measurement, those subsoils recognised as vulnerable are actually negatively effected by the critical operations identified. Negative effects need to be illustrated on a range of levels, including those that farmers can readily detect in their own fields through their own efforts and expertise. Environmentally negative effects alone will not be sufficient to promote change in working practices: monetary incentives that can be clearly identified, whether these emanate from added costs, poorer crop yields or reduced subsidies associated with soil structural damage, are also needed.

Training which allows farmers to determine the most appropriate course of action on their own farms is a pre-requisite for reducing the risk of subsoil compaction.

9. References

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