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

Proceedings of the first workshop of the Concerted Action 'Experiences with the impact of subsoil compaction on soil, crop growth and environment and ways to prevent subsoil compaction', 28-30 May 1998, Wageningen, The Netherlands

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ABSTRACT

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Subsoil compaction is persistent and affects highly productive soils and heavily mechanized agricultural land. About 50 % of the European subsoils are moderate to highly vulnerable to compaction. The extent and complexity of wheel/soil/crop/climatic interactions require a multidisciplinary approach to the problem and an uniform design of experiments and measurements. Data is lacking to run and validate models used to assess maximum allowable wheel loads and to predict effects of too heavy wheel loads on soil properties, crop growth and environment under a range of weather conditions. The Concerted Action was initiated to collect and combine experiences and data on subsoil compaction. An overlook of subsoil compaction research in Western Europe is presented.

Keywords: review, soil compaction, soil degradation, state of the art, subsoil compaction

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Contents

INTRODUCTION

In case of arable land with annual ploughing topsoil and subsoil compaction can be distinguished. In the scope of sustainable agriculture subsoil compaction is much more a problem than topsoil compaction. A severely compacted topsoil which is loosened annually will recover in one or some years. Even a topsoil which is not artificial loosened, can recover partly by biological and weather influences. Subsoil compaction is very persistent especially in case of soils with a low clay content. Subsoil loosening costs great effort and a high energy input and loosened soil is highly susceptible to recompaction making a system of loosening the subsoil every 4 to 5 years necessary. Severe subsoil compaction is caused by heavy machinery used during harvest and the spreading of slurry with heavy tankers. Another important cause of subsoil compaction is the passage of tractor wheels on the subsoil through the open furrow during ploughing. Soil compaction mostly affects highly productive soils and heavily mechanized agricultural land. Due to the increasing weights and wheel loads of farm vehicles, subsoil compaction is becoming an urgent soil conservation problem. Subsoils low in clay content with hardly any crack and structure development during drying are most sensitive to subsoil compaction. These loamy and sandy soils cover large areas in a connected band starting in The Netherlands, Belgium and northwestern France and going east passing Germany, Denmark, Poland up to the Baltic States and the former Soviet Union. Contrary to erosion subsoil compaction is not easily detected without specific measurements. Therefore the area affected by this type of soil degradation tends to be underrated. Altogether about 50 % of the European subsoils are moderate to highly vulnerable to compaction. In most countries with a wet climate and heavy machinery farmers are aware of the risks of subsoil compaction. In the southern European countries subsoil compaction was a long time not an important research issue. However, now the interest for soil degradation by subsoil compaction is increasing and subsoil compaction proves to be a problem in southern Europe too.

The extent and complexity of wheel/soil/crop/climatic interactions require a multidisciplinary approach to the subsoil compaction problem. Greater uniformity in the design of traffic experiments and in the measurement of the impact of compaction on soil properties, crop growth and environment is required to create a basis for scientific understanding of the subsoil compaction problem. Models are likely to be an effective way to assess the maximum allowable wheel loads on subsoils and predict the effects of too heavy wheel loads on soil properties. The impact of subsoil compaction on crop growth and environment under a range of weather conditions can be predicted with models. However, considerably more data must be collected before such models can be fully developed and subsequently validated for general application.

These were reasons to initiate the Concerted Action "Experiences with the impact of subsoil compaction on soil, crop growth and environment and ways to prevent subsoil compaction" which is supported by the Commission of the European Communities, Directorate-General for Agriculture, DG VI.F.II.3, Contract No: FAIR5-CT97-3589. The Concerted Action started January 1, 1998 and will end December 31, 2000. The Concerted Action is described in more detail in the next chapter of these proceedings.

These proceedings concern the papers presented during the first workshop of the Concerted Action, the Concerted Action on Subsoil Compaction, 28-30 May 1998, Wageningen, The Netherlands. All participants are acknowledged for their contribution.

J.J.H. van den Akker, coordinator of the Concerted Action ""Experiences with the impact of subsoil compaction on soil, crop growth and environment and ways to prevent subsoil compaction"

DESCRIPTION OF THE CONCERTED ACTION "EXPERIENCES WITH THE IMPACT OF SUBSOIL COMPACTION ON SOIL, CROP GROWTH AND ENVIRONMENT AND WAYS TO PREVENT SUBSOIL COMPACTION"

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Preface

The description of the Concerted Action "Experiences with the impact of subsoil compaction on soil, crop growth and environment and ways to prevent subsoil compaction" is based on the Technical Annex to Contract No: FAIR5-CT97-3589 between the Winand Staring Centre for Integrated Land, Soil and Water Research (SC-DLO) in Wageningen and the Commission of the European Communities, Directorate-General for Agriculture, DG VI.F.II.3. The Concerted Action started January 1, 1998 and will end December 31, 2000.

Introduction

Soil compaction is estimated to be responsible for the degradation of an area of 33 million ha in Europe (Soane and Van Ouwerkerk, 1995). However 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 and results of natural loosening or artificial loosening techniques have been disappointing (Kooistra, 1984). A compacted subsoil is economically and environmentally suboptimal. 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. A healthy subsoil, which is a habitat for soil fauna and flora, is an environmental aim in itself, a precondition for organic farming. A subsoil with good soil physical qualities allows plants to make optimal use of nutrients and water and permits reduction of inputs. A 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 kECU. 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 kECU. 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 tonnes of grain (7 - 8% total yield), two million tonnes of sugarbeet (3%), and half a million tonnes of maize (4%). During ploughing, annual fuel consumption is claimed to be one million tonnes 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.

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.

Objectives

The general objectives of the concerted action are:
- bring experts together in order to create a representative working group on subsoil compaction, involving 14 EC member countries, Switzerland, Norway and Poland;
- make a contribution to an economically viable and environmentally friendly agriculture, based on an exchange of scientific knowledge and practical experience concerning subsoil compaction and ways to prevent it;
- identify soils and farming systems throughout Europe where there is a risk of significant subsoil compaction;
- disseminate the results effectively throughout the EC by means of publications, harmonization of methods and creation of databases;
- identify gaps in current knowledge on subsoil compaction and determine the need for further research.

Three specific objectives will need to be met to fulfill the general objectives and make the Concerted Action successful.

1) Construction of three databases compatible with related important soil databases. The three databases to be constructed involve: (a) literature on subsoil compaction; (b) impact of subsoil compaction on soil physical properties, crop production and environment; (c) soil mechanical properties.

2) Publication of conclusions and results in national and international reviewed soil science journals and at an International Soil Science Conference.

3) Submission of one or more EC-proposals for further research to fill in gaps in current knowledge on subsoil compaction.

Main tasks

Six tasks can be distinguished. Task 1 concerns the organization of the CA and the Workshops. The other Tasks are defined in accordance with the specific objectives.

Task 1: Organization of Concerted Action and Workshops

Coordination by coordination board: J.J.H. van den Akker (SC-DLO), J. Arvidsson (SLU) and R.Horn (CAU-Kiel)

Task 2: Construction of database 'Literature on subsoil compaction and soil mechanical properties'
Coordination: J.J.H. van den Akker (SC-DLO)

Task 3: Construction of database 'Impact of subsoil compaction on soil physical properties, crop production and environment'
Coordination: J. Arvidsson (SLU)

Task 4: Construction of database 'Soil mechanical properties'
Coordination: R. Horn (CAU-Kiel)

Task 5: Identification of gaps in data and knowledge; inventory and selection of methods and design field experiments resulting in recommendations; provision and dissemination of conclusions and results
Coordination: J.J.H. van den Akker (SC-DLO)

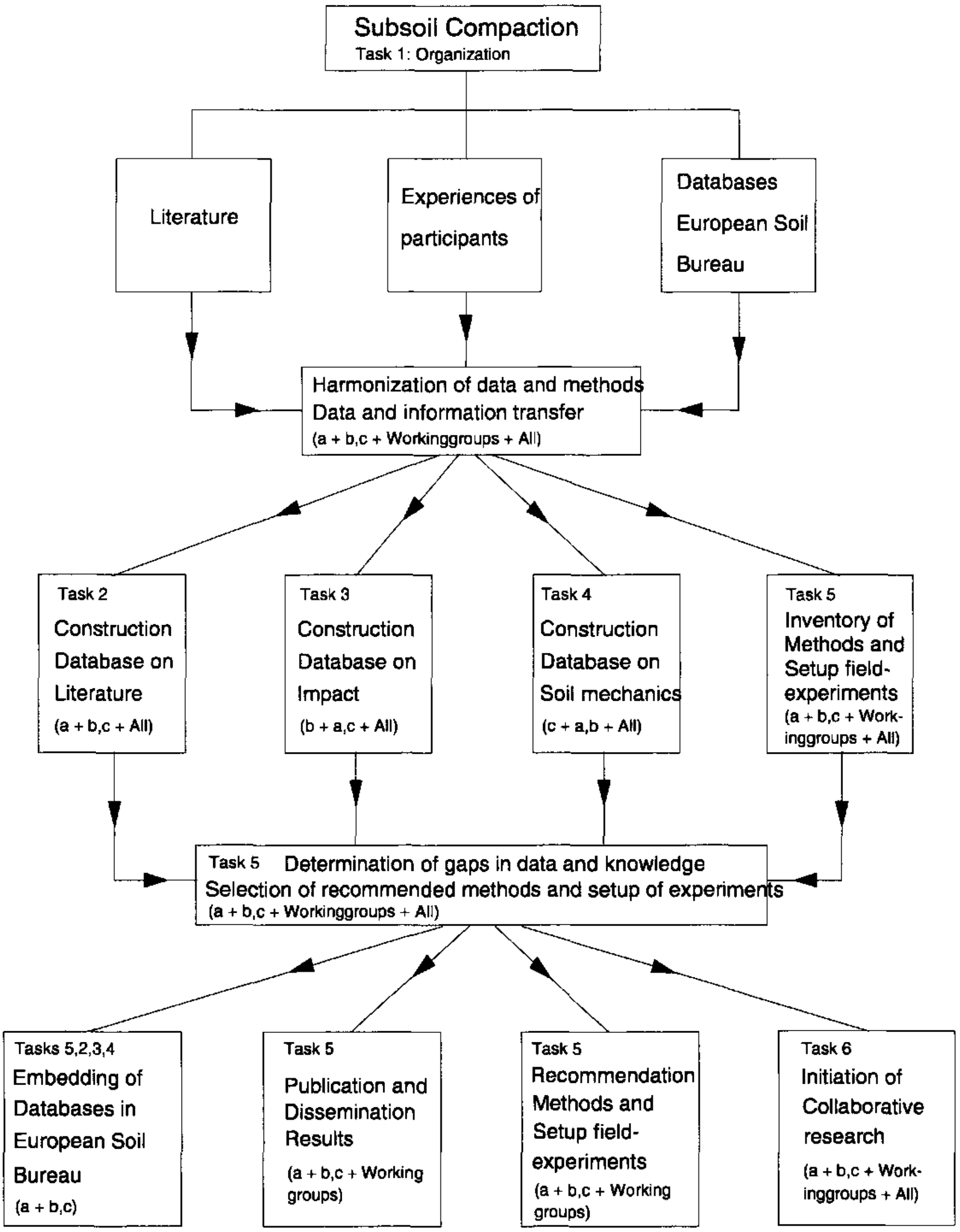
Task 6: Determination of required research, initiation of collaborative research
Coordination: J.J.H. van den Akker (SC-DLO)

An overview of the methodology for implementing the CA is presented in figure 1

Results
Results to be expected from the Concerted Action are:

1. Proceedings of the workshops, a final report and papers offering a synthesis of the information and data provided by the participants. Subjects considered in the proceedings, reports and papers include:

i) impact of subsoil compaction on soil physical properties, crop production and the environment throughout Europe;
ii) ways to prevent subsoil compaction;
iii) recommended methods to determine the strength of (sub-)soils;
iv) recommended ways to set-up field experiments to study the impact of subsoil compaction on crop production and the environment;
(v) gaps in current knowledge and recommended research.



a = Coordinator, J.J.H. van den Akker, SC-DLO
b = Subcoordinator, J. Arvidsson, SLU
c = Subcoordinator, R. Horn, CAU-Kiel
Initiative and responsibility for the action decreases from left to right

Figure 1. Implementation of the Concerted Action on the impact of subsoil compaction on soil, crop growth and environment and ways to prevent subsoil compaction.

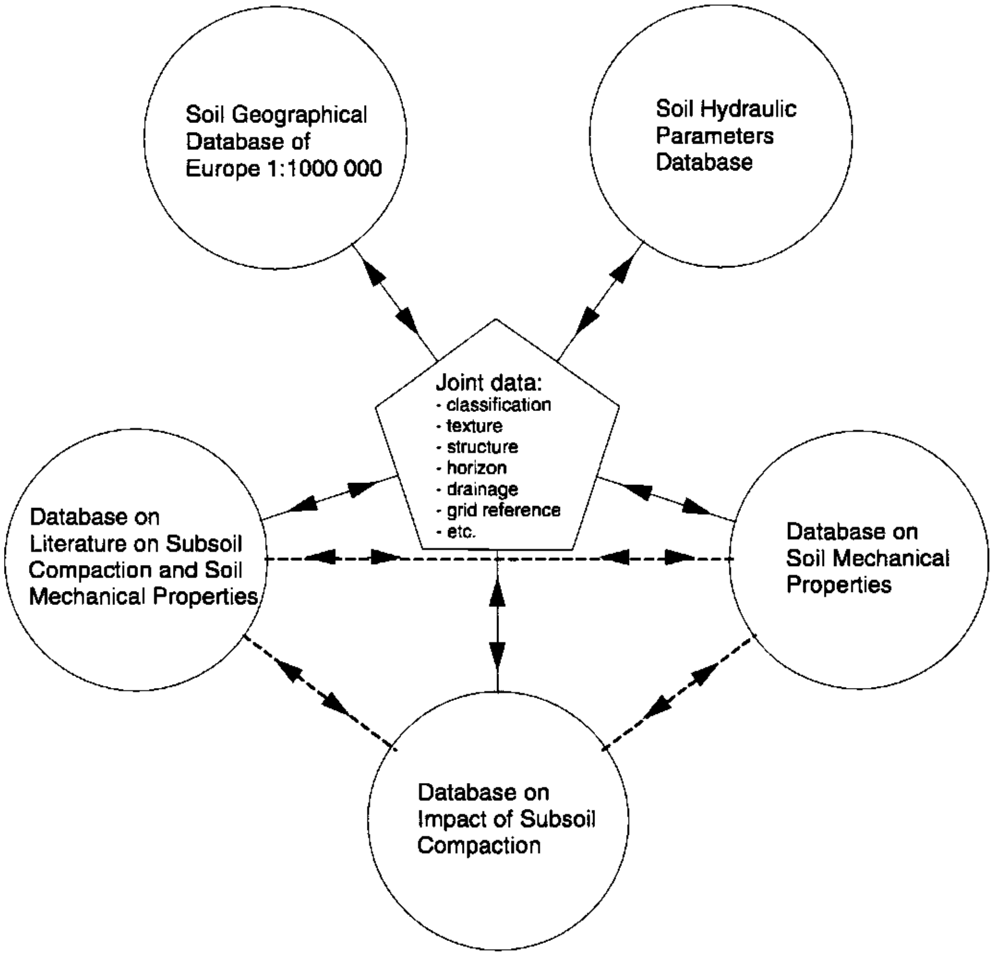


Figure 2. Compatibility of the databases of the CA to the soil databases of the ESB. The dashed lines represent the inter-relations between the databases of the CA through keywords and codes.

2. Three databases which are compatible with the soil databases of the European Soil Bureau (Montaranella, 1997):

i) a database of literature on subsoil compaction;
ii) a database on the impact of subsoil compaction on soil physical properties, crop production and environment;
iii) a database on soil mechanical properties.

3. Optimized dissemination of scientific and practical conclusions and results will be achieved by:

- publications in international reviewed scientific journals;
- contributions to national journals, conferences, meetings of national and international societies etc.;
- contributions to magazines for farmers and consultants;
- production of practical guidelines;
- publication of results of the CA on a special Internet site;
- publication of a newsletter;
- publication of a brochure.

4. Collaboration in future research and proposals. This must be the result of the improved and extended collective knowledge and interest of the participants resulting from discussions, the harmonization of methods and data, the identification of gaps in current knowledge and the assessment of research required.

The databases will be compatible with important databases such as the Soil Geographical Database of Europe 1 : 1 000 000 and the Soil Hydraulic Parameters Database (see figure 2) and related databases such as the Soil Profile Analytical Database for the European Union (Madsen and Jones, 1995), and will enable researchers of subsoil compaction and related fields to take the effects of subsoil compaction into account in, e.g., crop growth and environmental impact models, water management, land evaluation and scenario studies. The information will be easily available to consultants and allow them to improve their recommendations, taking into account the effects of subsoil compaction on crop production and environment and to provide well-founded advice on measures to prevent subsoil compaction. The database of soil mechanical properties makes it possible to compute allowable wheel loads.

Special attention will be given to the effect of subsoil compaction on the availability of soil water to plants. Subsoil compaction hampers root development, and in some soils the rooting depth is even restricted to the topsoil. This means that part of the soil water, including dissolved nutrients, is unavailable for use by the plants. This increases the need for irrigation and also makes the use of available irrigation water less than optimal.

The dissemination through national and international reviewed journals will include a special issue of an international journal on soil science/agricultural engineering. This will provide a very effective presentation of the databases, their construction, structure and use, computation of allowable wheel loads, limitations and gaps in data and knowledge, as well as a presentation of the best methods to measure soil mechanical properties and to investigate the impact of subsoil compaction on crop production and the environment, and the results of a first exploration of the databases.

The project will pay special attention to making the results easily available to many potential users. The databases to be initiated will be compatible with the soil databases of the European Soil Bureau (Montaranella, 1997), which means they can be easily used in land evaluations on the effects of subsoil compaction based on crop growth and environmental impact models. This offers the opportunity to implement and use the results of the project in, e.g., the CORINE information system and the MARS programme. Due to lack of data, however, some parts of the EU will only be marginally covered. A future extended and more complete database will allow the translation of the scientific output into a readily accessible information retrieval system in the form of maps and GIS and will enable the research results to be of immediate use to decision makers.

This will allow the evaluation of:
- existing and future agricultural machinery in relation to its potential damaging effect on the subsoil structure;
- areas that should be treated with special care;
- the need for legislation regulating the machinery allowed to access the agricultural land;
- the effect of subsoil compaction on rooting depth and so on soil water availability.

Because the project is linked to a successful working group of the International Soil Tillage Research Organization, results will be widely disseminated and will have their implications not only on an European but also on a world-wide scale.

Benefits

Economic benefits

The costs of subsoil compaction in Europe are not precisely known. However as was stated in the introduction, annual costs in the EU can be estimated at several hundreds of millions of ECUs. The quantification of the problem will be improved by the construction of the database on the impact of subsoil compaction on crop growth, soil physical properties and the environment, both directly, i.e., through the inventory of the effects of compaction on crop growth and yield throughout the EU, and indirectly by providing the required input data for simulation of the effects of subsoil compaction on crop growth. A healthy subsoil is a requirement for high quality products produced in an environmentally friendly way. The improved knowledge of the impact of subsoil compaction on crop production will result in prevention of subsoil compaction where required and will contribute to a competitive European agriculture.

Environmental benefits

Subsoil compaction decreases the water storing capacity and water conductivity, resulting in increased erosion risk. A compacted subsoil hampers rooting and restricts rooting depth. Prevention of subsoil compaction results in a healthy subsoil, which promotes efficient use of nutrients and reduces the so-called 'inevitable' loss of nitrogen in crop production, resulting in a better balance between nitrogen input and output. This 'inevitable' loss of nitrogen includes N_2O, a powerful greenhouse gas. The low permeability of the subsoil can result in too wet, anaerobic situations for the roots, and the hampered rooting makes the plant susceptible to draught. In these circumstances the plant is vulnerable to diseases and plagues, requiring more agro-chemicals. Prevention of subsoil compaction will thus reduce the use of agro-chemicals.

Benefits to the development of environmentally and economically sustainable agriculture and to the management of natural resources

Subsoil degradation by compaction decreases crop production and increases the risks for the farmer and the environment. Measures to reduce both nutrient inputs and technical solutions such as drainage and irrigation can make the effect of subsoil compaction more manifest and can sometimes have catastrophic effects on crop production and the environment. This frustrates i) the farmers in implementing environmental measures and ii) the aims of the EC to develop a more environmentally friendly and economically viable agriculture. A healthy subsoil allows plants to make efficient use of nutrients and water and makes crops less vulnerable to climatic extremes. This makes a low input system more profitable and less hazardous and synchronizes the interests of farmers and the environment.

Benefits to organic and ecological farming

Organic and ecological farming systems use minimized ploughing depth to prevent disturbance of the soil system as much as possible. Such systems aim to minimize the input of nutrients and ban the use of chemicals. A healthy subsoil is essential in such systems, and prevention of subsoil compaction is even more urgently required than in regular agriculture.

Benefits to end-users

A better understanding of the susceptibility of subsoils to compaction and of the load-bearing capacity of subsoils allows a more precise determination of where, when and how subsoil compaction can be prevented. This enables consultants to give well-founded and more precise recommendations. Without enough knowledge, the risk of compaction may not only be underestimated, but, also overestimated, resulting in unnecessary prevention costs.

Benefits to the improvement, consolidation and harmonization of agricultural research in Europe

The present Concerted Action brings together field knowledge and expertise on theory and modeling of soil compaction in all countries in Europe. Surveying and sharing of experience and data, which is envisaged in this Concerted Action, will contribute significantly to a better understanding of the risks of subsoil compaction in different field soils under different climatic conditions. The harmonization and recommendation of measurement methods and ways to design field experiments will promote standardization. The collective effort will promote the acceptation and use of these methods, resulting in the expansion of the databases initiated.

Expertise and role of the participants

All participants are experts on soil compaction research, specifically on soil mechanical properties and the impact of subsoil compaction on the different soils and climates in Europe. The expertise can broadly be grouped into four areas:

1. soil management and tillage;
2. soil mechanics and soil physics;
3. effects of soil and subsoil compaction on crop growth, crop yield and economics;
4. interaction between tyre and soil, tyre performance, agricultural engineering.

Many participants combine expertises. The combining expertise and knowledge of the partners will improve our insight into the problems relating to subsoil compaction and ways to prevent it. The tasks of the participants will be:

- contributing to the databases;
- contributing to the survey of methods and designing of experiments;
- participating in and contributing to the workshops;
- playing their roles in assessing recommendable methods and designing experiments;
- taking part in the dissemination of results and the initiation of collaborative research.

In this concerted action, the coordinator J.J.H. van den Akker (SC-DLO) and the subcoordinators J. Arvidsson (SLU) and R. Horn (CAU) will be responsible for the organization of the three workshops and the creation of the three databases.

The coordinator, subcoordinators and their institutes are leading experts on subsoil compaction, on both the European and world scale. They will take a leading part in the coordination and stimulation of the inventory of experience on: (1) the impact of subsoil compaction on soil, crop production and the environment; (2) ways to prevent subsoil compaction; (3) ways to set-up field experiments; (4) methods to measure soil mechanical properties. The coordinator and subcoordinators will play the same role in the assessment of recommended methods to measure soil strength properties and of recommended designs for field experiments. In the latter activity they will be assisted by individual participants or participants organized in small working groups.

J. Arvidsson (SLU) will be responsible for the development of the database on the impact of subsoil compaction on soil, crop production and the environment. The SLU has a long history of field experiments on subsoil compaction, especially on its impact on crop production and on the persistence of subsoil compaction. It has collected data of field experiments at about 100 sites with various soils all over Sweden. In 1980-1992, it coordinated the activities of the "Working Group on Subsoil Compaction" within the International Soil Tillage Research Organization (ISTRO).

R. Horn (CAU-Kiel) will be responsible for the development of the database on soil mechanical properties. The soil physics group of the Christian Albrechts University at Kiel has created a large and expanding database on soil mechanical properties in relation to soil texture, soil structure and soil physical properties. The measurement procedure developed to obtain the required soil mechanical and soil physical data has been introduced and is currently used in many other institutes and countries.

J.J.H. van den Akker (SC-DLO) will be responsible for the database of literature on subsoil compaction. SC-DLO is closely related to the Winand Staring Library, part of the Wageningen Library system (PUDOC), and specializes in soil, water, land use, GIS and remote sensing topics. J.J.H. van den Akker (SC-DLO) will manage the overall coordination of the three databases to be created and the coordination with the soil databases of the European Soil Bureau. SC-DLO has a great deal of experience in the construction and evaluation of databases, soil surveys and GIS. The Soil Survey of the Netherlands is an integrated part of SC-DLO, and the institute plays an active role in the creation of the soil databases of the European Soil Bureau, especially in the construction of the 1 : 250 000 Soil Geographical Database of Europe and the Soil Hydraulic Parameters Data set.

Coordination/subcoordination

The coordinator J.J.H. van den Akker and the two subcoordinators J. Arvidsson and R. Horn together form the coordination board. The coordination board will meet two or three times a year and keep in touch by correspondence, E-mail etc. Each coordinator or subcoordinator will be responsible for the construction of one of the databases. They are responsible for setting up the structure of the databases in such a way that they are compatible with each other and with the databases of the European Soil Bureau. The same goes for setting up the format of the (electronic) forms to be filled in by the participants contributing to the databases. The quality of the databases will be the responsibility of the particular coordinator or subcoordinator and of the coordination board. Each coordinator or subcoordinator will make a description of their database and make it accessible. The coordinator J.J.H. van den Akker is responsible for the general communication with the participants. Each coordinator or subcoordinator will be responsible for the organization of a workshop and for composing the proceedings in collaboration with the other members of the coordination board. The assessment of the gaps in current knowledge and data, recommended methods and design of field experiments and future research requirements will be a joint effort of all participants, coordinated by the coordination board and chairmen of working groups. The same goes for the dissemination of the results of the Concerted Action. One of the tasks of the coordinator will be to identify, with the aid of the subcoordinators and other participants, the gaps in current data and knowledge, and to indicate priorities in filling these gaps. The next step will be to take the initiative to start the required collaborative research. This will be the responsibility of the coordinator and other participants, although, the coordinator will take the initiative for at least one EC proposal. In addition the coordinator and subcoordinators will encourage collaborative research.

Communication
Communication between participants will be by correspondence, meetings, and E-mail. An Internet site will be constructed with up to date news, provided by the coordination board, indicating the progress of the CA. The Internet site will provide (controlled) access to the databases. All participants in the CA will be encouraged to contribute to the Internet site. In addition, an annual summary newsletter will be produced by the coordination board.

Dissimination
Copies of the proceedings of the workshops will be disseminated to the participants, the libraries of the participating institutes, relevant major libraries in the world, and EU-DG VI. Moreover, the report of the final workshop will be disseminated free of charge to relevant institutes throughout the EU. Conclusions and results of the Concerted Action will be disseminated through publications in international reviewed journals, contributions to national journals, conferences, meetings of national and international societies, etc. The second workshop will be combined with a European conference on subsoil compaction, allowing the exchange of experiences with especially Eastern European researchers. The Subsoil Compaction Internet site will be an important medium in the dissemination of the results of the Concerted Action and will provide (controlled) access to the databases.
Special attention will be given to providing consultants and farmers with practical information and conclusions.

Reporting to the EU-DG VI
An annual report will be submitted to EU-DG VI, detailing the work undertaken during the year and the results obtained from that work, in accordance with the Commission's guidelines. A draft final report and a final report will be submitted during the final year of the project.

The Commission will be invited to attend the Workshops.

The databases will be demonstrated in Brussels and will be diffused towards CORINE and MARS.

The EU-DG VI will receive:
- copies of all papers produced as a result of the CA;
- the proceedings of the workshops with a short report on the workshops;
- 50 copies of the final report for internal use and/or rediffusion;
- copies of a brochure highlighting the results of the CA.

During the period of the CA, the coordinator will be available to attend Progress Meetings in Brussels if requested.

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Workplan

TASK	DATES	PARTICIPANTS
Initial prepatory work	1997/1998	Akker, SC-DLO, J. Arvidsson, SLU and R. Horn, CAU-Kiel)
Setup structure databases		Coordination board
Setup Newsletter		Coordinator (J.J.H. van den Akker)
Setup Internet site		Coordinator (J.J.H. van den Akker)
Inventory experience, available data, methods and experiments of participants on (sub-)soil compaction in relation to soil mechanical properties and impact on soil physical properties, crop production and environment		Coordinator, all
Preparation contribution to first workshop		All
First workshop (3 days, Wageningen, NL)	May 1998	Coordinator (J.J.H. van den Akker) (+ subcoordinators, J. Arvidsson and R. Horn)
- Presentation structure and organization CA		Coordinator (J.J.H. van den Akker)
- Presentation and inventory of experience, methods, experiments and data available on (sub-)soil compaction in relation to soil mechanical and physical properties, crop production, environment		All
- Presentation proposed structure databases		Coordination board
- Discussion on and determination of database structure, information transfer and harmonization of data and methods		All
- Determination time table		
- Formation working groups on specific subjects		All, J.J.H. van den Akker
Produce Proceedings Workshop 1	Sept. 1998	Coordinator (J.J.H. van den Akker) (+ J. Arvidsson and R. Horn)
Providing forms	1998	Coordination board
Providing data	1998/1999	All
Creation databases	1998-2000	Coordination board
Preparation contribution to second workshop	1998/1999	All
Presentation CA at ISSS conf. Montpellier (FR)	Aug. 1998	Coordination board
Second workshop combined with European conf. on subsoil compaction (Kiel, DE, 3 + 2 days)	May 1999	Subcoordinator (R. Horn, CAU) (+ J.J.H. van den Akker, J. Arvidsson)
- Presentation progress construction databases		Coordination board
- Determination gaps in knowledge and data on soil and subsoil compaction in relation to soil mechanical and physical properties, crop production and environment		Coordination board
- Review by external experts		
- Reports working groups		Working group leaders
- Field/lab. excursion		Subcoordinator (R. Horn)
- Determination of recommended methods and recommended setup of field experiments		All
- Initiative on joint publications and research		All, J.J.H. van den Akker
- Formation working groups on specific subjects		All, J.J.H. van den Akker
Produce Proceedings Workshop 2	Sept. 1999	Subcoordinator (R. Horn) (+ J.J.H. van den Akker, J. Arvidsson)
Providing data	1998/1999	All
Finishing databases	May 2000	Coordination board
Preparation contribution to third workshop	1998/1999	All

Third workshop (Uppsala, SE, 3 days)	June 2000	Subcoordinator (J. Arvidsson, SLU) (+ J.J.H. van den Akker and R. Horn)
- Presentation databases on subsoil compaction: (1) Literature; (2) Impact and (3) Soil mechanical properties		Coordination board
- Determination gaps in knowledge and data on (sub-) soil compaction in relation to soil mechanical and physical properties, crop production and environment		Coordination board
- Field/lab. excursion		Subcoordinator (J. Arvidsson)
- Final reports working groups		Working group leaders
- Determination of recommended methods and recommended setup of field experiments.		All, coordinator (J.J.H. van den Akker) subcoordinator (J. Arvidsson)
- Determination of ways and guidelines to prevent subsoil compaction.		All, coordinator (J.J.H. van den Akker) subcoordinator (J. Arvidsson)
- Initiative on joint publications and research		All, coordinator (J.J.H. van den Akker)
- Presentation of future joint research		Coordinator (J.J.H. van den Akker)
Produce Proceedings Workshop 3	July 2000	Subcoordinator (J. Arvidsson) (+ J.J.H. van den Akker and R. Horn)
Transfer databases to European Soil Bureau	2000	Coordination board
Dissemination of results by joint publications	1998-2001	All, coordinator (J.J.H. van den Akker)
Presentation results at ISTRO Conference	July 2000	All, coordinator (J.J.H. van den Akker)
Production of brochure	Sept. 2000	Coordinator (J.J.H. van den Akker)
Draft final report	Dec. 2000	Coordination board
Final report	Feb. 2001	Coordination board

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FINNISH EXPERIENCE AND RESEARCH ON SOIL COMPACTION AND MOBILITY

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Abstract

A review is made of Finnish soil compaction and mobility experience and studies. The direct, long-term and cumulative effects of field traffic on soil physical properties and crop growth were examined in field experiments on fine-textured soils. Likewise, field experiments where the possibilities to avoid soil compaction by using a light, unmanned tractor were commenced. The effects of field traffic on (sub)soil macroporosity and crop yield were determined with a large number of parameters, and soil stress measurements were started.

Field traffic with a single axle load of 5 Mg compacted moist fine-textured mineral soil below the normal ploughing depth of 0.2 m, and traffic with an axle load greater than 11 Mg compacted it to 0.40-0.50 m depths. The compaction of the plough layer of clay persisted for three years following the single heavy loading despite annual ploughing, cropping and natural weathering. Changes in subsoil properties (below 0.25 m) were still measurable in clay, loam and organic soils nine years later despite cropping and natural processes. Light tractor traffic reduced the compaction of clay soil in the 0-0.20 m depth compared to the traffic with conventional (5 Mg) tractor. More experimental years will, however, be needed for the evaluation of the effects of the light tractor on subsoil compaction and crop growth.

Mobility studies contained the examinations of ploughing forces, tyre construction and extra ballast effects on tractor drawbar performance. Measurement system to examine forces between plough and tractor was designed and tested. Specific ploughing resistance, ploughing draught and changes in ploughing draught on undulating field were determined. Specific ploughing resistance increased rapidly when ploughing depth was increased from 0.20 m. The increase in ploughing speed clearly increased ploughing draught.

Wheel slip and rolling resistance of a combine harvester were measured and drawbar pull, tractive efficiency and wheel slip of a tractor with four different type of tyre constructions were determined in field conditions. Likewise, the effect of tractor weight on fuel consumption and work rate was determined. Combine harvester and tractor mobility was markedly improved by tyre selection. On slippery and soft clay field wheel slip was 2% when the tyres diameter of 850 mm was used in the rear axle of combine harvester. The slip increased to 23% when the tyre diameter was reduced to 650 mm. When cross-ply tyres were replaced by radial tyres, the wheel slip reduced from 23% to 9%. On clay and organic soil, the drawbar force of tractor equipped with low profile or corresponding radial tyres was better than that of tractor equipped with low profile half radial tyres. Likewise, the reduction of tyre inflation pressure clearly improved the drawbar performance. Relevant to the weight of tractor, the extra ballast on rear axle improved work rate and fuel efficiency.

Laura Alakukku
Experience with soil compaction

Soil compaction experiments

Subsoil compaction due to field traffic has been studied in field experiments at MTT since 1981. Main part of the experiments were located on fine-textured mineral soils which are common in southern part of Finland (Table 1). The studies carried out can be separated into three themes: (A) examinations of direct, short-term, long-term and cumulative effects of heavy loading, (B) examinations of possibilities to avoid subsoil compaction and to recover its effects, (C) examinations of soil stresses due to field traffic.

The direct, short-term and long-term effects of heavy loading were examined in field experiments (Table 1), where the high axle load traffic was applied in the beginning of the experiment. After that the field traffic due to field operations was relatively light. The cumulative effects of annually repeated field traffic were investigated in the same field experiment for four years (Table 1). Soil and crop properties determined during the experimental periods are shown in Table 1. Published results of these field experiments and also data on weather conditions during growing season and soil freezing during winter time is available for the CA.

The effects of tyre construction on the tractive performance of tractor and clay loam and organic soil compaction were examined in field experiments at MTT/VAKOLA (Elonen et al., 1995). In 1995 was commenced a study where clay soil compaction is controlled in two field experiments by using a light unmanned tractor. The objectives are to determine the effects of light field traffic on soil macroporosity, to investigate the functioning of a soil-plant system in ploughless tillage and to examine the effects of light field traffic on runoff and erosion. Those field experiments will be continued to year 2000. Some data on light tractor study is already available (Table 1).

Initial simple field experiments to examine the recovery of compacted subsoil by bioprocesses (biological tillage) were carried out. In field experiments on fine-textured soils, the effects of crop rotation and reduced tillage on physical properties of compacted (by heavy field traffic (two experiments) or natural structure poor (one experiment)) were examined. Likewise, an examination of the ability of the roots of different crops to create macropores in compacted clay subsoil was carried out. Unfortunately, most of the data is not yet published.

In connection with the light tractor study, also soil stresses were examined in field experiments. The objective is to determine the effects of stresses on top- and subsoil macroporosity in field conditions. Some measurements on clay soils have been made (Pöyhönen et al., 1997a) and the measurements are planned to continue in 1998-2000.

Measurement methods

The parameters used to determine the effects of field traffic are shown in Table 1. Particle size distribution (PD) was determined by pipette method (Elonen, 1971) and organic carbon content (OC) by dry combustion method (Sippola, 1982). Measurements on the fields were made and undisturbed soil samples for laboratory analyses were taken early in spring or late in autumn when the soils were at or near field capacity. The soil penetrometer resistance (PR) was determined with a hand-held recording penetrometer reported by Anderson et al. (1980). Soil dry bulk density (BD) was determined by gravimetric method.

In 1982-1984 (Table 1), small soil samples (200 cm^3) were used in laboratory analyses. Soil pore size distribution (MP) was estimated from the drying limb of the water-retention curve at a potential of -1 kPa on a sand bed and at a potential of -10 kPa on a pressure plate. Since 1990, greater soil samples (0.15 m in diameter, 0.55 m long) were used in laboratory analyses. Samples can be taken with a tractor driven soil auger (Pöyhönen et al., 1997b). In the laboratory, samples were usually cut into three subsamples and saturated hydraulic conductivity ($K_{sat,}$ constant head method), macroporosity (MP, on ceramic plates at potentials of -3 to -10 kPa, corresponding to

Table 1. List of soil and crop properties determined during the experimental periods. Soil particle size distribution (PD), organic carbon content (OC), macroporosity (MP), penetrometer resistance (PR), dry bulk density (BD), saturated hydraulic conductivity (K_{sat}) and bioporosity (BP) were determined to 0.55 m depths. Soil moisture conditions (TDR) were measured at 0-0.30 m layer and soil stress (VS) at 0.22 m depth. Grain yield (GY), seed moisture content at harvest (SMH) and nitrogen yield (NY) of annual crops (mainly cereals) were determined.

	Measurements made in experiments in different years						
	Direct, short-term effects in 1990-95		Compaction persistence since 1981			Cumulative compaction, in 1985-89	Light tractor, since 1996
Property	Clay loam	Silt	Clay	Organic soil	Loam	Clay loam	Clay
PD	1990	1990	1981	1981	1981	1985	1995
OC	1990	1990	1981	1981	1981	1985	1995
MP	1990, -95	1990, -94	1982-84, -90,-96$^{1)}$	1982-84, -90	1990		1996-97
PR	1990, -95	1990, -94	1990	1990		1987-89	1996-97
BD	1990, -94	1990, -94				1989	
K_{sat}	1990, -95	1990, -94	1990, -96$^{1)}$	1990	1990		1996-97
BP	1990, -95	1990, -94	1990, -96$^{1)}$	1990	1990		1996-97
VS	1990, -95	1990, -94	1990, -96$^{1)}$	1990	1990		1997
TDR							1996-97
STR							1996-97
GY	1991-95$^{2)}$	1991-94$^{2)}$	1982-97$^{1)}$	1982-90		1986-89	1996-97
SMH	1991-95$^{2)}$	1991-94$^{2)}$	1982-97$^{1)}$	1982-90		1986-89	1996-97
NY	1991-95$^{2)}$	1991-94$^{2)}$	1982-97$^{1)}$	1982-90		1986-89	1996-97

1) unpublished data since 1991
2) unpublished data

a minimum pore diameter of 100 to 30 µm) and bioporosity (BP, number and cross-sectional area of cylindrical biopores (≥ 2 mm)) were determined, and soil structure was described (VS) for the profile as presented in Alakukku (1997a). Soil moisture condition was determined by TDR (Time Domain Reflectometry, Soil Moisture Equipment Corp.) technique at 0-0.3 m layer during the growing seasons. The measurement system used to determine soil vertical stress (VS) is shown in Figure 1. The grain yield (GY), moisture content at harvest (SMH) and nitrogen uptake (NY) of crops were determined as reported in Alakukku and Elonen (1995a,b).

Review of Finnish compaction research

In Finland growing the season is short: in southern part of country the thermal growing season is 165 to 180 days and in northern part 110 to 145 days. Thus, slurry spreading, seedbed preparation and sowing should be done early in spring and often the crops are harvested and primary cultivated late in autumn. The risk of (sub)soil is severe since the heaviest machines of farm are used and soils are often moist during those operations. Soil compaction is found to be a problem especially in southern part of Finland where clay soils are common and mainly annual crops are grown.

Soil compaction due to field traffic has been studied in Finland since mid-1960s. Many field experiment were carried out where the compaction during seedbed preparation of spring cereals (Elonen, 1980, Aura, 1983), sugar beet (Raininko, 1988, Erjala, 1991) and carrot (Pietola, 1995) were examined. The extent and persistence of (sub)soil compaction owing to high axle load traffic has been studied since 1981 (Alakukku, 1996a,b, Alakukku, 1997b, Alakukku and Elonen, 1995a). Also the possibilities to avoid soil compaction by using dual (Aura, 1983) and low pressure tyres (Alakukku and Elonen, 1995b, Elonen et al., 1995) and combined field operations (Raininko, 1988) were investigated. Alakukku and Elonen (1997) examined the deep loosening of soil, and Alakukku (1998) made primary field experiments pertaining to biological tillage.

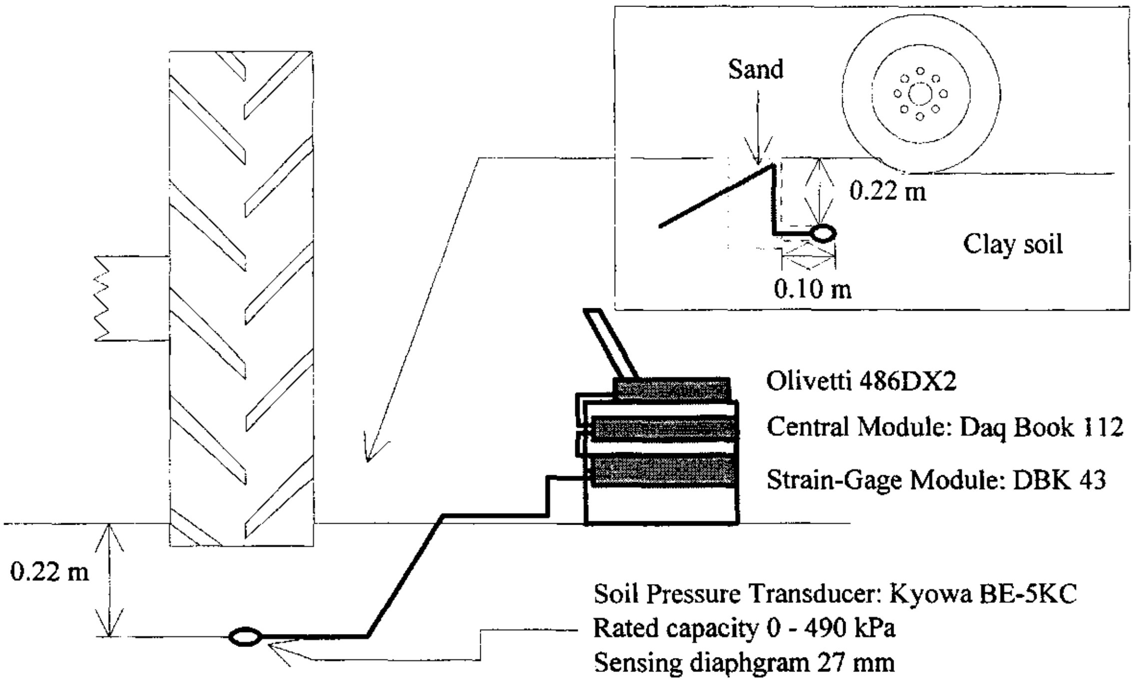

Figure 1. System used to determine in situ vertical stress in soil due to field traffic (Pöyhönen et al., 1997a).

Likewise, Simojoki et al. (1991) investigated in a laboratory the effects of compaction on soil air. In the present researches, the possibilities to avoid soil compaction by using light, unmanned tractor in conventional and conservation tillage systems are examined (Alakukku et al., 1997, Pöyhönen et al., 1997a).

Soil compaction during seedbed preparation

Elonen (1980) and Aura (1983) investigated the effects of tractor traffic in spring on spring cereal yield and soil porosity in six field experiments on fine-textured soil for four years. The clay content (particle size less than 2 µm) of the soils was 0.25 to 0.65 g g^{-1} in topsoil (0-0.20 m) and 0.24 to 0.76 g g^{-1} in layer of 0.20-0.40 m. The rear axle load of the tractor was 3 Mg and tyre inflation pressure 140 kPa.

The tractor traffic compacted most seriously the soil below the harrowed layer at the depth of 0.10-0.25 m (Aura, 1983). When seedbed preparation and sowing were performed under wet conditions about one week before normal sowing time, soils were compacted more seriously than when the field operations were carried out in normal time. Aura (1983) found that only under very wet conditions the traffic compacted the subsoil (Table 2).

Elonen (1980) reported that as a mean of four years, the clay soil compaction due to field traffic before seedbed preparation (two passes with single tyres before seedbed preparation wheel track completely covering the plot area) when the soils were wet reduced the grain yield of spring wheat by 19% compared to normal seedbed preparation with dual tyres. Likewise, Saarela et al. (1988) found that the compaction (two extra passes) reduced the nitrogen yield of spring wheat by 21%. The grain yield was significantly reduced when the volume of macropores (> 30 µm) was reduced to 10% or less (Aura, 1983). Interestingly grain yield was greater in normal seedbed preparation plots (tractor with dual tyres) than in uncompacted (no field traffic) plots. Elonen (1980) expected that this was owing to coarse seedbed in uncompacted plots. In the present study, the silt soil (clay content 0.25 g g^{-1}) was not found to affect by the field traffic (Elonen, 1980, Aura, 1983, Saarela et al., 1988).

At the Sugas Beet Research Centre, Raininko (1988) and Erjala (1991) compared conventional cultivation technique (three passes tillage + separated sowing and fertilization) to one pass system

Table 2. Depth of soil compaction due to field traffic with different axle loads in different soil conditions.

Soil		Axle load	TIP[1]	Compaction	
Type	Moisture	(Mg)	(kPa)	depth (m)	Reference
Fine sand	> FC	3	120[2]	0.25-0.30	Pietola (1995)
Silt	< 0.3 m FC[1]	11	600	0.50	Alakukku (1997b)
Clay loam	Near FC	5	150/350	0.35	Alakukku and Elonen (1995b)
Clay loam	85-90% of FC	21[3]	800	0.40-0.45	Alakukku (1997b)
Clay	Near FC	3	140	0.20	Aura (1983)
Clay	> FC	3	140	0.40	
Clay	> FC	3	120	0.25-0.30	Pietola (1995)
Clay	Near FC	19[3]	700	0.50	Alakukku (1996a)
Mull	> FC	3	120[2]	0.35	Pietola (1995)
Sedge peat	> FC[4]	16[3]	700	0.40-0.50	Alakukku (1996a)

1) TIP is tyre inflation pressure, FC is field capacity

2) average ground contact stress

3) tandem axle

4) sedge peat mixed with clay from 0.20 m to 0.40-0.50 m depths, and underlain gythia

(combined seedbed preparation, placement of fertilizer and sowing) on clay and silt soils for three years. They found that one pass method increased sugar beet hectare yield by 5% and crystallizable sugar yield by 4% in normal sowing time, and by 14 and 17%, respectively, when the beet was sown early. Likewise, the one pass system saved working time on average by 21% and fuel consumption by 13% (Raininko, 1988). Erjala (1991) reported that the yield increase was caused by several positive effects: decrease in soil compaction since all field traffic was eliminated from the cropped area, better use of nutrients and earlier sowing made possible by reduced compaction. Relevant to compaction, soil penetrometer resistance and vane shear strength were lower and macroporosity greater in the plough layer of 0.25 m when the one pass system was used (Erjala, 1991).

The effect of soil compactness on the growth and quality of carrot was studied by Pietola (1995). She carried out field experiments on fine sand, clay and mull. She determined the effects of field traffic (one or three passes with a tractor wheel tracks of rear axle completely covering the plot area) on soil physical properties, carrot yield, external and internal quality and fibrous root system for three years (Pietola, 1995).

Traffic with a tractor of rear axle load 3 Mg and average ground contact stress 120 kPa compacted the moist fine sand and clay to 0.25-0.30 m depths and the mull soil deeper (Table 2). Pietola (1995) found that compaction changed carrot external quality (short, deformed and conical tap roots with greater maximum diameter). Carotene and sugar contents were, however, only slightly affected by changes in soil physical properties. Soil compaction increased the fibrous root length and surface area to 0.30 m depths. Pietola (1995) reported that probably the larger surface area of fibrous root system promoted the carrot to maintain high levels of carotene and sugar contents in tap roots despite soil compaction.

Extent of compaction due to high axle load traffic

The direct, short-term, long-term and cumulative effects of high axle load traffic on soil physical properties and crop growth were studied in field experiments (Table 1). The soils contained 0.28 to 0.48 g clay (< 2 μm) g^{-1} in the topsoil and 0.36 to 0.65 g g^{-1} in the subsoil. Persistence of soil compaction was also investigated on an organic soil consisting of well-decomposed sedge peat mixed with clay below a depth of 0.20 m down to 0.40-0.50 m depths, and underlain by gythia. The long-term experiments were part of an international study on the effects of high axle loads on soils, coordinated by the working group on soil compaction by vehicles with high axle load within the International Tillage Research Organization (ISTRO) (Håkansson et al., 1987).

The experimental traffic was applied with a tractor-trailer combination or lorry. In the field experiments investigating the direct, short-term and long-term effects of compaction, soils were loaded with a tandem axle load of 16 to 21 Mg or with a single axle load of 11 Mg (Alakukku, 1996a,b, 1997b). Tyre inflation pressures (TIP) were 600 to 800 kPa. In the cumulative compaction experiment, the trailer single axle load was 5 Mg (TIP 150 or 350 kPa), and the experimental traffic was applied before autumn ploughing for four successive years (Alakukku and Elonen, 1995b). In loaded treatments (1 and 3 or 4 passes), wheel tracks completely covered the plot area. There was also a control treatment without experimental traffic. Except on one field, the mineral soils were near to field capacity (FC) during loading and the organic soil was moister than FC. The persistence of soil compaction was studied for 4 to 16 years after a single heavy loading. During this time, the main crops grown were spring cereals (barley, oats, wheat). In all experiments, the maximum axle load applied during field operations was 5 Mg and the maximum TIP was 400 kPa.

The direct, short-term and long-term effects of compaction were determined with a large number of parameters (Table 1). Soil measurements were concentrated on the soil macroporosity since macroporosity is important in determining soil properties and behaviour. The parameters examined were chosen to take into account both the volumetric and the non-volumetric changes in soil macroporosity. Even though many crop parameters were investigated (Table 1), except the short-term study (unpublished data) the parameters were only measured from the harvested grain yield. Measurements relevant to crop growth and soil properties during the growing seasons clearly would have enhanced the information about the soil/crop/weather interactions.

Field traffic with a single axle load of 5 Mg compacted moist mineral soil to 0.35 m depth, and traffic with an axle load greater than 11 Mg compacted it to 0.40-0.50 m depths (Table 2). The tandem axle load of 16 Mg compacted the organic soil to 0.40-0.50 m depth (Table 2). The increase loading passes increased intensity of compaction (Alakukku, 1997a).

Heavy loading changed many (sub)soil properties affecting soil workability, drainage and crop growth (Alakukku, 1996a, 1997b). In the direct compaction examination, soil properties were determined one day after a heavy loading (Alakukku, 1997b). Despite the heavy loading increasing soil dry bulk density, penetrometer resistance and homogeneity, the K_{sat} of the soils remained high (greater than 1 cm h^{-1}). Likewise, cylindrical burrows (> 1 mm) were present in all treatments in both soils. The vertical continuity of the burrows was usually reduced by compaction, but in the subsoil of the clay loam some large burrows (> 4 mm) escaped compaction, thus markedly increasing the K_{sat} of soil (Alakukku, 1997b). The present results indicated that fine-textured mineral (sub)soil with good natural structure can maintain moderate structure despite compaction due to high axle load traffic (Alakukku, 1997b).

Persistence of compaction

Elonen (1980) and Aura (1983) reported that compaction in the plough layer of clay soils due to traffic with an axle load of 3 Mg prior to seedbed preparation was relieved by ploughing and frost by the following spring. In the long-term study, the compaction of the topsoil (0.10-0.20 m) of the clay persisted three years (Table 3, Alakukku, 1996a) and that of clay loam in cumulative compaction study at least one year (Alakukku and Elonen, 1995b) after the loading despite annual ploughing, cropping and natural weathering. In the short-term experiments, the heavy loading ceased to have any significant residual effect on topsoil (0-0.20 m) properties by the fifth year (Alakukku, 1998).

The subsoil compaction (below 0.25 m) persisted in the clay, loam and organic soils nine years after the single heavy loading affecting many important soil properties (Table 3, Alakukku, 1996b). Likewise, Simojoki et al. (1991) found that when the clay soil was moist, O_2 content decreased and CO_2 content increased more in the compacted than in control plots below the

Table 3. Soil porosities in control (0) and with four passes (4) loaded treatments as means of the first three years after the heavy loading in the clay and organic soils, and soil properties in clay, loam and organic soils in the ninth year after the loading (Alakukku, 1996a,b).

	Total porosity ($m^3 m^{-3}$)		Macropores $\phi > 30$ μm ($m^3 m^{-3}$)		Penetrometer resistance (MPa)		K_{sat} ($cm h^{-1}$)		Macropores $\phi > 300$ μm ($m^3 m^{-3}$)		Pores[2] $\phi > 1$ mm (number m^{-2})	
Layer[1]	0	4	0	4	0	4	0	4	0	4	0	4
	Clay soil in 1982-1984				Clay soil in 1990							
P	0.56	0.54	0.18	0.15	0.79	0.80	590	482	0.148	0.122	322	265
M	0.50	0.46	0.10	0.07	1.90	2.25	28	14	0.022	0.019	406	130
B	0.51	0.48	0.07	0.06	1.83	2.16	31	0.5	0.015	0.005	133	145
					Loam soil in 1990							
P					-[3]	-	666	936	0.149	0.136	-[3]	-
M					-	-	42	14	0.043	0.029	474	321
B					-	-	10	4	0.029	0.017	208	95
	Organic soil in 1982-1984				Organic soil in 1990							
P	0.69	0.69	0.21	0.21	0.47	0.45	69	57	0.088	0.097	-[3]	-
M	0.73	0.69	0.25	0.15	0.94	1.21	79	31	0.049	0.036	-	-
B	0.74	0.71	0.20	0.10	0.83	1.21	8507	926	0.157	0.099	-	-

1) in 1982-84: P: 0-0.2 m, M: 0.2-0.4 m, B: 0.4-0.6 m.1990: clay P: 0-0.21 m, M: 0.21-0.41 m, B: 0.41-0.55 m; loam: P: 0-0.25 m, M: 0.25-0.4 m, B: 0.4-0.55 m; organic soil: P: 0-0.21 m, M: 0.21-0.36 m, B: 0.36-0.53 m

2) cylindrical pores > 1 mm were classified as earthworm (Alakukku, 1996b)

3) property was not determined

ploughing depth of 0.2 m in the seventh year after the loading. Also in the short-term experiment, the subsoil compaction (below 0.25 m) persisted in both soils four to five years, for the duration of the experiment, in spite of cropping and deep freezing (Alakukku, 1998). Annually repeated traffic (5 Mg) for four years caused no cumulative effects at the depth of compaction, nor any yield losses (Alakukku and Elonen, 1995b). Except in the first year, the clay loam (Table 1) was drier than FC in the 0.20-0.30 m layer, which probably impeded further subsoil compaction.

For several years after the single heavy loading, the compaction clearly affected yields and nitrogen uptake of annual crops on clay and organic soils (Fig. 2, Alakukku and Elonen, 1995a). Severe lodging of crops in the control complicated the interpretation of results for years two to six after loading (Alakukku and Elonen, 1995a). Soil compaction decreased crop lodging, thereby reducing the negative effects of compaction on crop growth.

Taken as a mean of the first eight years, compaction of the clay soil with four passes reduced the yields by 4% and nitrogen uptake of annual crops by 9%. For the most part, soil compaction reduced also the moisture content of annual crops in the same years as it reduced the yields (Alakukku and Elonen, 1995a). This can be explained by accelerated plant ripening in compacted plots. Interestingly nitrogen yield was found to be a more sensitive measurement of the influence of soil compaction than was grain yield (Fig. 2).

The effects of subsoil compaction on the yields seemed to depend on the weather during the growing season. After the three first years, yield changes were most pronounced in the rainy sixth year after the compaction (Fig. 2). Likewise, according to my unpublished data, clay soil compaction reduced still the grain yield by 8% and the nitrogen yield by 11% in the rainy 14th year after the loading. In that year, the precipitation of June was 118 mm (average 47 mm). When the beginning of the growing season was dry, the subsoil compaction had little effect on the yields (Alakukku and Elonen 1995a). On reason may be that in the present study the drought reduced

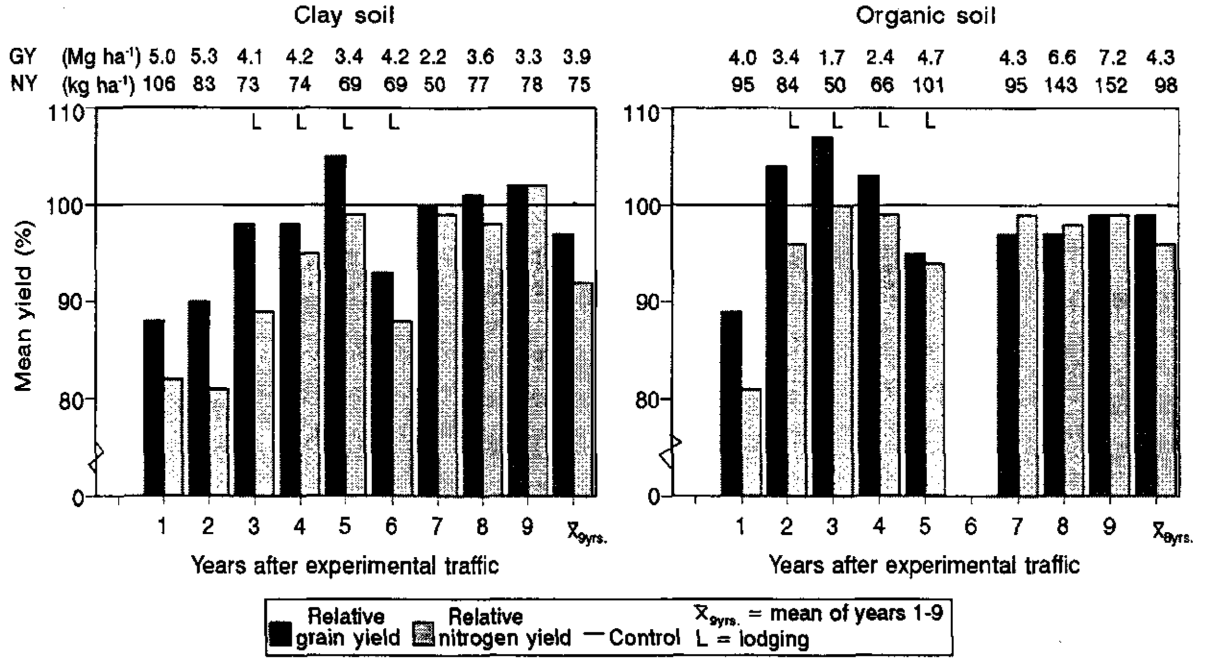

Figure 2. Mean grain (GY) and nitrogen (NY) yields of annual crops in control (=100%), and relative to control in loading treatments of four passes in 1981 on soils, for nine (1-9) successive years after the loading. In the sixth year the crops failed in all plots on the organic soil and the results were rejected.

the yields in all plots on the clay. Likewise, fine cracks and biopores present in the compacted clay soil (Alakukku, 1996b) provided pathways for root growth, even though the soil penetrometer resistance was high and the soil structure massive.

Prevention of compaction

Elonen (1980) found that dual tyres on the rear axle of tractor reduced the yield losses owing to seedbed preparation field traffic by 3% compared to single tyres. Trailer (axle load 5 Mg) tyre inflation pressure reduction from 350 to 150 kPa by using low-profilile tyres did not lessen clay loam compaction or yield losses due to compaction for the reasons discussed in (Alakukku and Elonen, 1995b). Raininko (1988) and Erjala (1991) reported that using one pass system in sugar beet seedbed preparation and sowing reduced compaction clearly. Raininko (1988) pointed out that the reduction of the number of passes was more important way to prevent soil compaction than changes in tyre construction.

Field experiments investigating the possibility to avoid soil compaction in two tillage systems by using a light, unmanned tractor were commenced at MTT in 1995. In fixed field experiments were examined the effects of light field traffic on soil macroporosity and functioning of soil-plant system when small grain cereals were grown (Alakukku et al., 1997). In separate field experiments were investigated the dynamic stresses transmitted to soil by the light tractor and the effects of the dynamic stress on soil physical properties (Pöyhönen et al., 1997a). Field experiments were on clay soils having 0.60 to 0.74 g clay (< 2 µm) g^{-1} in the topsoil and 0.60 to 0.83 g g^{-1} in the subsoil. The light tractor (2.5 Mg, rubber tracks 2000 mm length, 320 mm width) was used in tillage and sowing operations. In control plots medium size, conventional (weight 5 Mg, tyre inflation pressure 80-100 kPa) was used in those operations. Tractors were compared in two primary tillage systems: ploughing to 0.2-0.25 m depth, and stubble cultivation to 0.1 m depth. Details of the field traffic and tractors can be found in Alakukku et al. (1997) and Pöyhönen et al. (1997a).

Soil and crop parameters examined in the field experiments are given in Table 1. The preliminary results of field experiments show that in both conventional (autumn ploughing) and conservation (autumn stubble cultivation) tillage, the peak vertical stress in clay soil at 0.22 m depth was clearly less with a light tractor than the conventional tractor (Pöyhönen et al., 1997a). Further stress and soil measurements are needed, however, for a proper evaluation of the effects the dynamic stresses on top- and subsoil structure in different tillage systems.

According to results from measurements in the fixed experiments in 1996, in both tillage systems the light tractor traffic compacted the 0-0.20 m layer less than the conventional tractor traffic. In that layer, soil saturated hydraulic conductivity (K_{sat}) and macroporosity (> 300 µm, M) were:

	Autumn ploughing		Autumn stubble cultivation	
	Light tractor	Medium-size tractor	Light tractor	Medium-size tractor
K_{sat} (cm h^{-})	168	75	79	35
M (m^3 m^{-3})	0,128	0,097	0,099	0,095

Even though the plough layer of the light tractor plots was less compacted than that of the conventional tractor plots, there was no significant reduction in yield. In 1995, only the results of ploughed plots were available for the reason given by (Alakukku et al., 1997). As an average of years 1996 and 1997 (four yield years) the grain yield was in ploughed plots when the light tractor was used 4820 kg ha^{-1} and 4700 kg ha^{-1} when the medium-size tractor was used. In stubble cultivated plots the yields were 4690 (light) and 4730 (medium-size) kg ha^{-1}. For each three years, we had problems in seedbed preparation and sowing operations when the light tractor was used. Those problems probably affected the yields. More experimental years will be needed for the evaluation of the effects of the light tractor on subsoil compaction and crop growth.

Deep loosening and biological tillage

The effects of deep loosening on the structure of compact soil were investigated in 17 field experiments conducted on mineral soils in southern Finland (Alakukku and Elonen, 1997). Most of the field experiments were established in autumn, after the crops had been harvested. In seven experiments, which examined the effect of soil moisture content during loosening, also uncropped soil was loosened (bare fallow or ploughed). The soils were loosened to 0.70-0.80 m depths, as far as possible perpendicular to the drainage.

The effects of deep loosening on crop yield were investigated in the subsequent 3 years. Main crops grown were small grain cereals and sugar beet. 43 crops were harvested during the experimental period. The yields were not significantly affected by deep loosening. The mean difference in relative yields between deep loosened and control treatments was 1 percentage unit. Likewise, in many field experiments, the bearing capacity of the loosened soil was clearly poorer than that of soil in control plots. These results showed that mechanical deep loosening of soil seldom can ameliorate the structure of compacted soil in Finnish conditions.

A preliminary study, where was examined the recovery of compacted subsoil by bioprocesses (biological tillage), where particular cultivation methods and crop rotation were applied to enhance the functioning of those processes, was carried out in 1990-1995 (Alakukku, 1998). According to the penetrometer resistance results, the subsoil compaction (below 0.25 m) persisted in clay loam and silt soils in all four cultivation treatments for the duration of the experiment (Alakukku, 1998). Cultivation method was found to affect the physical properties of the soils. However, for proper evaluation of the effects of cultivation method on the properties of compacted soils, more detailed information on macro- and bioporosity and the continuity of the pores is required.

Jukka Ahokas

Experiments and review of mobility studies

1 Ploughing studies

1.1 *Instrumentation*

During the past we have done quite a lot of ploughing studies (Ahokas 1994, Ahokas & Mikkola, Ahokas 1994, Ahokas 1996). The purpose of these studies has been to measure the forces between the plough and the tractor. From these forces both the specific ploughing forces, the forces acting on the tractor and the behaviour of this combination can be calculated. The measuring system which we have used is represented in Fig. 1.

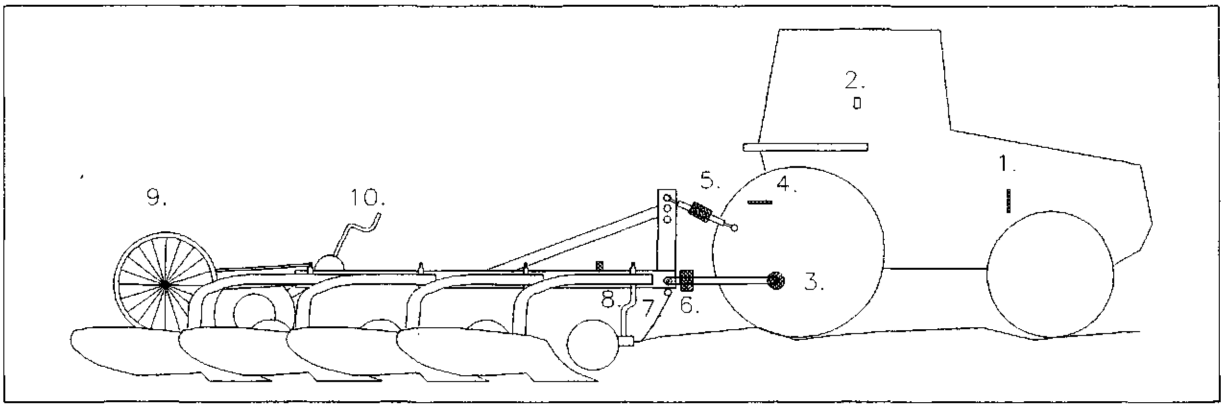

Fig. 1. Locations at which measurements were made. 1. Engine speed 2. Tractor inclination 3. Lower link angle 4. Hydraulic pump pressure 5. Top link force 6. Lower link forces 7. Front ploughing depth 8. First slice width 9. Rear ploughing depth and driving speed 10. Rear wheel support force

Ploughing depth was measured both at the front and at the rear of the plough (Fig. 1 locations 7 and 9). Ploughing width was measured from the first furrow slice by pressing a blade against the furrow edge. The force transducers (Fig. 1 locations 5,6 and 10) measured directly the link forces and the support force of the plough support wheel. Driving speed was measured with the same wheel which was used for rear ploughing depth measurements. The lowering and lifting movements of the tractor hitch were measured with the lower link angle transducer and with the hydraulic pump pressure transducer (Fig. 1 points 3 and 4).

1.2 Coefficients of specific draught

The specific draught can be expressed with two different equations. The first one does not specify the different components of the draught and it is called the 'total specific draught'.

$$F_x = k_t bt$$

F_x = horizontal ploughing force
k_t = coefficient of total specific draught
b = ploughing width
t = ploughing depth

The problem with the total coefficient is that it depends besides the soil condition also on the driving speed. The second equation divides the draught to different components:

$$F_x = k_s bt + \varepsilon btv^2$$

k_s = static coefficient of the draught
ε = dynamic coefficient of the draught

The first term of the equation gives the force at zero speed and the second term adds the effect of the ploughing speed and plough body shape.

1.3 The effect of ploughing depth

In the ploughing depth tests the driving speed was the same in all tests and the total specific coefficient was calculated from the test data. The Cone-index pressures as a function of depth are shown in Fig. 2 and the corresponding total specific draughts are shown in Fig. 3.

The total specific draught has increased clearly after 20 cm depth and the same has happened to soil-index pressures. The specific draught value indicates that the soil resistance was low and the soil was easy to plough.

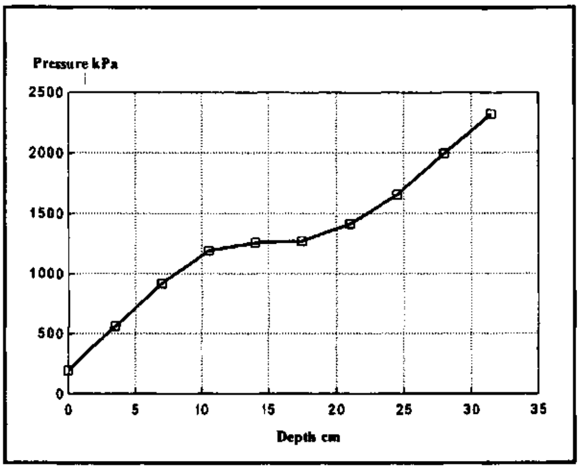

Fig. 2. Cone-index pressures as a function of depth

1.4 The effect of driving speed

In the ploughing speed test only the driving speed was changed and all the other adjustments were kept the same. The ploughing force was plotted against driving speed and a regression function of $y=a + bx^2$ was fitted through the points. From the coefficients of a and b both the static specific draught k_s and the dynamic coefficient ε could be calculated. The results are shown in Fig. 4.

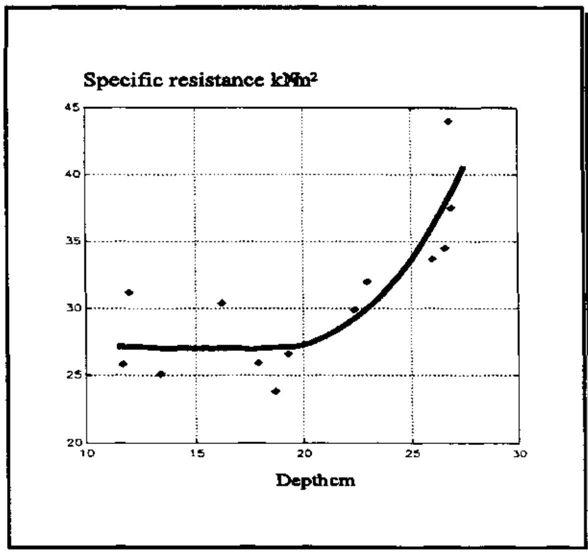

Fig. 3. Specif ploughing resistance as a function of ploughing depth.

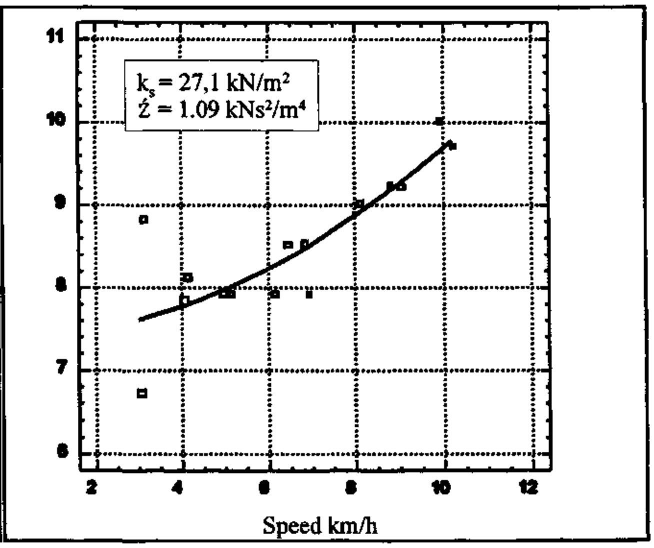

Fig. 4. Ploughing draught as a function of driving speed.

1.5 Changes in ploughing draught on undulating field

With the same instrumentation system it was possible to measure the ground profile and the tests could be done also on undulating fields. In Fig. 5 is an example of ground profile, cone-index values in different parts of the profile and specific draught in the profile.

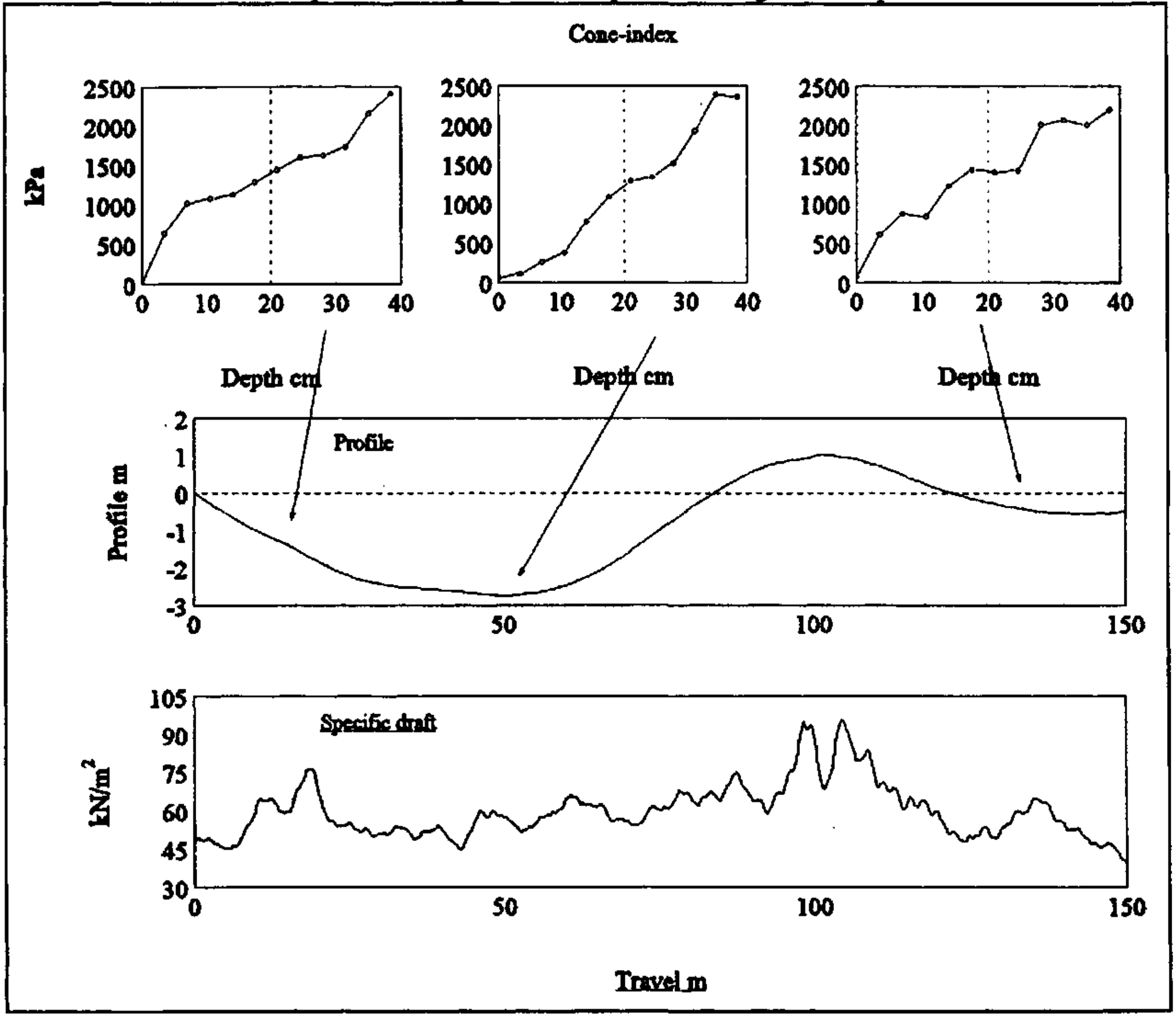

Fig. 5. Changes in specific resistance during a test, top: cone-index values at three points, middle: soil profile, bottom: specific resistance.

2 Tyre tests

2.1 The mobility of combine harvesters

Due to the weather conditions in Finland during autumns it is sometimes quite difficult to move on a soft soil. The yield is valuable and it has to be harvested in order to get money from it. This means that one must drive on wet and soft soils although moving is difficult and the

soil is disturbed by deep truts.

In the study (Mäkelä & Laurola, Mäkelä & al.) different tyre types and rear axle constructions were

Fig. 6. Combine harvester on a wet soil.

of rear axle were measured. The effect of front wheel type is shown in Fig. 7. The original tyre type was a 18.4 - 26 cross-ply tyre. This was replaced by two different makes of radial tyres, with a low profile tyre and with a larger diameter cross-ply tyre. On slippery and soft clay field the largest diameter gave the best results. When it was introduced the tyre slip reduced from 23 % to 2 % which is a considerable change in mobility. When the tyre diameters were same the radial tyres and the low-profile tyre reduced the wheel slip from 23 % into 8 - 9 % but the slip variation range was lower with the radial tyres than with the low profile tyre.

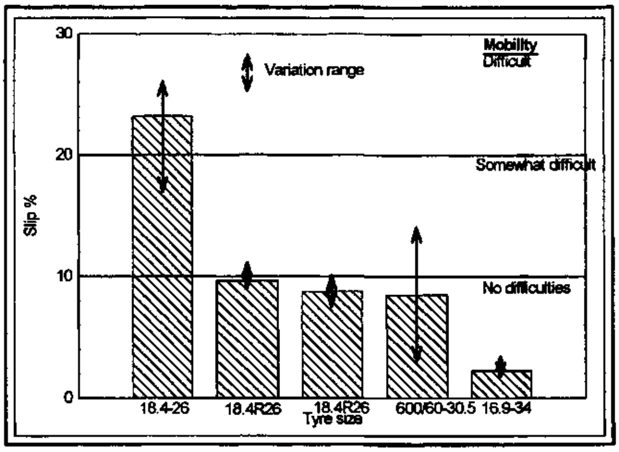

Fig. 7. Combine harvester wheel slip on a wet clay soil.

The rear axle track width, tyre type and rear wheel drive were also tested. When then rear track width was the same as the front track width the rolling resistance was reduced. This was especially so if the rear tyres had same kind of tread as the front tyres (agricultural driving wheel tread). This improved the rolling of the tyres and thus reduced the rolling resistance. Also hydrostatic drive on the rear axle was tested. This improved the mobility of the combine harvester but economically it is often too expensive and adequate improvement can be obtained with better front and rear wheels and rear axle.

2.2 Tractor tyre tests

As with the combine harvester the tractor mobility can be improved with tyre selection. In Fig. 8 test data from two soils is represented (Ahokas & Mikkola). There were five tyres which had the same size and two of these had cross-ply construction and three radial construction. If according to Fig. 8 if the tyre type is changed and the implement draught is the same, there is a clear reduction in wheel slip. In Fig. 8 an example is drawn at 10 kN force and with the radial tyres the wheel slip is reduced 4 to 7 %, which means that work rate is improved almost with the same amount.

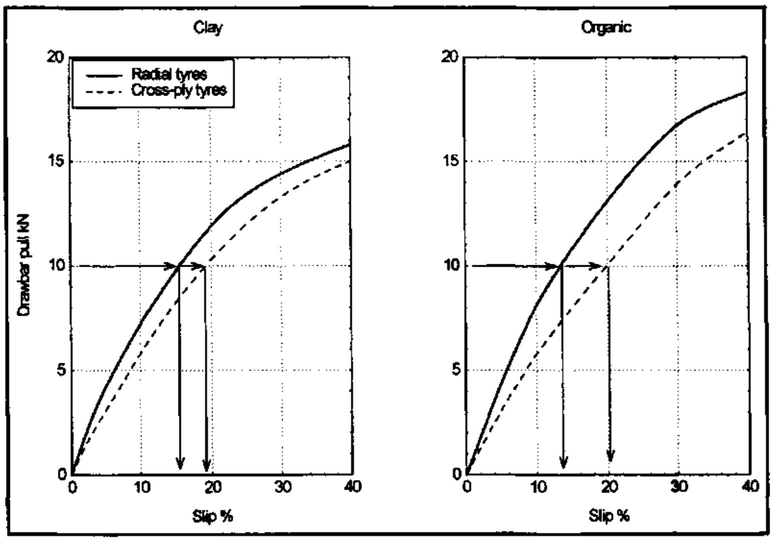

Fig. 8. The effect of tyre type on drawbar pull on two fields.

The tractor tyres have changed during the last years so that besides the radial tyres also low profile radial tyres has been introduced. The low profile tyre has a larger air volume which makes possible to use lower inflation pressures. Radial tyres were compared with low profile radial tyres and with low profile half radial tyres. In Fig. 9 is shown the pull forces of a tractor equipped with different tyres (Elonen & al.). The low profile radial tyre had a little bit better

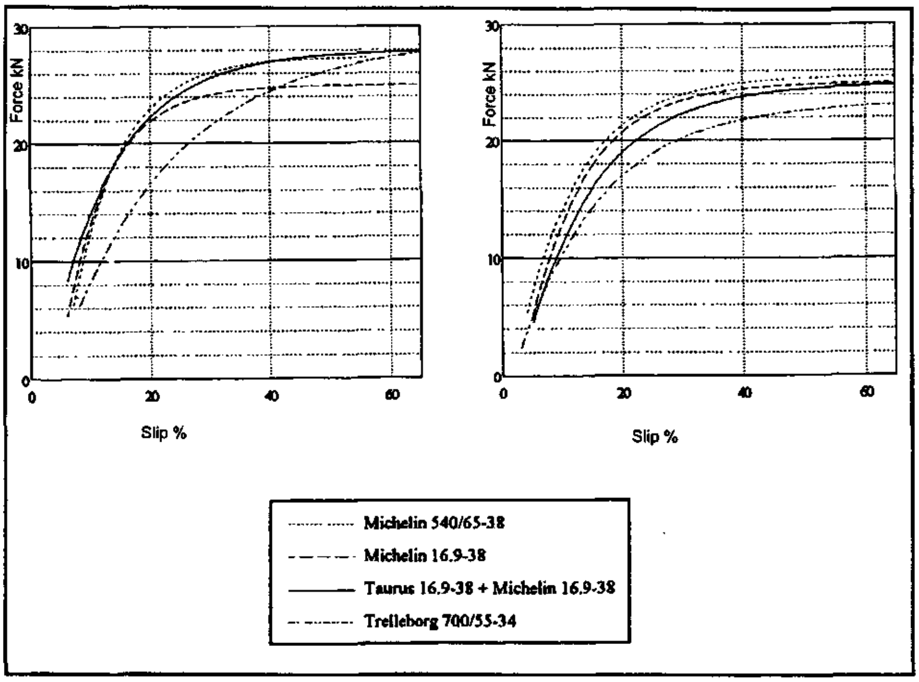

Fig. 9. Drawbar force on two different soils, left: clay and rigth: organic.

drawbar force than the corresponding radial tyre. The low profile half radial tyre had the weakest drawbar performance. In Fig. 9 also a dual configuration is included in the tests. The axle weight was always the same during the tests so that with single tyres extra ballast was used to get the same axle weight as with dual tyres. The dual tyres performed worse than radial tyres but better than the low profile half-radial tyre. In normal use dual tyres increase the axle weight and this normally improves drawbar force. Besides the drawbar pull also the effect of inflation pressure and the riding characteristic were measured. Inflation pressure has a clear effect on drawbar pull, the lower the pressure the better the drawbar performance. The difficulty lies in the loading of the tyres, load capacity can be exceeded with low pressures and this leads to tyre damage. With 'soft' tyres the riding characteristic is different from the 'hard' tyres. Although a soft tyre is more flexible and thus absorbs better obstacles the driving stability is poorer.

3 Tractor weight

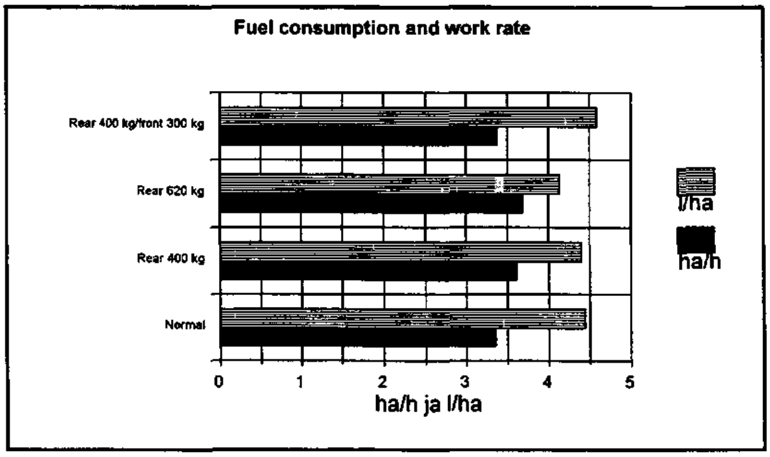

Fig. 10. The effect of extra ballast on fuel consumption and work rate.

Although the weight of the tractor increases the soil deformation and compaction it on the other hand improves drawbar performance. The effect of extra ballast on work rate and fuel consumption can be seen from Fig. 10 (Ahokas & Mikkola).

The tractor was rear wheel driven and the ballast on the rear axle improved work rate and fuel efficiency but ballast on the non driving axle (front) weakened them. Improvement goes normally on as long as the rolling resistance remains moderate. After the tractor sinks deeper into the soil work rate and fuel economy are decreased

Conclusions

Field traffic with a single axle load of 5 Mg and tyre inflation pressure of 150 kPa can compact a moist fine-textured soil below normal primary tillage depth of 0.25 m. Because subsoil compaction tends to be persistent, it increases the risk of long lasting soil physical degradation. Subsoil compaction often also leads to long-term reductions in crop yield. However, the present results suggest that subsoils with a good natural structure can tolerate a single heavy loading and maintain a moderate structure with biopores and relatively large saturated hydraulic conductivity, so avoiding the harmful effects of deep compaction.

Deep loosening seldom completely alleviates the compacted subsoil, and may lead to even worse soil structure after recompaction. Subsoil compaction should be avoided rather than relying on alleviating the compacted structure afterwards. The alleviation of soil compaction by biological tillage by earthworms and plant roots is in need of further study.

In Finnish condition the growing period is short which causes the fact that one has to do the spring work as early as possible and on the other hand the fall work is often done in bad conditions. With proper tyre selection and axle construction mobility can be improved and also soil damage may be reduced. Especially on fine-textured soils, the risk of subsoil compaction is, however, severe during slurry spreading in early spring, and during tillage and harvest. In the long term, new lighter loading practices should be developed. When new practices are developed, the whole farming system and the machinery as part of that system should be examined. Likewise, when the compaction is controlled by changing the farming system, the effects of the changes on the other matters of the system should also be taken account. For instance, if ground contact stress is reduced, will the tractive performance of a machine be worsened.

Interests in CA

In the CA we are interested in following questions:

A) bearing capacity of subsoil
B) soil stress measurements, stress/macroporosity relationship
C) methods and technical solutions to avoid and recover subsoil compaction
E) measurement methods and assessment of their reliability

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SUBSOIL COMPACTION RESEARCH IN SWEDEN - A REVIEW

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Abstract

There has been an extensive research activity concerning subsoil compaction in Sweden. Some different types of experiments are shortly described:
(1) Present field experiments with heavy sugar beet harvesters. (2) Previous experiments with effects on crop yield. (3) Measurements of soil mechanical properties. (4) Measurements of soil displacement during wheeling in old and in ongoing experiments. (5) Measurements of penetration resistance in arable compared to undisturbed land. The emphasis in this investigations has been to study the effects of traffic on bulk density and on crop yield, but also on penetration resistance, shear strength, soil hydraulic properties and air permeability. No measurements were made of for instance root growth or aeration conditions and soil water uptake during the growing season. This makes it difficult to use the results for modelling effects of heavy traffic on soils and crops. The most important result of the research is probably its practical relevance: it has been clearly demonstrated that high axle loads causes compaction to great depth, that compaction increases soil strength and reduces permeability at great depths, and that the effects in the subsoil are very persistent.

Introduction

The climate in Sweden is humid, and much of the traffic in the field is carried out under wet conditions, in the early spring and in the autumn. The arable soils are often clay soils. These are reasons why soil compaction has been of great concern to Swedish farmers, which is also reflected in an extensive program of field experiments carried out during recent 35 years (Håkansson, 1985, Håkansson, 1990, Arvidsson & Håkansson, 1991, Arvidsson & Håkansson, 1995). This program also included research on subsoil compaction, and the activities in this area are reviewed in the present article under the following headings: present research activities; field experiments on crop yield effects; mechanical properties of Swedish subsoils; other experiments and conclusions. The main objective is to show which type of data are available from the experiments, but some results are also presented.

Present research activities

The introduction of six-row sugarbeet harvesters with axle loads of almost 20 tonnes has led to a renewed interest in subsoil compaction research in Sweden. In a project initiated in 1995, two field experiments were started each year in 1995, 1996 and 1997 with the following treatments:

A=control
B=four passes track-by-track with a three-row sugar beet harvester (approx. 18 tonnes total load on four axles)
C=one pass track-by track with a six-row sugar beet harvester (approx. 38 tonnes total load on two axles)
D=four passes track-by track with a six-row sugar beet harvester
E=four passes track-by track with a six-row sugar beet harvester under dry conditions

All traffic except in treatment E was applied under wet conditions in the autumn. Five of the experiments are situated on till soils with clay contents in the topsoil ranging from 12 to 25 %, and one experimental site consists of a wind-blown sand. Some results were presented by Arvidsson (1997).

In the spring, penetration resistance was measured and soil cores (50 mm high, 72 mm in diameter) were taken to determine bulk density and saturated hydraulic conductivity in the four experiments started in 1995 and 1996. Measurements in the experiments started in 1997 are still not completed.

The bulk density and saturated hydraulic conductivity in subsequent spring after autumn traffic are given in Tables 1 and 2. Only treatment A and D are shown for clarity. Except for the last site, the trend was similar; traffic with the heavy sugar-beet harvester increased bulk density and decreased saturated hydraulic conductivity at both 30 and 50 cm depth; differences were statistically significant ($p<0.05$) in many cases. Especially the saturated hydraulic conductivity was a sensitive parameter, and was sometimes reduced to very low values by the applied traffic. Despite the large differences in bulk density and saturated hydraulic conductivity, there were no significant differences in penetration resistance between the treatments in the spring after compaction. The trend was similar on all sites: traffic did not increase penetration resistance in the subsoil, but caused significant increases in the topsoil.

There is yet only few data available on crop yield response from these experiments, but they will be harvested during a 10 year period.

Within the same project, the precompression stress is determined on a number of soils in southern Sweden. Also within the same project are measurements of soil displacement during wheeling. Results are presented in another article in this publication (Arvidsson & Trautner, 1998).

In a new project, measurements of soil displacement during wheeling will be made for different loads at different soil water contents. This will be coupled to determinations of mechanical properties of Swedish subsoils, to estimate the risk for subsoil compaction. The project has just been financed and will be started in 1998.

Table 1. Bulk density (g/cm^3) after field traffic on four sites. Control=no traffic, compacted=4 passes with a six-row sugarbeet harvester

	30 cm		50 cm	
Treatment	Control	Compacted	Control	Compacted
Site:				
Virke	1.68	1.74**	1.57	1.63
Tornhill	1.66	1.67	1.60	1.69
Sandby	1.71	1.84*	1.71	1.79
Hemmesdynge	1.70	1.69	1.64	1.67

Table 2. Saturated hydraulic conductivity (cm/h) after field traffic on 4 sites. Control=no traffic, compacted=4 passes with a six-row sugarbeet harvester

	30 cm		50 cm	
Treatment	Control	Compacted	Control	Compacted
Site:				
Virke	1.89	0.12	8.27	1.44*
Tornhill	2.90	1.21	5.19	0.73*
Sandby	5.78	0.25*	6.7	0.67
Hemmesdynge	1.58	2.52	12.0	6.1

Field experiments with effects on crop yield

A series of field experiments were conducted from 1977 to 1988 with the following treatments:

A=Control
B=One pass by a vehicle with axle load (10 tonnes) in the plot
C=One pass track-by-track with high axle load (10 tonnes)
D=Four passes track-by-track with a high axle load

Nine experiments were carried out in Sweden, and they formed a part of an international series with similar field plans that were conducted in northern Europe and North America (Håkansson, 1994). Main emphasis in the Swedish experiments were on crop yield response, but bulk density and vane shear strength were also determined on some sites. Results have been presented by Håkansson (1985) and Etana and Håkansson (1994). One of the important results is that the soil strength increase in compacted soil persisted also 10 years after traffic was applied (Fig. 1). There was also on average lower yield in the compacted treatments still 7-12 years after traffic was applied. Results from the international series on subsoil compaction were used in a statistical model to estimate effects of traffic on crop yield (Arvidsson & Håkansson, 1991).

Mechanical properties of Swedish subsoils

The most extensive investigation of the mechanical properties of Swedish subsoils under unsaturated conditions was made by Eriksson (1982). Subsoils from 21 sites were compressed in uniaxial compression in sequential steps of 25, 50, 100 200, 400 and 800 kPa. Load was applied for 45 minutes for each step at three water tensions: 0.5 kPa, 10 kPa and 60 kPa. The mechanical properties of the soils were expressed as an equation of the form

$$n=a+be^{cp}$$

where n=porosity, p=applied pressure, and a, b and c are constants. There were no clear relationship between texture and the compressibility of the subsoils. The reduction in pore volume for the 30-40 cm layer at an applied stress of 200 kPa as a function of clay content is given in Fig. 2.

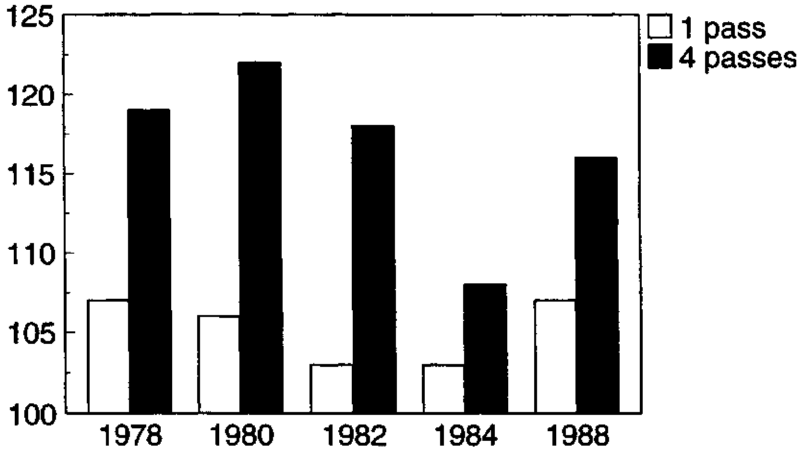

Fig. 1. Relative shear strength (no traffic=100) measured with a shear vane at 35-45 cm depth, average for four experiments with high axle load traffic. Traffic was applied in 1977. After Etana and Håkansson (1994).

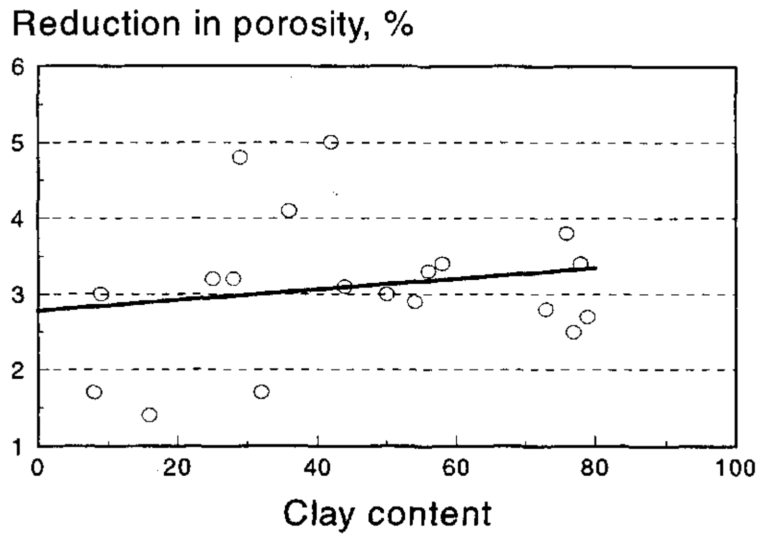

Fig 2. Reduction in porosity after compression with 200 kPa as a function of clay content. Results are for the 30-40 cm layer in 19 Swedish subsoils. After Eriksson (1982).

Other experiments

In 1971-73, soil displacement during traffic with high axle loads were measured by Danfors (1974). Most of the measurements were made on clay soils near Uppsala, with axle loads ranging from 2 to 16 tonnes. The displacement was measured at 30, 50, 80 and 120 cm depth at two different water contents. Complementary to the measurements of soil displacement, measurements were also made of bulk density and air permeability. It was found, that an axle load of 6 tonnes under wet conditions compacted the soil to at least 40 cm depth. Originally based on these results, there is a general recommendation in Sweden that axle loads should be limited to 6 tonnes to avoid subsoil compaction.

Danfors (1994) also measured the impact of inflation pressure on subsoil compaction. At an axle load of 8-10 tonnes reducing the inflation pressure from 150 to 50 kPa reduced compaction at 30-40 cm depth, but had little influence at 40-50 cm depth.

Håkansson et al. (1996) measured the penetration resistance in the subsoil on soils in southern Sweden. Measurements were made on arable land and in adjacent untrafficed soil, normally a garden. As an average from 17 sites, penetration resistance was significantly higher to more than 50 cm depth on the arable land (Fig. 3).

Summary and conclusions

As shown in this review there has been an extensive research activity concerning subsoil compaction in Sweden. The type of measurements made in these experiments are summarized in Table 3. The type of experiments are listed as they were presented in this review.

1. Present field experiments with heavy sugar beet harvesters (Arvidsson, 1997).
2. Previous experiments with effects on crop yield (Etana and Håkansson, 1994).
3. Measurements of soil displacement by Danfors (1974).

As can be seen from table 3, the emphasis in this investigations have been to study the effects of traffic on bulk density and on crop yield. Some measurements have also been made of soil properties that may be related to root growth, such as penetration resistance and shear strength, and of hydraulic properties and air permeability. No measurements were made of for instance root

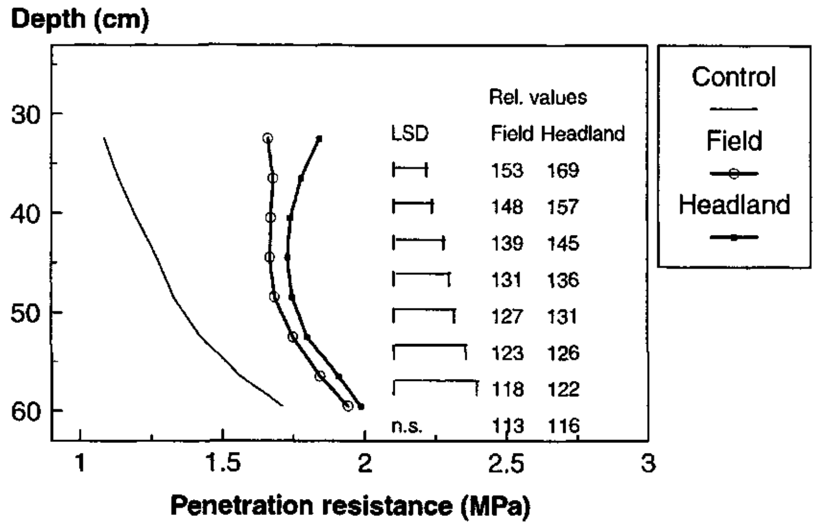

Fig. 3. Penetration resistance in arable land compared to adjacent untrafficked land. From Håkansson et al. (1996).

Table 3. Types of measurements made in experiments to study impact of subsoil compaction on soil and crops. For field plans, see text

Exp. type	1	2	3
Number of sites	6	9	6
Effects on soil			
Displacement	x	-	x
Bulk density	x	x	x
Sat. hydraulic conductivity	x	-	-
Unsat. hydraulic conductivity	-	-	-
Air permeability	-	-	x
Air diffusivity	-	-	-
Water retention	-	-	-
Precompression stress	-	-	-
Cohesion	-	-	-
Penetration resistance	x	x	-
Vane shear strength	-	x	-
Effects on crop			
Crop yield	x	x	-
Root depth	-	-	-
Root density	-	-	-
Root/shoot ratio	-	-	-
Nutrient uptake	-	-	-
LAI	-	-	-

growth or aeration conditions and soil water uptake during the growing season. This makes it difficult to use the results for mechanistic models concerning the effects of heavy traffic on soils and crops. The most important result of the research is probably its practical relevance: it has been clearly demonstrated that high axle loads cause compaction to great depth, that compaction increases soil strength and reduces permeability at great depths, and that the effects in the subsoil are very persistent.

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SUBSOIL DISPLACEMENT DURING SUGARBEET HARVEST AT DIFFERENT SOIL WATER CONTENTS

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Abstract

Soil displacement during traffic with a heavy sugarbeet harvester was determined at different water contents during harvest in the autumn. Soil mechanical properties were determined on each wheeling occasion. Gravimetric water content at the experimental site was measured throughout the growing period. With increased water content, such as during late harvest, soil displacement was greater and reached greater depth. A model to prevent subsoil compaction, based on soil mechanical properties and soil water models run by meteorological data, is proposed.

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 & 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, and an outline of a model to prevent subsoil compaction, are presented.

Methods

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. 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 (Fig. 1). The transducer could measure pressures from -1 to +1 kPa, which corresponded to a displacement of ±102 mm with a repeatability of 0.1 mm. The pit in Fig. 1 was stabilized with wooden boards.

Alongside the displacement sensors, stress sensors were installed to measure vertical soil stress. The stress sensor consisted of an aluminium plate, 17.5 mm in diameter, attached to a load cell and placed in a 40x70x20 mm aluminium box. This was mounted on a steel shaft, and installed in the soil in the same way as the displacement sensor. Three displacement sensors and three stress sensors were connected to the same datalogger.

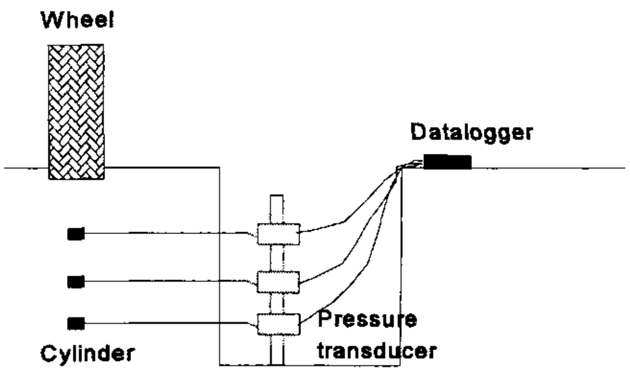

Fig 1. Displacement sensors. Cylinders containing silicon oil, which is connected through a hose to a pressure transducer, are installed horizontally into the soil. When the soil is subjected to wheel traffic, vertical movement will be registered as a change in pressure by the transducer.

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) Water content in the soil profile 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 sugar beets were harvested. Sampling was done every two weeks with a soil drill in sugar beets and in adjacent spring wheet.

(2) The measurements of soil displacement were made during harvest with a six-row sugarbeet harvester, weighing approximately 35 tonnes fully loaded and 20 tonnes without load. The front wheels were Trelleborg TWIN 850/60-38 and the rear wheels Continental 800/65 R32, with inflation pressures 200 and 170 kPa, respectively. The wheelings were made at two occasions, 15 and 28 Oct, in sugar beets and in wheat stubble. One area in the sugar beets field was covered from 10 Oct to prevent precipitation, and one area in the wheet 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 and stress 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.

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

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 speed 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) in 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 after the soil had relaxed for 30 minutes.

Results and discussion

Soil water content

The gravimetric water content at 30, 50 and 70 cm depth in the sugar beet and the spring wheat crop is shown in Fig. 2, a and b. The water content gradually decreased until late September in the sugar beets, when it started to increase. In the wheat crop, there was a more rapid decrease in water content during early summer, but a higher water content in the autumn than in the sugar beets. The differences between the crops can be explained in the later establishment for the sugar beets and their growth late in the autumn. Precipitation in 1997 was approximately 600 mm, somewhat less than normal, but the changes in water content during the year can be seen as typical for Swedish conditions.

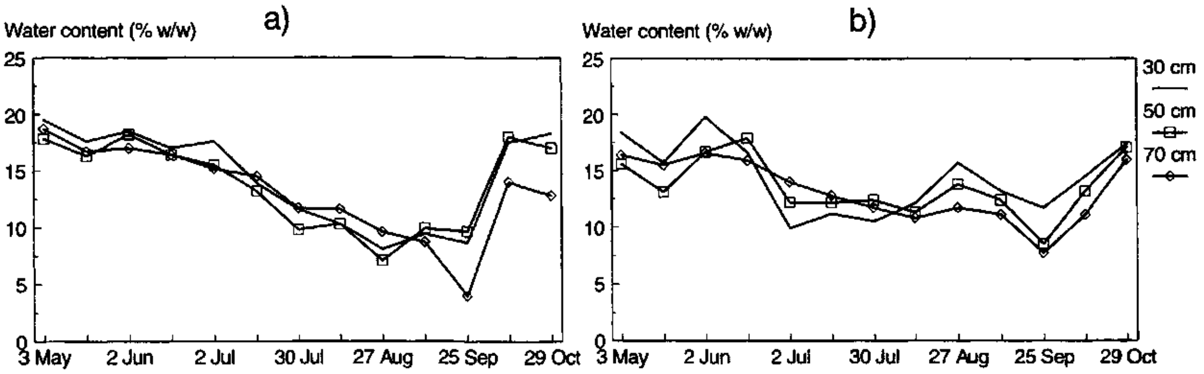

Fig 2. Soil water content at three depths at Elvireborg in a) sugar beets, b) spring wheat.

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 is a plastic deformation during all tests. At 50 cm depth there is a plastic deformation in the wetter soil, whereas there is 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).

Soil mechanical properties

The cohesion and the angle of internal frictionof 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.

The results from the uniaxial compression of soil samples were not yet evaluated at the time of writing this manuscript.

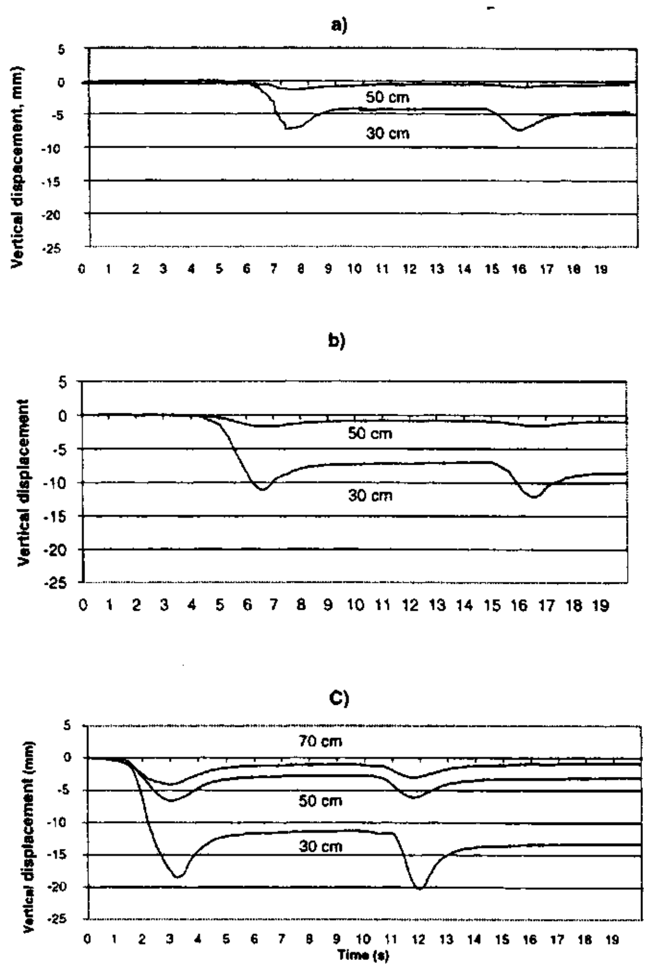

Fig. 3. Soil displacement 28 Oct during wheeling with a sugar-beet harvester (total weight approx. 35 tonnes). Each "dip" represents the pass of a wheel. a) Soil covered from 10 Oct. b) Natural water content. c) Irrigated.

Table 1. Soil water content, cohesion, angle of internal friction and vertical soil displacement at 30, 50 and 70 cm depth at the different wheeling occasions

Treatment	Depth (cm)	Water content (% w/w)	Cohesion (kPa)	φ	Displacement (mm) Empty	Loaded
28 Oct, plot covered since 10 Oct.	30	17.6	87	35	-3.7	-4.2
	50	11.0	>154 (a)	-	-0.2	0.0
	70	11.8	>154 (a)	-	- (b)	- (b)
Sugar beets 15 Oct.	30	17.0	129	27	-1.6	-1.9
	50	16.2	140	26	-0.7	- (b)
	70	12.9	147	47	- (b)	- (b)
Stubble 15 Oct.	30	18.0	129	41	-4.5	-4.9
	50	20.8	125	30	-1.1	-2.1
	70	16.6	166	40	- (b)	- (b)
Sugar beets 28 Oct.	30	17.2	91	37	-5.5	-8.5
	50	17.3	103	31	-1.3	-0.9
	70	16.8	154	31	-0.3	0,0
The plot irrigated, 28 Oct.	30	18.6	74	46	-10.9	-13.2
	50	20.0	96	25	-0.9	-3.0
	70	21.4	118	46	-0.1	-0.5

(a) Estimated value, the soil too hard to install the shear annulus by hand.

(b) The missing values is in most cases caused by the soil being too hard to install the measuring equipment

Conclusions

The results of this research confirms well-known facts about soil compaction: heavy axle loads compact the subsoil, especially at high soil water contents. However, the type of measurements made are suitable in developing a more general model to prevent subsoil compaction. Measurements of soil displacement and stress could be combined with determinations of soil strength at different water contents and models run by meteorological data to predict soil water content. This could form the basis to give locally adjusted recommendations of permissible wheel loads and tyre inflation pressure as proposed by van den Akker (1994). In Fig. 4 is shown a preliminary model how to develop these recommendations. At present we are using the model SOCOMO (van den Akker, 1988), to compute the stresses exerted in the subsoil, and whether these stresses exceed the precompression stress or the shear strength of the soil. Calculations of soil water content are made with the model SOIL (Jansson, 1974). Field measurements like those presented in Fig. 2 are used to calibrate the model. Based on meteorological data for a large number of years, it will be 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 new technique for soil displacement measurements presented here is suitable for the field validation of the estimated soil compaction. The main gap in our knowledge is probably how to correlate the mechanical properties to the compaction obtained in the field.

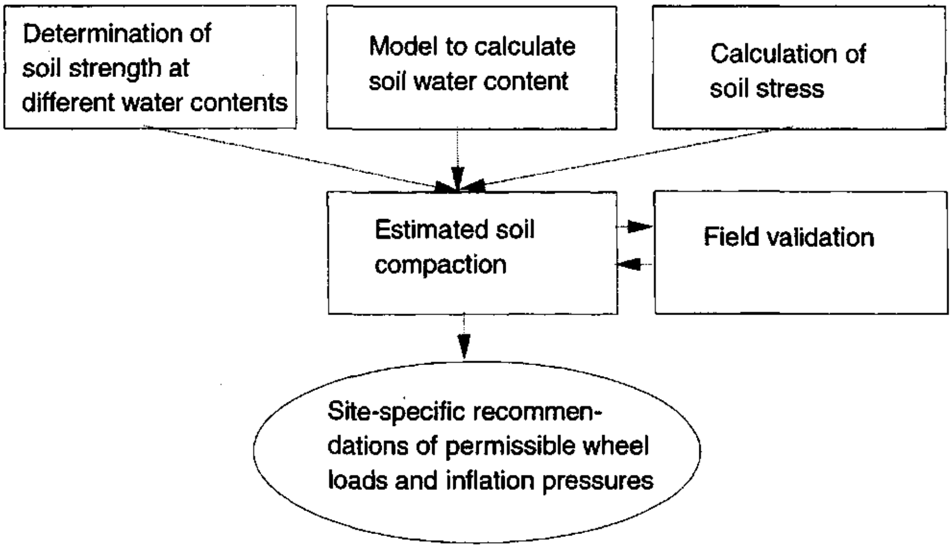

Fig. 4. A proposed scheme how to develop recommendations of allowable wheel loads and inflation pressures for traffic at different soil water contents.

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SUBSOIL COMPACTION OF AGRICULTURAL SOILS - A REVIEW OF RESEARCH IN SWITZERLAND

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Abstract

Subsoil compaction due to excessive mechanical stress exerted by agricultural machinery has been recognised as a potential problem for the fertility of agricultural soils in Switzerland for about twenty years. While agricultural vehicles used in Switzerland are generally not as heavy as in many other countries, primarily due to limiting topographical conditions, many agricultural soils in Switzerland tend to be sensitive to compaction because of their clayey texture and because of the humid climate. Recently the problem of subsoil compaction has received attention in soil protection as agricultural land has become increasingly affected by its temporary use for access ways for heavy machinery in the course of pipeline and road construction work.

Most research related to soil compaction in Switzerland has focussed on effects on physical soil quality associated with various farming practices. Such effects were primarily assessed in terms of bulk density, porosity, and hydraulic conductivity and air permeability. More recently structural effects were also determined in situ by the analysis of infiltration patterns of dye tracers. In order to find measures for the sensitivity of subsoils to compaction, recent studies also assessed soil parameters such as soil-water potential, preconsolidation pressure, and penetration resistance.

Of all the parameters considered in these studies so far, preconsolidation pressure has proved to be the best predictor for the sensitivity of a soil to compaction. Attempts to predict this parameter from other soil properties such as textural and hydraulic characteristics have in general been promising for light-textured soils, but have met with little success for heavy-textured soils. Furthermore, while experience has shown that soil compressibility may depend critically on soil moisture, proposed predictive relationships for this dependence remain to be validated.

Background of subsoil compaction research in Switzerland

Mainly because of topographical limitations, agricultural vehicles in Switzerland are in general not as large and heavy as in many other countries. Nonetheless, soils in many places are subject to compaction by agricultural machinery because of the humid climate and the relatively widespread occurrence of poorly drained fine-textured soils. Soil compaction was recognised as a problem for soil fertility in Switzerland in the late seventies. Since then various studies have dealt with the risks of agricultural soil compaction. Thus, Schmid and Thöni (1986) investigated soil compaction caused by fodder production. Vez and Neyroud (1979) and Reust and Neyroud (1985) found that compaction decreased yields of spring wheat by more than 15% and also reduced the effect of nitrogen fertilization. In a long-term study, Kramer (1983, 1988, 1991) compared the effects of light-weight versus heavy-weight machines on soil structure and crop yields. He found that, over two decades, light-weight agricultural machinery performed slightly, but significantly better.

While earlier studies primarily had focussed on topsoil quality and only marginally considered subsoil compaction, Weisskopf et al. (1988, 1989) and Schwab et al. (1989) specifically addressed the problem of subsoil compaction. Within the framework of the Swiss National Research Programme 'Soil' these authors performed a nation-wide assessment of the compaction of Swiss agricultural soils and the risk-determining factors. They estimated that 10-15 % of Swiss agricultural soils were over-compacted.

As the size and weight of agricultural vehicles continued to increase, more and more concern arose about the eventual effects of their use on subsoil compaction (Kramer, 1991), and the lack of scientific basis to predict them (Schulin, 1993) motivated further studies on agricultural subsoil compaction. These studies include the investigation of soil compaction caused by trailers on caterpillar tracks (Anken et al., 1993), by two different plough systems (Weisskopf et al., in preparation), and by heavy sugar-beet harvesters (Diserens, 1996; Diserens et al. 1998; Weisskopf et al., 1997). Furthermore, the regeneration of the physical structure of topsoil and subsoil compaction is under investigation, using the analysis of dye tracer infiltration patterns in addition to traditional methods of soil physics (von Albertini et al., 1995).

Until the early nineties, soil compaction research in Switzerland focussed on the comparison of effects of different farming practices and equipment. At that time the construction of gas transport pipelines through agricultural land also made soil compaction an issue for soil protection agencies, which were being called by worried farmers. Guidelines were drafted in collaboration with soil protection agencies and the gas industry and these were issued by the Federal Office of Energy Management (BEW, 1993) as part of federal government concessions for pipeline construction. These guidelines, which were revised in 1997, rule the allowable weight and contact pressure of construction machinery according to a postulated dependence of soil compaction sensitivity on the tensiometric soil-water potential.

Debate about the validity of the assumed relationship between soil moisture and compaction risk (e.g. Schulin, 1995) not only spawned a series of pilot studies in form of university theses and other student works (e.g., Sabbadini, 1995; Berli & Hoerner, 1996; von Rohr, 1996; Schönbächler, 1997; Weber & Zimmermann, 1997; Jauslin & Zimmermann, 1998), but also led to the initiation of a research project funded by the gas industry to investigate the compaction effects of heavy construction machinery on various Swiss agricultural and forest subsoils in terms of parameters such as bulk density, pressure-consolidation curves, water retention characteristics, hydraulic and pneumatic permeability, and infiltration characteristics, as well as the relationship of such effects to soil properties assumed to characterize the sensitivity of soils for compaction, e.g. tensiometric soil-water potential, preconsolidation pressure, soil type and texture. First results of the latter project have been summarized in internal reports by Kulli et al. (1997) and Berli et al. (1998). A journal article is in preparation.

Publicity of soil compaction risks associated with pipeline construction has led to an increased awareness of the problems of physical soil degradation in Switzerland. As a consequence, physical soil protection, in particular protection of physical soil quality against erosion and compaction, became incorporated explicitly into the 'Federal Law relating to the Protection of the Environment' (USG) recently revised by the Swiss Parliament (Schweizerische Bundesversammlung, 1997). Detailed regulations on how the general principles of the Environmental Protection Law are to be made effective in practice is subject to the `Federal Ordinance relating to Impacts on Soil' (VBBo), which is currently in preparation to be issued later on this year (1998) by the Swiss Government (Schweizerischer Bundesrat, 1998).

Research into subsoil compaction: state of the art in Switzerland

Table 1 lists major research projects dealing with subsoil compaction in Switzerland. Soil properties recorded in these projects are compiled in Table 2, and Table 3 gives a short description of the methods used to determine these properties. We do not claim that these lists are complete; they contain the material that our search has turned up.

Although Project 5 gave estimates of the abundance of soil compaction in Swiss agricultural soils on the basis of sample information and soil maps, no comprehensive survey of the areal extent and distribution of compaction has been performed in Switzerland up to now. As mentioned before, previous research related to soil compaction in Switzerland has focussed mainly on its effects on physical soil quality associated with various farming practices. In addition to effects on soil properties, effects on crop production have been assessed, e.g. in Projects 1 and 3. In recent work, more emphasis has been given to specific load situations in order to get a better mechanistic understanding of processes involved in soil compaction.

Table 1. Selected research projects dealing with agricultural subsoil compaction in Switzerland

No.	Description	Institution	References
1	Long-term impact of farming machinery on physical soil properties: comparison between systems of light and heavy machinery	Federal Agricultural Research Station Tänikon	Kramer (1991), Diserens (1996)
2	Comparison of the effects of various plough types on soil structure	Federal Agricultural Research Stations Tänikon and Zürich Reckenholz	Weisskopf et al. (in preparation)
3	Soil compaction effects of various sugar-beet harvesters	Federal Agricultural Research Stations Tänikon and Zürich Reckenholz	Weisskopf et al. (1997) Diserens et al. (1998)
4	Soil compaction caused by track-driven vehicles for the distribution of manure compared to conventionally-driven trailers with wheels	Federal Agricultural Research Stations Tänikon and Zürich Reckenholz	Anken et al. (1993)
5	Risk of agricultural soil compaction in Switzerland	Federal Agricultural Research Stations Tänikon and Zürich Reckenholz	Weisskopf et al. (1988), Schwab et al. (1989), Weisskopf et al. (1989)
6	Subsoil compaction on agricultural land due to heavy machinery used in gas pipeline construction	Institute of Terrestrial Ecology, ETH Zürich	Berli et al. (1996), Kulli et al. (1997), Berli et al. (1998)

The soil properties listed in Table 2 may be divided into three groups: properties primarily determined to assess effects of mechanical stress on soil structure; properties determined to characterize the consistency of the soil, in particular its sensitivity to compaction; and parameters characterizing the stress situation itself. The first group of properties comprises bulk density, porosity, water retention characteristics, pneumatic permeability and hydraulic conductivity; the second group comprises preconsolidation stress, shear strength, penetration resistance, soil structure, aggregate stability, grain size distribution, stone content, organic matter content and soil water potential; while the third group is represented here by one parameter only, i.e. mean soil stress as determined by Bolling pressure probes.

As compaction will in general also affect the resistance of soil to further compaction, parameters directly characterizing this resistance may also be used to assess effects. Preconsolidation pressure has been used in such manner (e.g. Project 6). By the same reasoning, parameters primarily used to assess compaction effects such as bulk density may also be used as indicators of the mechanical stability of a soil. Although no strict distinction between the three groups of parameters is possible, Table 2 shows that half the projects were primarily effect-oriented, while in the other projects the focus was, or still is, on the soil conditions determining resistance to compaction.

Of all the parameters investigated so far, preconsolidation pressure was found to be the best predictor of soil sensitivity to compaction. Using the method of DVWK (1995), other parameters such as soil structure and organic matter content were usually found to provide fairly good predictions of soil resistance to compaction for sandy to loamy textures, but in general not for clayey soils. Furthermore, so far field methods such as soil penetrometry have not proven to be useful for mapping soil sensitivity to compaction. Like other indicators, soil penetrometer resistance may, however, be useful for assessing compaction effects by differential comparison, i.e. by comparing measurements of compacted soils with reference measurements of uncompacted, but otherwise comparable soils (including measurements of the same soil before compaction).

Table 2. Soil properties determined in the projects listed in Table 1 with respect to subsoil compaction (for description of methods see Table 3).

Property	No. of project in Table 1					
	1	2	3	4	5	6
Bulk density	x	x	x	x	X	x
Porosity	x	x	x	x	X	x
Water retention characteristics	x	x	x	x	X	x
Pneumatic permeability		x	x	x	X	x
Saturated hydraulic conductivity	x	x	x			x
Preconsolidation pressure						x
Shear strength						x
Penetration resistance	x			x		x
Soil structure	x				X	x
Aggregate stability					X	
Grain size distribution	x				X	x
Stone content	x				X	x
Organic matter content	x				X	x
Soil-water potential	x				X	x
Soil stress		x	x	x		x

Current trends, new approaches, and future research needs

Current work on subsoil compaction includes the development and improvement of methods suited for assessment of soil compaction in situ and its effects on pore structure, the application of numerical models to assist the design and analysis of experiments, and investigations of the regeneration of compacted soils.

At the Institute of Terrestrial Ecology, one sub-project focusses on the potential of numerical image analysis of dye infiltration patterns and X-ray tomograms (Kulli et al., 1997; Berli et al., 1998) to assess subsoil compaction. This follows on from work by von Albertini et al. (1995), who found that dye infiltration patterns were sensitive indicators of natural regeneration of soil structure in a previously compacted agricultural soil. Preliminary results show that this technique may also be very useful for studying soil compaction impacts of heavy construction machinery on farm land (Sabbadini, 1995). Recently, Diserens et al. (1998) applied this method to assess the spatial extent of soil compaction caused by sugar-beet harvesters.

At the Institute of Land Improvement and Water Management of ETH Zurich, a device called 'Large Area Subsidence Meter' (LASM) has been adapted to determine vertical compression within soil profiles (S. Tobias, personal communication). The device consists of pairs of water-filled probes to be inserted at different levels into the soil profile and connected by plastic tubes to a pressure gauge that measures changes of the vertical distance between the two levels of the probes in terms of the hydrostatic pressure difference between them.

As already mentioned, there is now increased interest in Switzerland in the mechanical processes of subsoil compaction. Current studies focus on the investigation of the precise nature of the relationship between soil moisture and resistance to compaction, on the analysis of stress transition between wheels or caterpillar tracks and soil, and on the analysis of stress propagation in heterogeneous soils.

Table 3. Methods used to determine the soil properties listed in Table 2.

Property	Method	Reference	Comment
Bulk density	oven-drying of 'undisturbed' core samples	Blake and Hartge (1986)	Sample sizes varying between 0.1 and 1 L
Porosity	calculation from real and bulk density		Real density determined by pyconometer method or estimated from soil composition
Water retention characteristics	pressure plate method (Richards apparatus)	Klute (1986)	Sample sizes varying between 0.1 and 1 L
Pneumatic permeability	Eijkelkamp air permeameter, as well as own method with air pressure relaxation at constant water content	Berli and Hoerner (1996)	'undisturbed' core samples varying between 0.1 and 1 L
Saturated hydraulic conductivity	constant head method.	Klute and Dirksen (1986)	'undisturbed' core samples varying between 0.1 and 1 L
Preconsolidation pressure	analysis of pressure-consolidation curves (oedometer method) by method of Casagrande (1936)	Lang et al. (1996)	'undisturbed' cylindrical samples of various sizes: 3 cm height x 9 cm diameter or 11 cm height x 11 cm diameter
Shear strength	consolidated undrained triaxial test	Lang et al. (1996)	
Penetration resistance	cone-penetrometer	Bradford (1986)	various types of probes and cones used
Soil structure	qualitative assessment by visual inspection	Brunner et al. (1997)	no standard classification scheme
Aggregate stability	settling of loosely packed aggregates in a stamping apparatus	Hartge (1969)	
Grain size distribution	wet sieving and sedimentation (pipet method)	Gee and Bauder (1986c)	
Stone content	wet sieving	Gee and Bauder (1986b)	1 L samples, not applied to soils with large stones
Organic matter content	potassium permanganate method or gravimetric determination of 'wet-ashing' with H_2O_2	Gee and Bauder (1986a)	
Soil-water potential	tensiometry	Cassel (1986)	
Soil stress	Bolling pressure probes	Bolling (1987)	indicator of mean stress (depending on soil stiffness)

Another subsoil-compaction subject which deserves much more attention in Switzerland is the problem of scale. The size of samples analyzed in the laboratory has usually been insufficient to represent soil heterogeneity in the field even on the local scale of a soil profile. To study the spatial variability of soil properties and processes involved in compaction is of particular importance for Switzerland. Swiss soils tend to be extremely heterogeneous even over very short distances, due to the diversity in topography and geology.

To conclude this brief overview of Swiss research into agricultural subsoil compaction, we should like to emphasize that drawing more attention to the soil mechanical problems in subsoil compaction research does not in general mean that our knowledge about the effects of subsoil compaction on soil fertility and soil functions is already sufficient. Although beyond the scope of this review, we found that, in the framework of compaction research, several topics other than those mentioned here require much more in-depth investigation. These topics include the detailed nature of soil structure deformation, changes in the air, water, nutrient and temperature regimes of affected soil, and changes in the functioning of compacted soils as a vital part of our environment.

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EFFECT OF CROPPING SYSTEMS ON SUBSOIL COMPACTION : PRELIMINARY RESULTS OF A LONG-TERM EXPERIMENT IN FRANCE

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Abstract

A field experiment has been conducted since 1989 in northern France to evaluate the effects of cropping systems on the structure of a loamy soil. Three cropping systems involving different crop rotations (based on winter wheat, pea, rape, maize and sugar beet) and combinations of cultivation (early or late sowing, early or late harvesting) were studied. Compaction of the ploughed layer depended largely on the system, the nature of the crop and sowing or harvesting decisions, which controlled the soil moisture content at each operation. This experiment was used to study the effect of cropping system on subsoil compaction in 1998. Two or three treatments were examined for each cropping system depending on the frequency of cultural operations in wet conditions. Soil compactness was described by resistance to penetration, bulk density and saturated hydraulic conductivity. Preliminary results show that subsoil compaction was not pronounced. Bulk density was very similar for all 3 cropping systems. Resistance to penetration was slightly higher in the subsoil layer between 35 and 42 cm under wheeled zones at sugar beet harvesting in wet conditions, or at pesticides spraying.

Introduction

The structure of the ploughed soil layer in cropping systems undergoes frequent changes due to compaction during tillage and harvesting. The soil water content at the time of field operations and characteristics of the machinery (load, tyre type) influence the extent of structural changes and their consequences for the crop. The soil conditions during tillage and harvesting operations depend on previous soil management techniques and the climate, and on the decisions made by farmers, who have to deal with conflicting constraints such as the crop biological requirements, climatic conditions, and work planning.

An 8-year field experiment was designed to study the effects of cropping systems on soil structure in northern France and to assess how seedbed quality was affected by soil conditions during previous operations. We have used this field experiment to study the effect of cropping system on subsoil compaction. This paper describes the experimental design and the preliminary results obtained in 1998.

Materials and methods

Treatments

The field experiment was initiated in 1989 in northern France (Péronne, 50°N latitude, 3°E longitude, 85 m elevation). Three cropping systems were compared :

- cropping system **I.** Rotation was pea/winter wheat/rape/winter wheat. Sowing and harvesting were always carried out in summer or early autumn, i.e. during a dry period of the year (except for pea sowing), to suit the physiology of the crops involved.

- cropping systems **II** and **III**. Rotation was sugar beet/winter wheat/maize/winter wheat. Cropping system **II** was managed so as to avoid sowing and harvesting in wet conditions. Cropping system **III** was managed so as to maximise light interception by sugar beet and maize : sugar beet and maize were sown in early spring and harvested in late autumn, during wet periods of the year.

Each crop of each cropping system was grown every year, giving 12 treatments. The experimental design consisted of two blocks (total of 24 plots), with a plot area of 0.40 ha. This plot size made it possible to reproduce the patterns of machinery use on commercial farms. Each plot underwent mouldboard ploughing (30 cm depth) every year.

The characteristics of the machinery used for tillage and harvesting operations are described in Table 1. They differed greatly in terms of machinery weight, tyre width and tyre inflation pressure.

Table 1 : Characteristics of the equipment used for the cultural operations

Cultural operations	Rear tyre width (cm)	Tyre inflation pressure (kPa)	Rear axle load (T)	Speed (km h^{-1})
Seed bed preparation	65	70	3-5	6-9
Sowing	27-40	200-250	2-4	4-6
Harvesting	50-75	200-350	5-12	4-7
Fertiliser spreading and pesticides spraying	30-40	150-300	3-6	7-9

Three treatments per cropping system were used in 1998 to evaluate the effect of cropping system on deep soil compaction. Each treatment occupied a sub-plot located under one or more existing wheel tracks. The choice of treatment depended on the frequency of wheel tracks in the area under wet conditions. This preliminary paper considers only 3 treatments, which had the potential to produce a large range of risks of deep soil compaction.

Table 2 : Characteristics of the 3 treatments

Teatment	Description
A	No cultural operations in wet conditions
B	Sugar beet harvesting in very wet conditions
C	Pesticide spraying and fertiliser spreading

The soil was a silt loam (Luvisol Orthique, FAO classification) with a pH of 7.6 and contained 200 g clay kg^{-1}, 738 g silt kg^{-1}, 50 g sand kg^{-1}, 17 g organic matter kg^{-1} and 5 g $CaCO_3$ kg^{-1}. Soil water content was 0.252 g g^{-1} at -10 kPa and 0.093 g g^{-1} at -1500 kPa.

Soil measurements

The location of wheel tracks on the plot was noted and recorded after each operation, except annual ploughing. Spreading and spraying operations were always done at the same location in each plot. The soil water content of each plot was measured gravimetrically before each cultural operation except pesticide spraying and fertiliser spreading.

The structure of the ploughed soil layer was evaluated after each operation by measuring structural porosity and analysing the soil profile morphology to determine the proportion of the soil volumes with a massive structure and no visible macropores (Manichon, 1987). These zones, called Δ zones, result from severe anthropic compaction.

Measurements were made in 3 parts of each treatment in 1998, depending on the frequency of wheel tracks. Soil profiles were done on a vertical surface of a 3 m wide soil profile. The layers were visually delimited on the soil profile and the thickness of each layer was measured (Fig. 1). The ploughed layer from the last ploughing was estimated at 0.30 m thick. The deepest ploughing depth was 0.31-0.38 m. Bulk density was determined from undisturbed cores (5 cm diameter, 5 cm long) taken from a depth of 0.3-0.7 m. Six cores were taken at each depth for each treatment. Soil penetrometer resistance was measured to a depth of 0.70 m using a hand-held soil penetrometrer with a 30° conical probe, 12.9 mm in diameter. There were 18 measurements per depth per treatment.

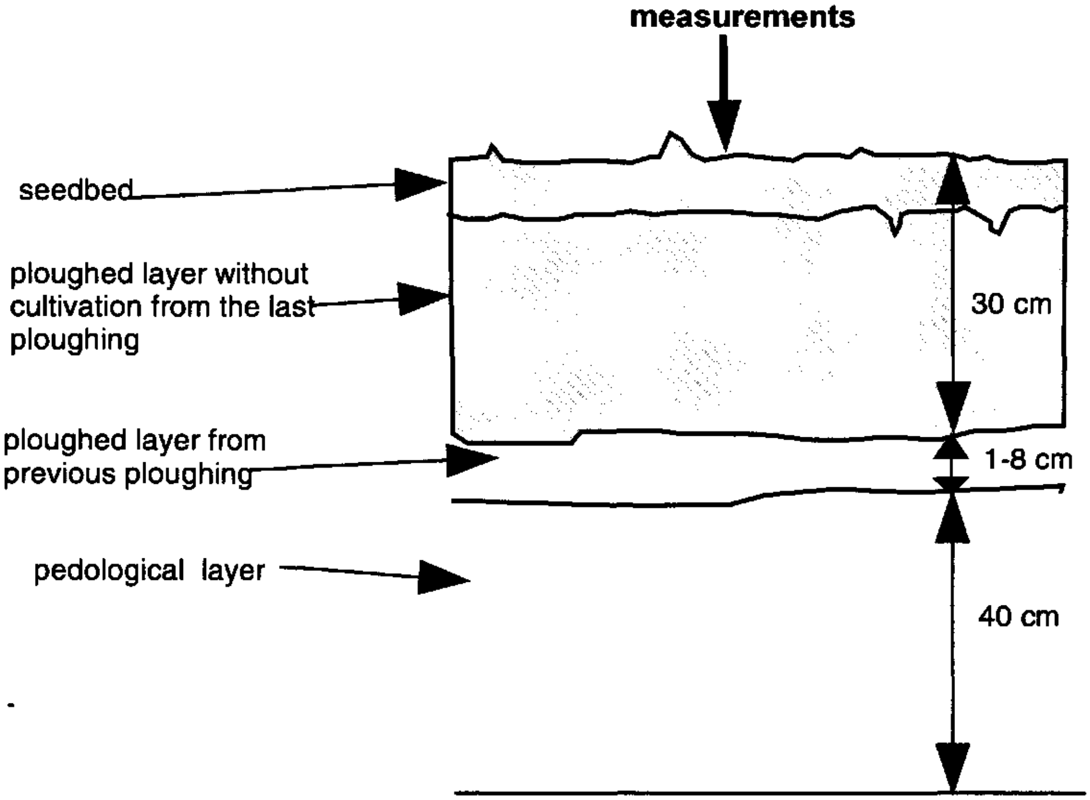


Figure 1: The layers in the soil profile

Preliminary results

Assessment of the risk of deep soil compaction

Compaction of the ploughed soil layer, estimated by the proportion of Δ areas under wheel tracks, increased with soil moisture and depended on the equipment used (Fig. 2). Wheel tracks made at seed bed preparation did not generate Δ zones unless the soil water content was very high. In contrast, Δ zones occurred over a wide range of moisture conditions at sowing and harvesting.

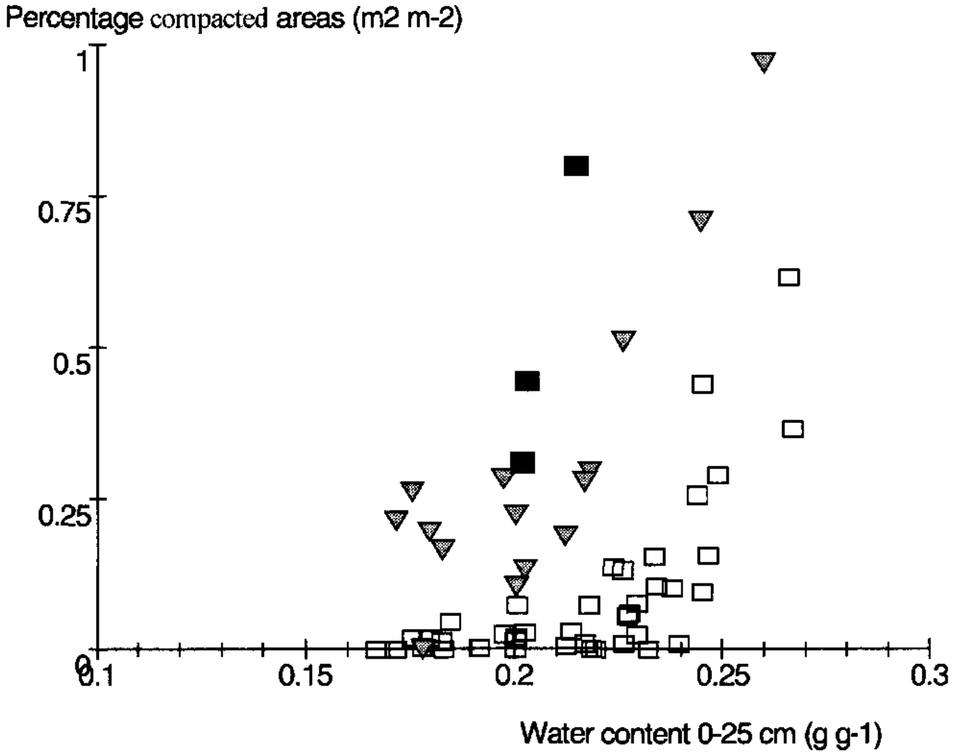


Figure 2: Percentage area of the cultivated profile under wheel tracks that had massive structure and no visible macropores (Δ zones) as a function of soil water content at the time of track-making

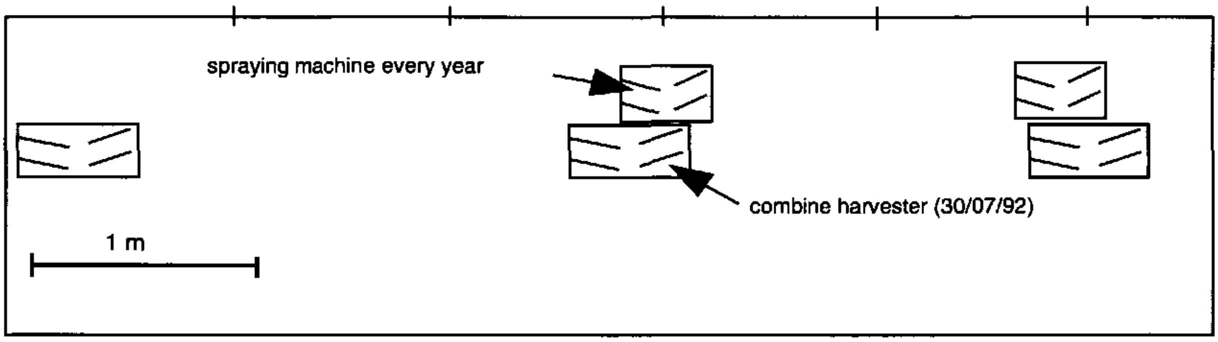
☐ : Wheel tracks at seed bed preparation
▼ : Wheel tracks at sowing
■ : Wheel tracks at harvesting

The risk of deep soil compaction was assessed assuming that deep compaction under wheel track could only occur if the Δ zones reached the bottom of the layer from the last ploughing, which was true for about 50% of Δ zones under a wheel track. We therefore considered the soil water contents of the ploughed layer that could induce deep compaction were :

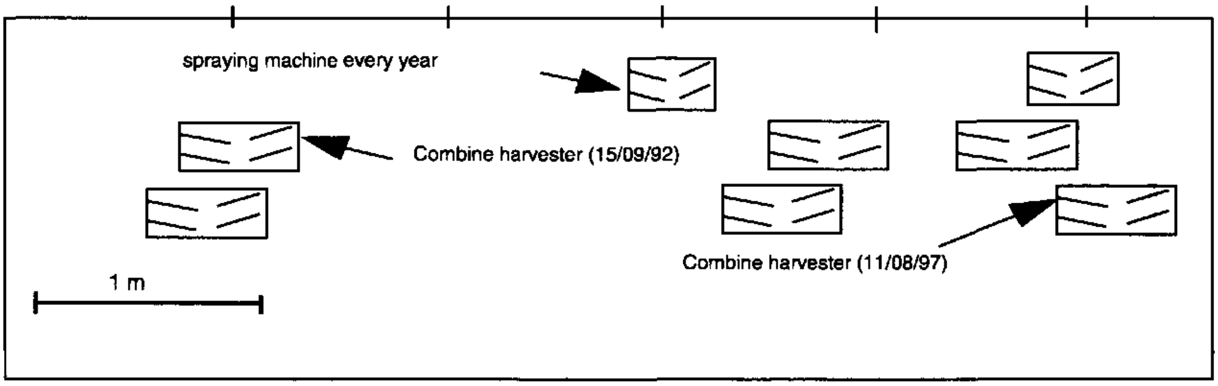
0.20 g g^{-1} for harvesting
0.22 g g^{-1} for sowing
0.24 g g^{-1} for seed bed preparation.

Fig. 3 shows examples of maps of traffic in the 3 cropping system using these limits of soil water content. The risk of subsoil compaction depended on the cropping system. There was very little risk of compaction in the subsoil in system I, but it was high in system III. Sugar beet harvesting resulted in a high proportion of the surface being affected by wheel tracks in the very wet conditions in 1990 and 1994. But the risk of subsoil compaction also depended on the location of the wheel tracks, which were always at the same place at pesticide spraying and fertiliser spreading.

cropping system I



cropping system II



cropping system III

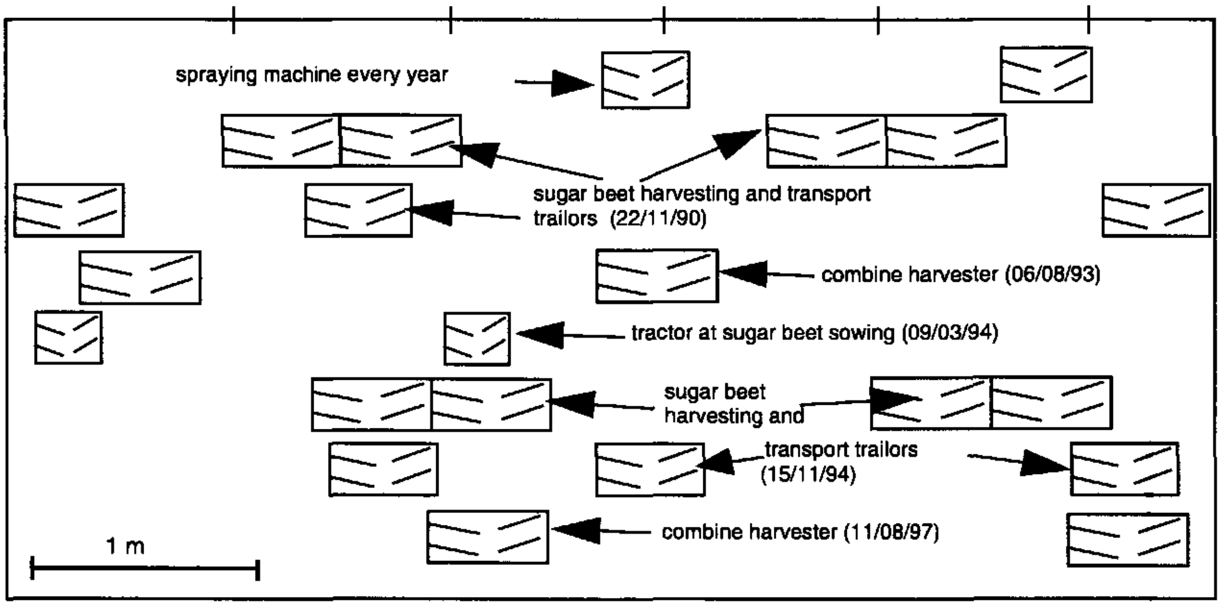


Figure 3: Wheel tracks that could cause deep soil compaction from 1989 to 1997. There are shown on different horizontal axis, depending on the cultural operations. Tillage always occurred in the same direction on a vertical axis.

Changes in bulk density and penetration resistance

Bulk density increased slightly with depth in all 3 treatments (Table 3). Differences in bulk density for the 3 treatments were very small 0.01-0.03 g cm^{-3} (Table 3). Ardvisson (1997) also showed that the change in bulk density is small in the subsoil. He measured an increase in bulk density of 0.00-0.13 g cm^{-3} after 4 passes with a sugar beet harvester weighing 38 tonnes.

Table 3 : Change in bulk density as a function of soil depth and treatment (g cm^{-3})

Depth (m)	No cultural operations in wet conditions	Sugar beet harvesting in very wet conditions	Pesticide spraying and fertiliser spreading
0.33	1.57	1.60	1.58
0.40	1.56	1.57	1.57
0.50	1.57	1.59	1.59
0.60	1.58	1.60	1.59
0.70	1.58	1.61	1.61

The mean standard deviation per treatment per depth was 0.03 g cm^{-3}.

Resistance to penetration, like bulk density, increased with depth. The resistance to penetration at 0.33 m depth in the ploughed layer from previous ploughing was, surprisingly, the lowest in the wheeled tracks at sugar beet harvesting. The reason may be due to heterogeneity of this layer. Resistance to penetration was slightly higher under wheel tracks at sugar beet harvesting and pesticide spraying in the subsoil layer at 0.35-0.42 m depth. Differences were only statistically significant ($p<0.05$) for a depth of 0.37 m and 0.59 m.

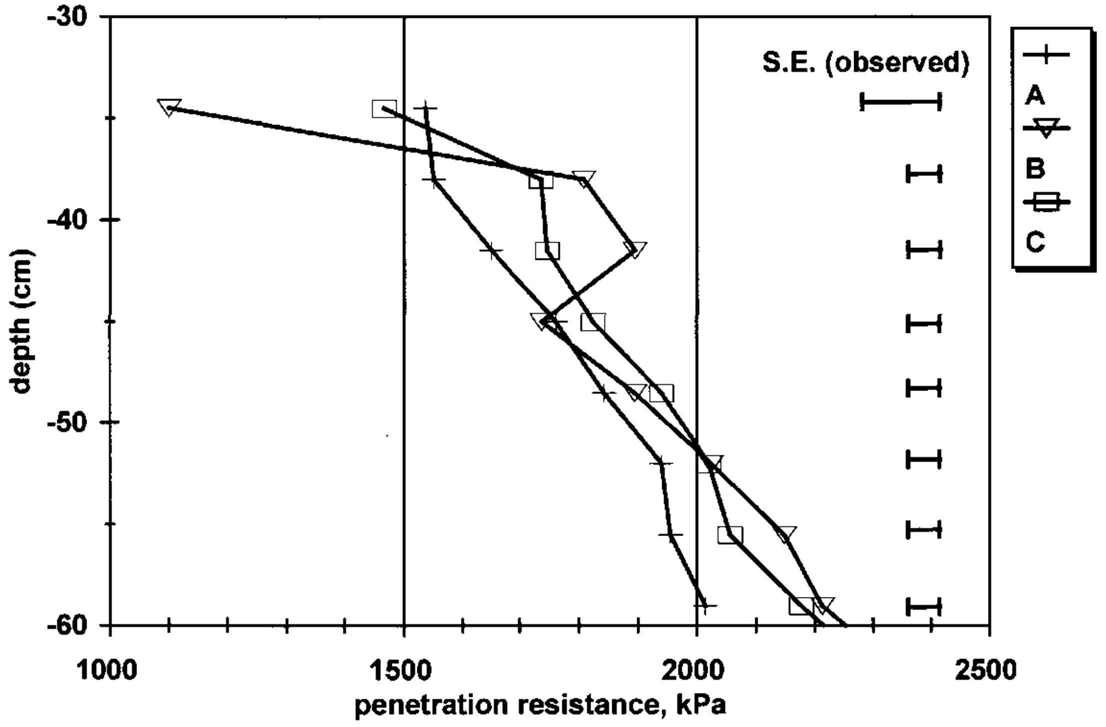


Figure 4: Change in penetration resistance with depth.
A : No cultural operations in wet conditions
B : Sugar beet harvesting in very wet conditions
C : Pesticide spraying and fertiliser spreading

Conclusion

Preliminary results show that the bulk density of the subsoil was very similar in the 3 cropping systems. Penetration resistance was slightly higher in the subsoil layer around 0.4 m depth under wheel tracks of sugar beet harvesting and spraying. We must now confirm this tendency by carrying out more detailed analysis of all the results and by measuring the hydraulic conductivity. Nevertheless, it appears that the cropping systems that we have used since 1989 did not induce great risks of subsoil compaction.

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SOIL COMPACTION RESEARCH IN NORWAY

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Abstract

In Norway the first field experiment with soil compaction was established in 1957. Soil compaction research has been concentrated about the effect of tractor traffic in grain and grass production. Because of small farm units the size and weight of the machinery used in Norwegian agriculture is rather small compared with many other countries in Europe. Both climate and soils vary a lot from district to district in Norway. Studies of soil compaction in Norway showed that compaction with light tractors in grain production reduced the porosity, the infiltration capacity and increased the bulk density, shear strength and the denitrification of the soil. The effect of compaction increased both with higher water content in the soil and number of passes. The yield reduction was almost 20% after compaction of wet soil. Increased number of passes on wet soil reduced the grain yields even more.

Introduction

Soil compaction is studied in many field experiments in Norway. This activity was on its top from about the middle of the seventies to the middle of the eighties. These experiments were mainly conducted to study wheel traffic in grain and grass production. Norway has a climate which vary a lot from one part of the country to another. In the western and northern part of the country the annual rainfall is high. This area is normally used for grass production. The main grain production area is located in the south eastern part of the country with a drier climate. The Norwegian agriculture is based on rather small farms as compared to many other countries in Europe. The size and weights of the machinery have not been so large in Norway as you see other places in Scandinavia. Our research with soil compaction is of this reason been conducted with rather light equipment.

In our soil compaction research different factors are studied;
* compaction by tractor traffic, 1.8 - 3,5 Mg
* number of passes
* high axel loads (14 - 26 Mg)
* soil water content at the time of compaction
* compaction in autumn and spring
* tire equipment
* number of harvests in grass production
* nitrogen fertiliser
* liming
* manure
* skidding of tire on ley

Two or three of these treatments was normally combined in a factorial experimental design. In these experiments different effects of soil compaction was measured;
* yields, quality and quantity

* root growth
* infiltration
* air permeability
* shear strength
* pore size distribution
* bulk density
* pore volume
* degree of compactness
* aggregate size distribution
* denitrification
* infestation of weeds
* earthworm population

All these parameters are not measured in all treatments mentioned earlier, but the effect of yields and the soil volumetric conditions are very often measured in our compaction fields. The effect of soil compaction is also measured in two erosion field lysimeters for one or two years.

Soil physical methods
Soil physical measurements are done by different laboratories, but these laboratories normally use the same methods. The relative volume fractions of air, water and solids were determined from 100 cm^3 undisturbed soil samples (von Nitzsch, 1936). Pore size distribution was measured using ceramic pressure plates (Richards, 1947, 1948). Air porosity at -10 kPa matric potential (pF2) was determined with an air pycnometer (Torstensson and Eriksson, 1936), and the total porosity was calculated as the sum of air porosity and volumetric water content at -10 kPa matric potential. Degree of compactness was measured according to Håkansson (1990). Aggregate size distribution of the soil layer 0-5 cm were measured by dry sieving 2 litre of soil through sieves of 20 mm, 6 mm, 2 mm and 0.6 mm as described by Njøs (1967). Aggregate stability were measured on two aggregate fractions (0.6 - 2 mm and 2 - 6 mm) in a rain simulator where 20 g of dry aggregates is placed on 0.5 mm sieves (Marti, 1984). Modulus of rupture was determined by the Brazilian method (Kirkham et al., 1959) on cylindrical soil samples which were equilibrated at a matric potential of -100 kPa. Air permeability was measured at -10 kPa matric potential as described by Green and Fordham (1975). The field shear strength of soil was assessed with a vane and torquemeter according to Schaffer (1960)

Sampling of earthworms were carried out in end of august. Visible worm casts at soil surface were counted and worms in the layers, 0-10, 10-25 and 25-40 cm sampled by hand sorting and grouped into three groups (Nordström and Rundgren 1972). The root length was measured by using pinboards (Schuurman and Goedewaagen 1971).

A short review of Norwegian soil compaction experiments
Arnor Njøs startet with soil compaction experiments in Norway in 1957 (Njøs 1962). He found reduced yields, increased bulk density and more coarse aggregates after compaction with a light tractor on wet soil. Compaction on dry soil had no significant effect. Ekeberg (1986) studied the effect of transport on stubble fields in autumn before ploughing on a morainic loam soil. The compaction treatments was done in both 1977 and 1978 on the same plots. Compaction with tractor and trailer carrying 6 Mg and three passes reduced the yields by 15% the first year and 20% the second year. No negative after-effect was measured in

1979. Riley (1983) studied the relationship between dry bulk density and grain yields. Nine fields experiments were established on different soil types in south east Norway. The compaction treatment was light tractor (<2 Mg) (one pass) and medium tractor (3-3.5 Mg) (one and three passes). He found a good correlation between degree of compactness and porevolun, air permeability and air capacity. The effect on yields was small if the degree of compactness was between 80-90%, but the yields were reduced if the degree compactness was higher than 95%.

Marti (1983) studied the effect of compaction from a tractor (2.4 Mg) with one and four passes on moist and wet soil in three experiments on siltig loam soil. Liming with 5 and 15 Mg CaO per hectare was combined with the compaction treatments. Pore volume, bulk density, pore size distribution, shear strength, aggregate size distribution and aggregate stability were measured after 8 years with annual compaction on two of the trials. Liming increased the stability of the aggregates but had no effect on the other parameters. The compaction treatments affected the pores in the soil at 10-15 cm depth at one trial, but in 30-35 cm depth no effect was found. On these three trails 4 passes on wet soil reduced the yields by 15 to 30 % during the period with annual soil compaction. The after-effect of eight years with soil compaction treatments was not significant.

From 1963 to 1973 conducted Njøs (1976) a field experiment with soil compaction and nitrogen fertiliser on a clay loam soil. No compaction, compaction of wet soil in spring on autumn ploughed soil and compaction on wet soil in autumn before ploughing were combined with 3 levels of nitrogen fertiliser (47, 94 og 140 kg per hectare for grain). The crops were four year grain, two year oil seed rape and two year grass. After these eight years with annual compaction the after-effect on yields was measured in four years. The compaction in spring reduced the yields significantly on all N-treatments. However, the negative effect of compaction in autumn was reduced by increased amount of nitrogen application. The pore volume was reduced by the compaction in 20-25 cm depth. This effect was still significant five years after the compaction treatments was ended.

In 1964 two soil compaction experiments with the same treatments were established on a loam and a clay soil. The main treatments were; soil moisture content (wet and moist), tractor traffic in spring (none, one pass wheel by wheel with a tractor, 1.8 Mg). Additional treatments were harrowing of the surface direct after compaction and liming. These two experiments were treated annually to 1979. The after-effect was measured to 1983 and so the experiments were continued with new compaction treatments; soil moisture treatment was as earlier, tractor traffic was none, one pass with light tractor, 1.8 Mg, and one pass with medium tractor, 4.0 Mg, liming was as earlier and the loosening of the surface was conduct on all plots. From 1963 to 1990 these two trails were ploughed in autumn and from 1991 they were only harrowed before sowing or direct drilled. The trail on the clay soil was ended in 1995 but the trail on the loam soil is being continued. The main crops has been grain, but there has been some years with grass production on these trails. Generally, tractor traffic on wet soil affected soil physical properties (pore volume, shear strength, infiltration capacity), root length and yields negatively (Njøs 1976, Gaheen & Njøs; 1977, 1978a, Hofstra et al. 1986). Denitrification was studied in the trail on loam soil (Bakken et al. 1987). Tractor traffic on wet soil showed 10-15 kg nitrogen per hectare higher denitrification as compared to no traffic.

In another field experiment tractor traffic, soil moisture, number of passes and liming were combined from 1971 to 1982 with annual treatments on a clay loam soil. The after-effect of these treatments were measured from 1982 to 1985. One and six passes wheel by wheel were carried out with a tractor (1.8 Mg). Grain and grass were cropped 7 and 4 years, respectively. Njøs (1978) found that air capacity in 10-15 cm and 20-25 cm was reduced because of the tractor traffic. The size of the aggregates increased by tractor traffic especially on wet soil. Gaheen & Njøs (1978b) found reduced infiltration rates because of the compaction treatments.

The effect of high axle loads on a moranic loam soil was studied by Hugh Riley as a part of the series of compaction trails co-ordinated by Inge Håkansson

Myhr & Njøs (1983) studied the effect og tractor traffic, number of harvests and liming on yields and soil physical properties i grass production. Nine trials were established in different districts in Norway and most of them was continued for 8 yeas. They found an interaction between soil compaction and number of harvests. Soil compaction by tractor traffic increased the shear strength of the soil. Riley (1985) found that one pass with a tractor on ley increased the degree of compactness from 87% to 91% on loams and to 94% on soil with higher content of silt and clay. His teen trails were loacted at different soil types.

In the western and northern part of Norway the precipitation is high. Under this condition the combination of soil compaction and use of big amount of manure is a serious problem. The infiltration capacity of the soil is very often low and a lot of water is pounding on the areas. This reduced the ability for the grass to survive the winter period. A lot of experiments are conducted to study this problem (Myhr 1984, Haraldsen 1990, Myhr et al. 1990, Øpstad 1991, Myhr & Sveistrup 1993).

How the different types of grasses are effected by soil compaction and wheel skidding by tractor traffic is studied by Mosland 1985, Celius 1990, Ullring 1993a, 1993b and Ullring &Lunnan 1993. The effect of compaction on the different grass spices was not consistent in the different experiments. Increased wheel skidding reduced the grass yields.

Hansen (1993) studied the effect of tractor traffic in conventional and organic farming system. The reduction of yield was higher in organic farming system than in conventional systems. Hansen & Bakken (1993) explained the general yield reduction in these experiments to be caused by increased denitrification, reduced root growth and direct damage on the plants from the wheels. The air content at a matric potential of -10kPa was very low on the compacted plots in these experiments.

The effect of soil compaction on surface runoff and erosion was studied in field lysimeters by Njøs & Hove (1986) and Børresen & Uhlen (1991). Tractor compaction along the slope increased the soil erosion by 3-5 times on ploughed plots (Børresen & Uhlen 1991).

Ongoing activities with soil compaction

Our research activity on soil compaction is rather low for the moment. However, two soil compaction trails are conducted at Department of Soil and Water Sciences where the objective is to look at the effect of tractor traffic in combination with reduced tillage or direct drilling. So far there are no publications form these experiments.

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SUBSOIL COMPACTION IN ENGLAND AND WALES

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Abstract

An overview of agriculture in England and Wales, shows that unlike Scotland (O'Sullivan and Vinten, 1998), the areas of arable agriculture in England have relatively low rainfall, and in the Eastern Counties, are often prone to drought. The moist conditions of Wales and the West Country make these areas ones of mixed and livestock farming. Potential drainage problems exist throughout the two countries, but one much better addressed in the arable and intensive grassland areas. These problems make the introduction of heavier machines on vulnerable soils of particular concern. Mouldboard ploughing at around 0.2 m depth is practised on around 90% of the cropped area.

Over the past 40 years, research on subsoil problems gradually increased to reach a peak in the period 1976 - 1986. Studies of topsoil compaction have also been widespread. A number of studies concentrated specifically on machinery induced compaction in the subsoil, but most addressed either related issues or shallower profiles. Quantitative and qualitative techniques for assessing soil structure have included bulk density, shear strength, penetrometer resistance, plate sinkage, saturated hydraulic conductivity and matric potential. Specific areas of study have been tabulated in line with suggested database requirements for the Concerted Action.

Practical and theoretical studies of soil structural problems associated with compaction have been conducted at both Silsoe College and Silsoe Research Institute for the past 25 years, but few experiments have concentrated on subsoil compaction alone.

Introduction

A definition of the subsoil is perhaps a useful starting point. In this context it is considered to be that layer of soil which starts below the depth of annual cultivation, or where there is a distinct change in texture from the topsoil. Thus, there will be quite a range of depths at which the subsoil is considered to commence, and this depth may change depending on the tillage practices adopted.

In this paper a brief overview is given of agriculture in England and Wales. Also included are pertinent results of a recent survey of tillage practices, and a summary of research experiences at Silsoe College and Silsoe Research Institute in particular. References drawn from the past 40 or more years covering different aspects of subsoil management and conditions in England and Wales are tabulated. Future papers will look at this research in detail to provide information for the database, and to draw on the results to provide a management framework for future field operations.

Agriculture in England and Wales

Soils within the regions have been comprehensively surveyed over the past 60 years and vary considerably. In central and northern England in particular, soils are dominated by surface-water gleys. In the eastern counties these are interspersed with ground-water gleys, pelosols and brown soils. Wales and the West Country are dominated by podzolic and brown soils, but also some surface-water gleys. Middle southern England has a large proportion of lithomorphic soils, and these also occur in areas to the north and east. Rainfall falls sharply from west to east across the two countries (1100mm to 550 mm), creating a dominance of livestock production in the west and arable in the east. Horticultural and fruit production occurs in pockets throughout the countries, dictated by suitable soils and weather, soils ranging from silts to sandy loams to peats. In the eastern areas, conditions are often dry enough for effective subsoiling with most equipment. Historically this has not been the case in the west, necessitating the development of new techniques. Predictions of the effects of climate change suggest that the current situation in the east may not always be the case (Brignall et al., 1994). As with all other areas of mechanised agriculture, the size and weight of machines have steadily increased (see Fig 1, O'Sullivan and Vinten, 1998) with no indication that this trend is likely to change.

Over the past 40 years, research on subsoil problems gradually increased to reach a peak in the period 1976 - 1986, but has recently reduced in scale and extent. This concentration of subsoiling research is almost certainly explained by a number of very wet seasons and by tillage practices. Traditional ploughing techniques, particularly on the finer textured soils, were being replaced in the 1980s by extensive shallow cultivation and direct drilling. These systems were being used within a new cereal mono-culture, made possible by advances in chemical weed control, autumn sowing and through the common practice of straw burning. Tillage to depths of only 80 mm often led to a build up of soil compaction in what had been the plough layer. As a result, extensive work was done to improve the efficiency of subsoiling techniques, particularly for shallower depths of operation. Subsoiling at 350 mm was often little below the traditional depth of ploughing.

Legislation against straw burning in the early 1990's led to dramatic change. A 1996 survey of tillage practices in England (ADAS, 1996) revealed that around 87% or the arable area was now mouldboard ploughed to around 0.2 m depth. Of those using non-plough cultivation, about one third of the farmers were on clays, demonstrating the difficulties often experienced when ploughing these soils.

The survey also revealed that around 70% of farmers sub-soiled with a frequency of between 1 and 6 years. 74% of these farmers worked in the depth range 300 – 500 mm, and around 40% alternated between loosening the whole field and only the tramlines (semi-permanent traffic lanes introduced at sowing to aid precision in the application of chemicals). Only about 20% of farmers never sub-soiled their land, and the indications were that these people were probably on chalk limestone or loam soils.

This evidence suggests that despite the greater depths of operation re-introduced with mouldboard ploughing, farmers are probably aware of the potential for damage at depth created by heavier vehicles. However, the exact nature and extent of the damage which they are addressing, is far more difficult to ascertain.

Drainage practices in England and Wales have always played a major role in minimising and overcoming subsoil problems and in improving subsoil structure. Both subsoiling and mole drainage operations are particularly important in this context.

Subsoil compaction work in England and Wales

Whilst some fundamental work on subsoil compaction processes has been carried out within England and Wales, the major emphasis has been on the effects of compaction, how it can be avoided or minimised, and once the problem has arisen, how it can be alleviated. In line with future requirements of the Concerted Action Database, specific papers have been identified from different research establishments and researchers, to indicate the particular aspects studied, and their general emphasis. These data are contained in the Appendix table. The list is by no means exhaustive and will be supplemented and the information gained expanded as appropriate for future discussions.

Soil compaction research at Silsoe College and Silsoe Research Institute

Research in the general area of soil compaction over the past 25 years has been extensive at both Silsoe College and Silsoe Research Institute. The work has concentrated in particular on compaction avoidance, its alleviation and effects on cropping, with some fundamental work on the compaction process under wheels.

Work on compaction alleviation has concentrated on improving the effectiveness of the operation through modifications to the equipment and techniques (Spoor & Godwin, 1978, Godwin et al., 1981, Spoor & Fry, 1984,Godwin et al. 1981). Clear guidelines have been developed, used nationally, for the subsoiling operation in different situations. The guidelines centre on investigation of soil profiles, experimentation with depth of operation, tine spacing, share design and method of field working. The latter can often overcome problems of tractor size in relation to subsoiler draught, and also address the problem of recompaction and damaging the soil just loosened.

A number of projects have also tried to discern the reasons why sub-soiling often has little or no advantage for following crops (Soane, 1986 & 1987, Marks & Soane, 1987). It was often concluded that poor management of subsequent operations led to immediate re-compaction of the soil. This is not surprising when one considers the fragile nature of the loosened profile. Some swelling and shrinking soils also appear to have considerable powers of self recovery.

On more fundamental aspects, a new approach to assessing the compactive nature of soils was proposed by Earl. (1997) From plate sinkage and confined compression tests he developed a theory to provide information about soil strength and behaviour under load. Three phases of soil compaction were identified, and further work (Alexandrou & Earl, 1997) showed that important parameters in the prediction process could be determined from initial volumetric water content and dry bulk density.

Work has also looked at the soil strain relationships during the compaction process under wheels. Techniques for determining soil strain and density changes have been developed for soil bin studies. (Trein, 1995)

Several approaches to the avoidance of soil compaction have been followed. Earl (1996) studied the relationship between the strength of field soils and soil water suction as a means of predicting trafficability. With this method he found he could determine the status of field soils from permanently sited tensiometers. In practice, this would allow a farmer to avoid working when soil conditions were unsuitable. Similarly, earlier work by Alexandrou and Earl (1995) looked at the pre-compaction stress within a soil using plate sinkage tests. If this stress is known, it is possible in theory to limit loading to a level at which no further damage will occur.

Other avoidance measures centred around low ground pressure systems (maintaining similar axle loads) and controlled traffic. (Spoor & Miller, 1989, Chamen et al., 1990, Chamen et al., 1992, Chamen et al., 1994, Chamen & Cavalli, 1994, Chamen & Longstaff, 1995). Avoidance using a low ground pressure approach has been shown to be successful, but only where axle loads have been maintained rather than increased. Practitioners need to be fully aware of the difference between ground pressure and axle load, and this education process continues. Controlled traffic systems (separation of wheeled and cropped areas) have been researched using both gantry and conventional tractor systems, and although adoption has been limited, the method seems to have great potential and is gaining recognition. Yield increases in cereals have averaged 15%, while tillage inputs have been reduced by around 50%. Soil structure improvements have also been widely studied (Watts et al, 1996, Watts & Dexter, 1997) and experienced, these having implications for drainage, water interception and root development.

In the remediation and avoidance work, measurements and techniques have been similar. Soil bulk and clod density, penetrometer resistance, shear strength, plate sinkage, confined compression tests, pore sizes and their distribution, matric potential, saturated hydraulic conductivity, water content and profile examination have all been used. Crop yield has usually been the means by which improvements have been judged, although with recent changes in the value of crops, this may not be the most important criterion in the future.

England and Wales soil data resource

Over the last 60 years the Soil Survey and Land Research centre at Silsoe, has compiled soils information across the two countries at a scale of 1:10,000. Since 1961 this has included water retention properties of undisturbed subsoil cores. As mentioned in earlier paragraphs, both soil and climatic conditions vary considerably across the two countries. As a result, the vulnerability of subsoils differs considerably. In some areas, they remain compact as a result of their origins and may become unstable if loosened. In other areas, high subsoil moisture levels make them vulnerable at all times, with effective loosening being difficult. In the east, drier conditions may reduce the risk of damage, but machines are often heavier and cropping patterns more varied.

Future requirements

The authors consider that any database should aim to provide growers with information which will help them to manage their soils competitively and in a sustainable manner for future generations. Use of existing Soil Survey information, together with research data on soil machine and crop effects, should allow some predictive systems to be developed, together with practical guidelines based on local soil and climatic conditions.

Conclusions

Well targeted local information on the effects of subsoil compaction is available, but these data are not widespread. In view of this, it will probably be difficult to gauge the level of subsoil compaction induced by machinery operations in England and Wales, other than on a local level. The soil information from long established and well documented surveying, will it is believed, form the most valuable resource from which a future strategy can be developed.

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Appendix Table 1A (scannen en invoegen)

Chamen & Spoor Appendix Table 1A Concerted Action on Subsoil Compaction: Information for Database

Principal author		Steinhardt	Trafford, B.D.	Rowse, K.R.	Smith, D.L.O.	Stone, D.	Rowse, K.R.	Soane, B.D.	Hull, R.	Chamen, W.
Journal		J Soil Sci	J Soil Sci	JAER	JAER	J Agr Sci	S & T	J of I Agr E	J Agr Sci	S & T
Yr of publication		1974	1973	1984	1990	1982	1980/81	1970	1967	1994
Vol/Start page		25/138	24/380	29/215	46/13	98/297	1/173	25/115	69/183	32/303
Location			ADAS	Wellesbourne	Scotland?	Wellesbourne	Wellesbourne	Scotland?	?	Silsoe
Emphasis			Drainage	Crops	Mechanics	Crops	Crops	Machine	Crops	Machine
No of Expts/sites		1	1	1	4/2	1	1		1	1
Duration, yrs		1	1		1	1	1		4	1
Soil:	Bulk density	+ (0.25 m)		+ (indicated)	+	+	+	+		+
	Sat. hyd. cond.	+ (0.25 m)	+							
	Non. sat. hyd. cond.									
	Water retention	+ (0.25 m)				+	+			
	Air permeability									
	Temperature									
	Air diffusivity									
	Pore space	+				+		+		
	Pen. resistance	+				+				+
	Shear strength									
	Water content				+					
	Drainage features	+	+				+			
	Structural features									
	Draught/disturbance									
	Type	+				+				
Crop:	Yield			+		+	+		+	
	Root depth					+				
	Root density					+	+			
	Root/shoot ratio									
	Nutrient uptake			+		+				
	Water use					+	+			
	No. of crops			3		5	4	1	4	1

Appendix Table 1B Concerted Action on Subsoil Compaction: Information for Database

	Principal author	Gooderham, P.	Soane, G.	Marks, M.J.	Soane, G.	McEwen, J.	Rowse, K. R.	Harris, G.	Goss, M.	Goss, M.
	Journal	Agric Progress	Soil U & M	Soil U & M	S & T	J Agr Sci	S & T	Agr Water Man	JAER	J Agr Sci
	Yr of publication	1977	1987	1987	1986	1979	1980	1993	1984	1984
	Vol/Start page	52/33	3/123	3/115	8/231	92/695	1/57	23/161	30/131	103/189
	Location	Wye	Silsoe	Silsoe	Silsoe	?	Wellesbourne	Rothamsted	Rothamsted	Rothamsted
	Emphasis	Crops	Machine/crop	Crops	Structure	Crops	Crops	Drainage	Stucture	Drainage
	No of Expts/sites	1	16	16	1	1	4/1	1	2	3
	Duration, yrs		3	7	1	4	1	10		
Soil:	Bulk density		+		+					
	Sat. hyd. cond.								+	
	Non. sat. hyd. cond.									
	Water retention	+								+
	Air permeability									
	Temperature									
	Air diffusivity									
	Pore space	+							+	
	Pen. resistance		+		+					
	Shear strength									
	Water content									
	Drainage features							+	+	
	Structural features									
	Draught/disturbance									
	Type		+	+	+	+	+	+		
Crop:	Yield	+		+		+	+			
	Root depth	+							+	
	Root density	+								+
	Root/shoot ratio									
	Nutrient uptake			+		+	+			
	Water use	+		+					+	
	No. of crops	4	4	4		4	4			

Appendix Table 1C

Concerted Action on Subsoil Compaction: Information for Database

	Principal author	Hulme, R.	Bamford, S.	Parker, C.	Webster, R.	Pollard, F.	Emmanuel, G	Chapman, R.	Barraclough, P	Barraclough, P
	Journal	Thesis	Thesis	Thesis	J Agr Sci	JAER	Thesis	Grass For Sci	ISSR Sym Uppsla	J Agr Sci
	Yr of publication	1982	1984	1991	1977	1978	1984	1994	1991	1988
	Vol/Start page	H/82/253	MS/84/435	D/91/103	88/455	23/217	MS/84/455	49/447	1/410	110/207
	Location	Silsoe	Silsoe	Silsoe	Oxford	Oxford	Silsoe	Notts	?	?
	Emphasis	Mechanics	Crops	Crops/stru	Crops/stru	Structure	Machine	Crops	Crops	Crops
	No of Expts/sites	1	1	3	400	1	1	1	1	1
	Duration, yrs	1	1		13	6	1			1
Soil:	Bulk density	+	+	+		+		+		+
	Sat. hyd. cond.									
	Non. sat. hyd. cond.									
	Water retention					+		+	+ ?	
	Air permeability									
	Temperature								+	
	Air diffusivity									
	Pore space			+					+	
	Pen. resistance			+		+	+		+ ?	
	Shear strength	+		+			+ (indicated)			
	Water content		+							
	Drainage features									
	Structural features				+	+				
	Draught/disturbance									
	Type	+		+	+	+				
Crop:	Yield		+	+	+			+	+	+
	Root depth								+	+
	Root density								+	+
	Root/shoot ratio									
	Nutrient uptake				+					+
	Water use									+
	No. of crops		1	1	1			1	1	1

Appendix Table 1D Concerted Action on Subsoil Compaction: Information for Database

Principal author		Spoor, G.	Spoor, G.	Spoor, G.	Chamen, W.	Bradley, I.	Spoor, G	Chamen, W.	Chamen, W.
Journal		JAER	JAER	JAER	Soil U & M	Soil Survey	Cranfield	S & T	S & T
Yr of publication		1983	1983	1978	1995	1968 -	1989	1994	1992
Vol/Start page		28/217	28/319	23/243	11/168			32/303	24/359
Location		Silsoe	Silsoe	Silsoe	Silsoe	Silsoe	Silsoe	Silsoe	Silsoe
Emphasis		Machine	Machine	Machine	Structure	Physical	Crops	Machine	Crops/stru
No of Expts/sites		6	7	2	1	5000	3?	1	1
Duration, yrs		1		1	2		3	1	5
Soil:	Bulk density	+	+		+	+	+	+	+
	Sat. hyd. cond.								
	Non. sat. hyd. cond.								
	Water retention				+	+			
	Air permeability								
	Temperature								
	Air diffusivity								
	Pore space	+ (indicated)	+ (indicated)	+ (indicated)	+				
	Pen. resistance				+		+	+	+
	Shear strength								+
	Water content								
	Drainage features								
	Structural features								
	Draught/disturbance	+	+	+				+	+
	Type	+	+	+	+	+			
Crop:	Yield				+		+		+
	Root depth						+		
	Root density								
	Root/shoot ratio								
	Nutrient uptake								
	Water use								
	No. of crops				1		1		2

BEWERTUNG VON LANDWIRTSCHAFTSREIFEN NACH AGROTECHNISCHEN, ÖKOLOGISCHEN UND TECHNISCH-ENERGETISCHEN KRITERIEN

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Das Problem

Effektivität der Landbewirtschaftung und des Ackerbaus verlangt leistungsfähige Maschinen. Das ist meist mit hohen Radlasten (bis 12 t) verbunden. Durch Raddruck verursachte, schädliche Bodenverdichtungen wirken negativ auf den Wasserhaushalt, Erosion und Ertrag.

Herkömmliche Methoden zur Untersuchung von fahrwerksbedingten Bodeneinflüssen sind sehr aufwendig und ungenau. Die Heterogenität des Bodens und der Einfluß von Bodenart und -feuchte führen nur zu begrenzten Aussagen und machen meist nur einen Variantenvergleich möglich.

Resultate zur Wirkung von Bodenverdichtungen auf das Pflanzenwachstum, der Ertragsbildung, auf den Wasser- und Nährstoffhaushalt liegen dagegen recht detailliert vor. Auf diesen bekannten Tatsachen beruhen Modelle zur Bodenverträglichkeit von Landmaschinen, die auf eine Begrenzung der technischen Parameter der Bodenbelastung zielen aber von völlig ungenügender Kenntnis der Fahrwerke begleitet sind und damit nicht zum Ziel führen.

Für eine mathematische Formulierung des Verdichtungsverhalten von Boden und des fahrwerksbedingten Energieaufwandes gibt es viele Ansätze (Druckzwiebel von SÖHNE bis YONG zur Methode der Finite-Elemente). Es fehlen aber experimentelle Daten der Druckverteilung zwischen Reifen und Fahrbahn sowie des Verdichtungsverhalten von Ackerböden unter kurzzeitiger Druckbelastung beim Befahren.

Agrotechnische Reifenprüfung

Von der Projektgruppe Rad-Boden werden auf experimenteller Grundlage und auf unkonventionelle Weise die Wirkung der Parameter von Fahrwerken (Reifen und Gleisbänder) sowie der Einflußfaktoren auf die Bodenverdichtung, den Pflanzenstreß, ökologische und energetische Parameter detailliert und systematisch untersucht (bis 12 t Radlast). Der gesamte Forschungskomplex Rad - Boden – Pflanze – Ökologie – Energie wird in seinen einzelnen Bestandteilen separat untersucht (Abb. 1).

Als Ausgangspunkt und Schnittstelle für den Bezug zu Boden- und Pflanzenstreß sowie zu energetischen Aussagen dient die sensible Messung des Druckes in der Kontaktfläche.

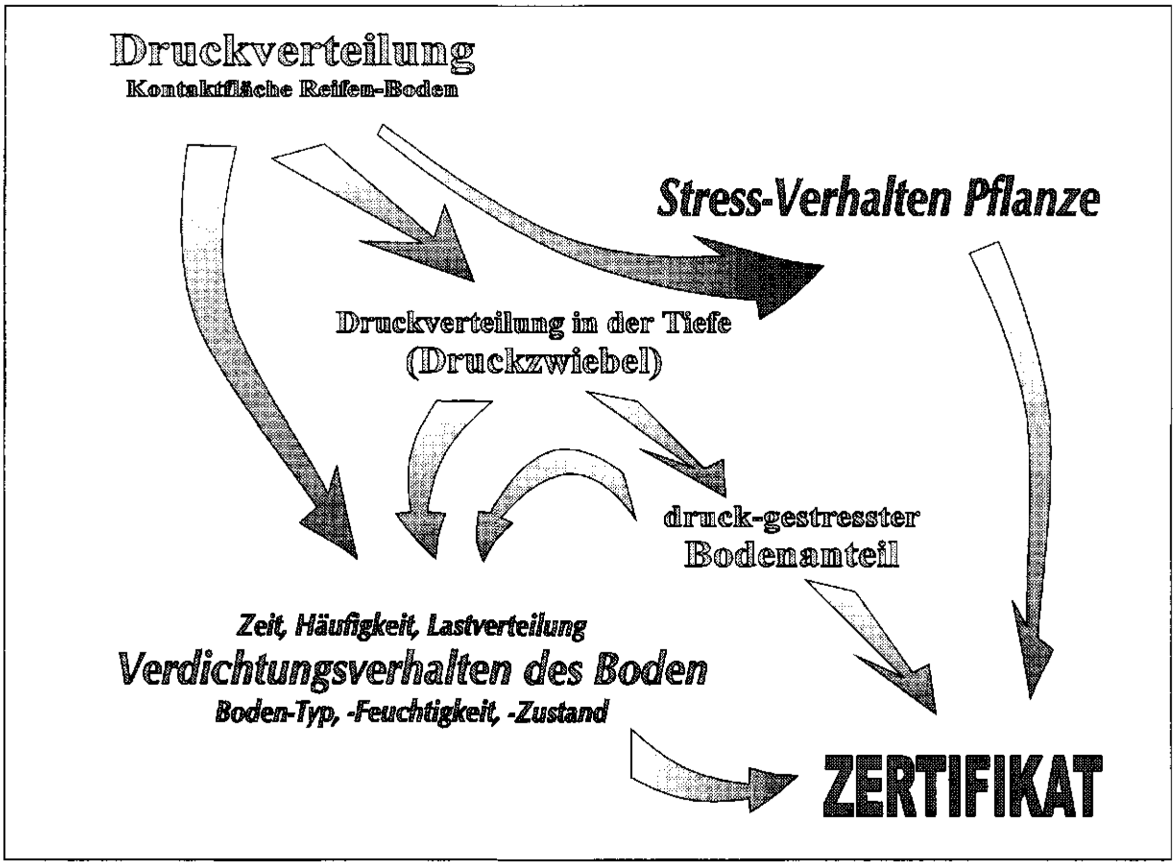

Abb. 1 Übersicht zum Zusammenhang der Forschungsschwerpunkte Rad - Boden - Pflanze für die agrotechnische Bewertung von Reifen

Aus dem Ergebnis der Prüfung von über 80 Reifen (Anlage 1) läßt sich feststellen, daß landwirtschaftliche Triebrad- und MPT-Reifen sehr unterschiedliche Eigenschaften beim Kontaktieren mit der Fahrbahn und in ihrer Wirkung mit dem Boden aufweisen. Das betrifft sowohl die Ergebnisse z. B. bei Kontaktflächenformen, mittleren Kontaktdrücken u. a. im Vergleich zu bestehenden Meinungen oder auch die Unterschiede zwischen gleichen Reifentypen unterschiedlicher Hersteller. Mit den Untersuchungen können neben allgemeinen Kriterien der agrotechnischen Qualität von Reifen (wie z. B. Kontaktfläche, mittlerer Kontaktdruck) wesentlich spezifischere Kriterien zur Beurteilung von Reifen und bereitge-stellt gemacht (wie z. B. Deformationsverhalten, Druckabbau im Boden u. a. m.). Insbesondere sind die Ergebnisse reproduzierbar und lassen sowohl einen Vergleich von Reifen miteinander zu und können in ihrer Wirkung auf die spezifischen Bodenbedingungen beurteilt werden.

- **Kontaktfläche, mittlerer Kontaktdruck und Druckverteilung in der Kontaktfläche**

Gemessen werden die Verteilung von Druck bzw. Last in der Kontaktfläche auf fester Fahrbahn. Das Meßraster von 1 cm x 1 cm ergibt eine Fehlerquote bis 3 % (aufgebrachte Radlast zur Summe aller Teillasten in der Kontaktfläche). Reifen können bis zu 12 t Radlast belastet werden. Zur Beurteilung der Reifen werden je nach Typ 2 bis 7 Radlasten mit je 4 bis 6 Reifendrücken geprüft. Die Ermittlung der Kontaktfläche erfolgt in herkömmlicher Weise der Umschreibung der äußeren Berührungspunkte des Reifens mit der Fahrbahn und ist der Ausgang für den mittleren Kontaktdruck.

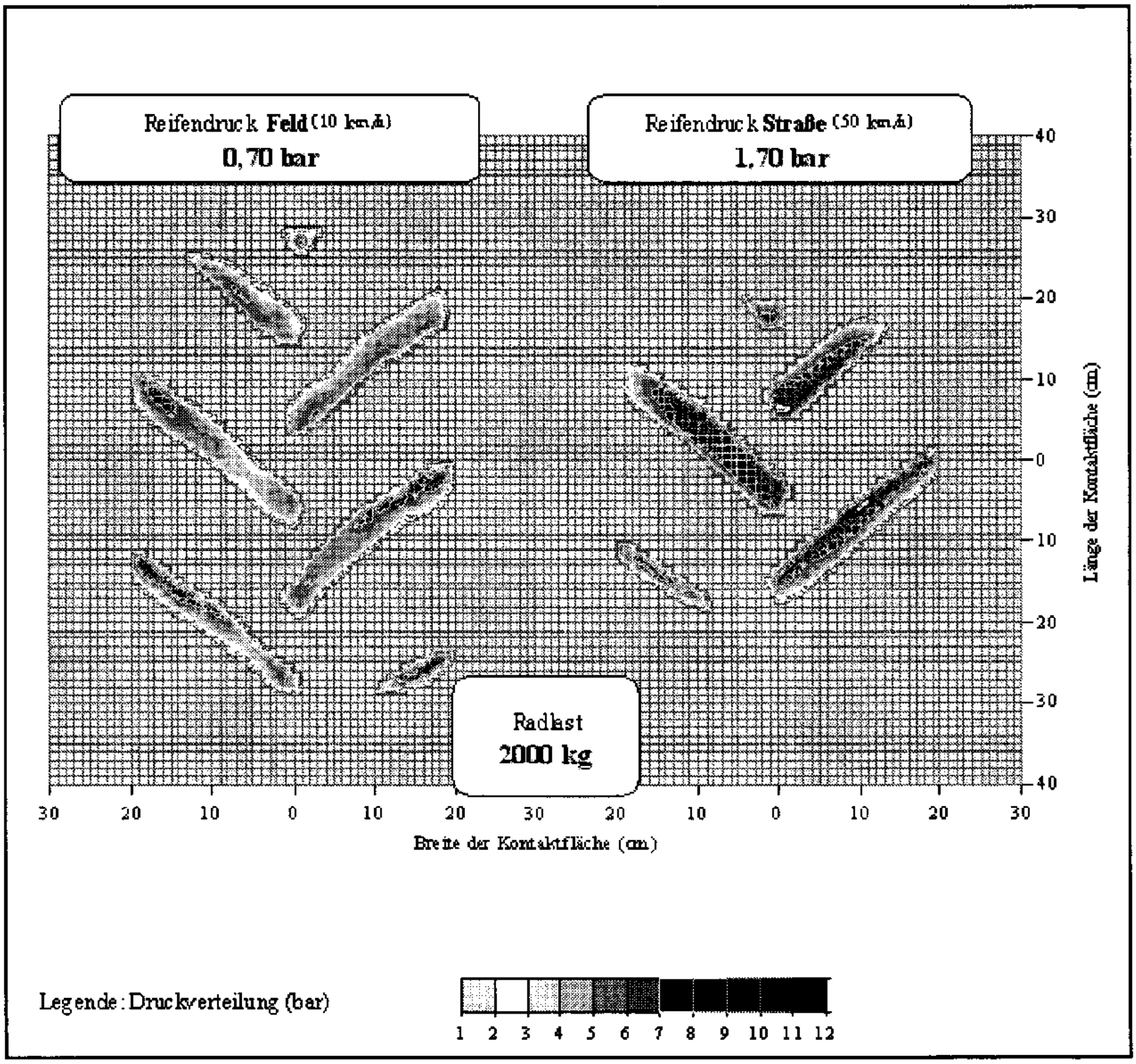

Abb. 2 Einfluß von Reifendruck auf die Druckverteilung in der Kontaktfläche (Reifen 16.9R24 STR)

In Auswertung der bisherigen Prüfungen kann festgestellt werden, daß die Größe der Kontaktfläche bei gleichen Reifentypen stark vom Hersteller abhängig ist (Differenzen bis zu 30 %).

In den vom Hersteller vorgegebenen Bereichen der Reifenbelastung (Radlast / Reifendruck) wird eine veränderliche Differenz zwischen Reifendruck zu mittleren Kontaktdruck festgestellt. Bei hohen Reifendruck für Straßenfahrt ist der mittlere Kontaktdruck ca. 40% niedriger als der Reifendruck und bei niedrigem Reifendruck für Feldfahrt ca. 60 % höher als der mittleren Kontaktdruck (Abb. 3). Damit ist die Nutzung des Reifendruckes mit konstantem Koeffizienten für die Bewertung der Bodenbelastung in Frage gestellt. Noch stärker wirkt die Druck- bzw. Lastverteilung in der Kontaktfläche auf die Bodenbelastung.

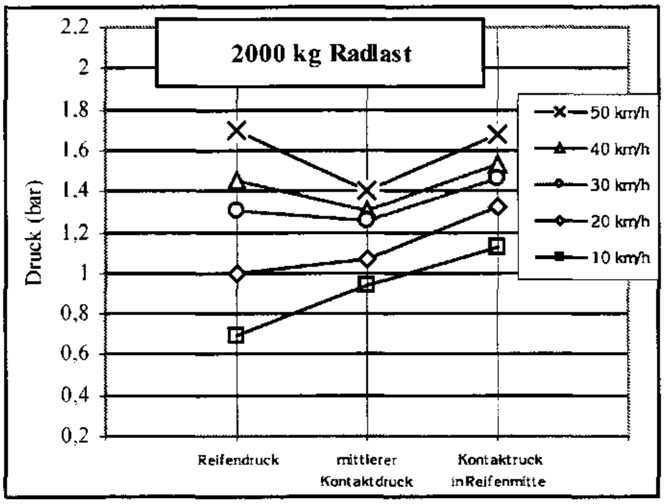

Abb. 3 Vergleich von Reifendruck, mittleren Kontaktdruck und Kontaktdruck in der Mitte des Reifens 16.9R24 STR

- **Deformationsverhalten des Reifens auf der Fahrbahn**

Die Lastverteilung in der Kontaktfläche ist ein direkter Maßstab für das Deformationsverhalten von Reifen auf der Fahrbahn (Boden). Sichtbar gemacht wird vor allem der Einfluß des Reifeninnendruckes auf die Anpassung des Reifens an die Fahrbahn (Abb. 4).

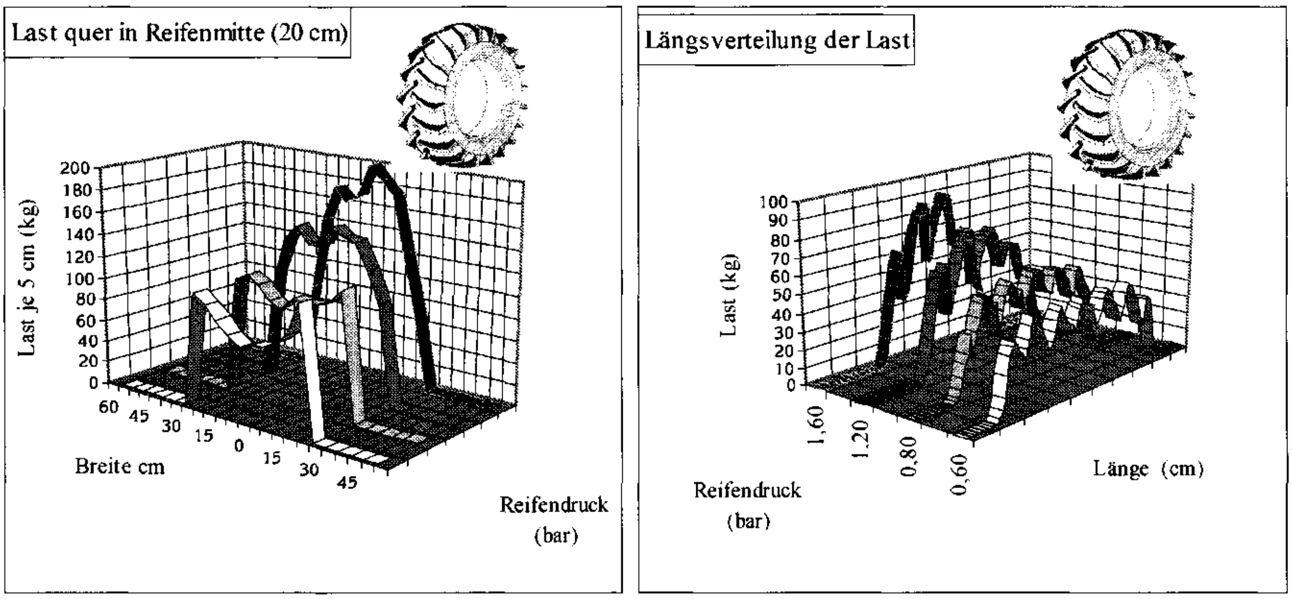

Abb. 4 Lastverteilung unter dem Reifen 600/65R38 XM 107, Radlast 2750 kg

Außer der Reifenkonstruktion besitzt vor allem der Reifeninnendruck einen entscheidenden Einfluß auf die Verteilung im Spurquerschnitt und in der Länge der Aufstandsfläche. Eine Lastkonzentration in der Mitte des Reifens wirkt stark negativ und eine Lastverlagerung nach außen bzw. nach vorn und hinten zeigt positive Effekte auf die Bodenverdichtung. Die Größe der Lastverlagerung in die Flanken meist bei Reifendruckminderung ist ebenfalls sehr stark vom Hersteller abhängig. Im vorgegebenen Reifendruckbereich können diese Lastunterschiede in den äußeren Dritteln zur Mitte (1/3) des Spurquerschnittes bis zu 40 % betragen (im Extremfall bis zu 80 %). Aus diesem Grunde werden die unterschiedlichen Formen der Querschnittsbelastung untersucht. Erste Ergebnisse zeigen, daß je nach Spurbreite eine gewisse Flankenbelastung zu einer Minderung der Bodenbelastung beitragen kann.
Die Lastverteilung in Fahrtrichtung läßt eine einfachere Wertung zu. Je nach Reifendruck und Radlast ist eine höhere Last in der Reifenmitte mehr oder weniger ausgeprägt und wird dementsprechend auf die Bodenverdichtung wirksam. Abgeleitet aus oben genannten Untersuchungen der Lastverteilung ist eine gleichförmige Lastverteilung in Fahrtrichtung unter der Kontaktfläche ein erstrebenswertes Ziel.

- **Druck im Boden (Druckzwiebel)**

Zum Bewerten der Bodenbelastung wird der Druckabbau im Boden (Druckzwiebel) unmittelbar aus der Druckverteilung in der Kontaktfläche rechnerisch ermittelt (Abb. 5).

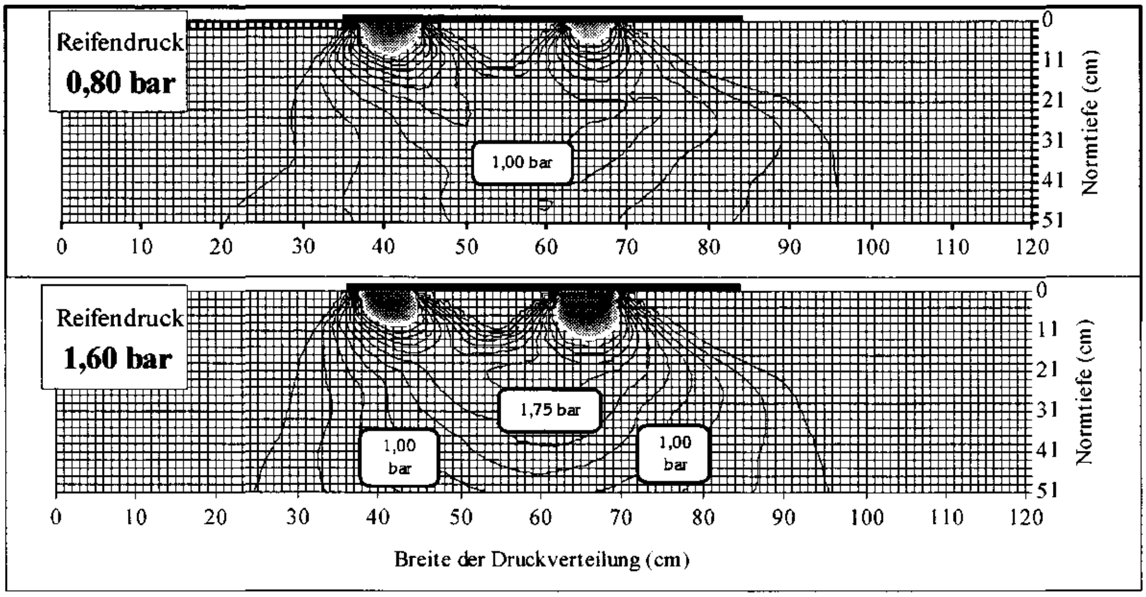

Abb. 5 Druckabbau im Boden (Druckzwiebel), Reifenmitte quer zur Fahrtrichtung (Reifen 600/65R38 XM 107)

Die Druckzwiebel wird als vertikaler Schnitt unter der Kontaktfläche in Reifenmitte längs und quer zur Fahrtrichtung vorgestellt. Sehr differenziert kann die Auswirkung der Änderung von Radlast und Reifeninnendruck entsprechend der unterschiedlichen Druckverteilung in der Kontaktfläche auf das druckgestreßte Bodenvolumen und die Tiefenwirkung sichtbar gemacht werden. Die Häufigkeit der gestreßten Druckzonen bezogen auf die Spur oder Arbeitsbreite stehen direkt für die Trendeinschätzung der Bodenverdichtung zur Verfügung.

- **Verdichtungsverhalten des Bodens**

Für die Beurteilung des durch Druck gestreßten Bodenvolumens wird das Druckverhalten von natürlichen Ackerböden (Ackerkrume und Unterboden) in Abhängigkeit von der Bodenart, dem Feuchte- und Strukturzustand untersucht. Die Zeitdauer des Druckimpulses wird als ein entscheidender technologischer Parameter zur agrotechnischen Bewertung der Bodenverdichtung angesehen (Abb. 6).

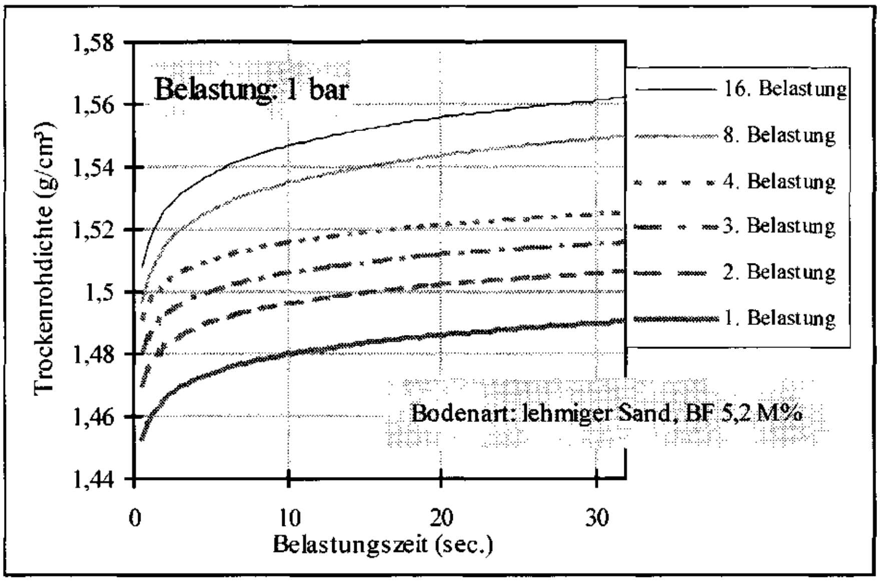

Abb. 6 Einfluß der Dauer des Belastungsimpulses und der Wiederholung der Belastung auf die Ver-dichtung des Bodens

Eine Fahrgeschwindigkeit von 5 km/h erzeugt einen Druckimpuls je nach Länge der Kontaktfläche von weniger als 0,6 Sekunden. Untersuchungen zur Dauer der Druckeinwirkung auf den Boden belegen, daß eine Belastung von 30 Sekunden 8 – 10 Belastungen bei 0,5 Sekunden entsprechen. Die Wiederbelastung mit zeitlichem Abstand mehrerer Tage vermindert die Empfindlichkeit des Bodens. Werden die Belastungsgrenzen des Bodens nach dem Setzungsverhalten von mehreren Stunden und Tagen aus dem Baubereich abgeleitet, wird nach solch einer Verfahrensweise die Verdichtung als viel zu hoch eingeschätzt.

Zur Untersuchung der Verdichtungscharakteristik werden Bodenproben vom Feld aus der Ackerkrume und dem Unterboden genommen. Als überragender Einflußfaktor für die Bodenverdichtung ist die Bodenfeuchte zu nennen (Abb. 7). Zum Beispiel entspricht die Bodenverdichtung auf einer Parabraunerde (Lö 3) in Druckzonen im Boden von 8 bar (Extrembelastung) bei 14 M% Bodenfeuchte (noch feucht krümlig) der Bodenverdichtung die in Druckzonen von 1 bar bei einer Bodenfeuchte von 20 M% (Bearbeitungsgrenze) erreicht werden. Vor allem bei niedriger Belastung (0,5 bis 1 bar) steigt z. B. auf bindigen Böden die Verdichtung mit zunehmender Bodenfeuchte drastisch an. Bei einem Anstieg der Bodenfeuchte von nur 5 M% (von 14 auf 19 %) nimmt der Belastungseinfluß um ca. das 10-fache zu.

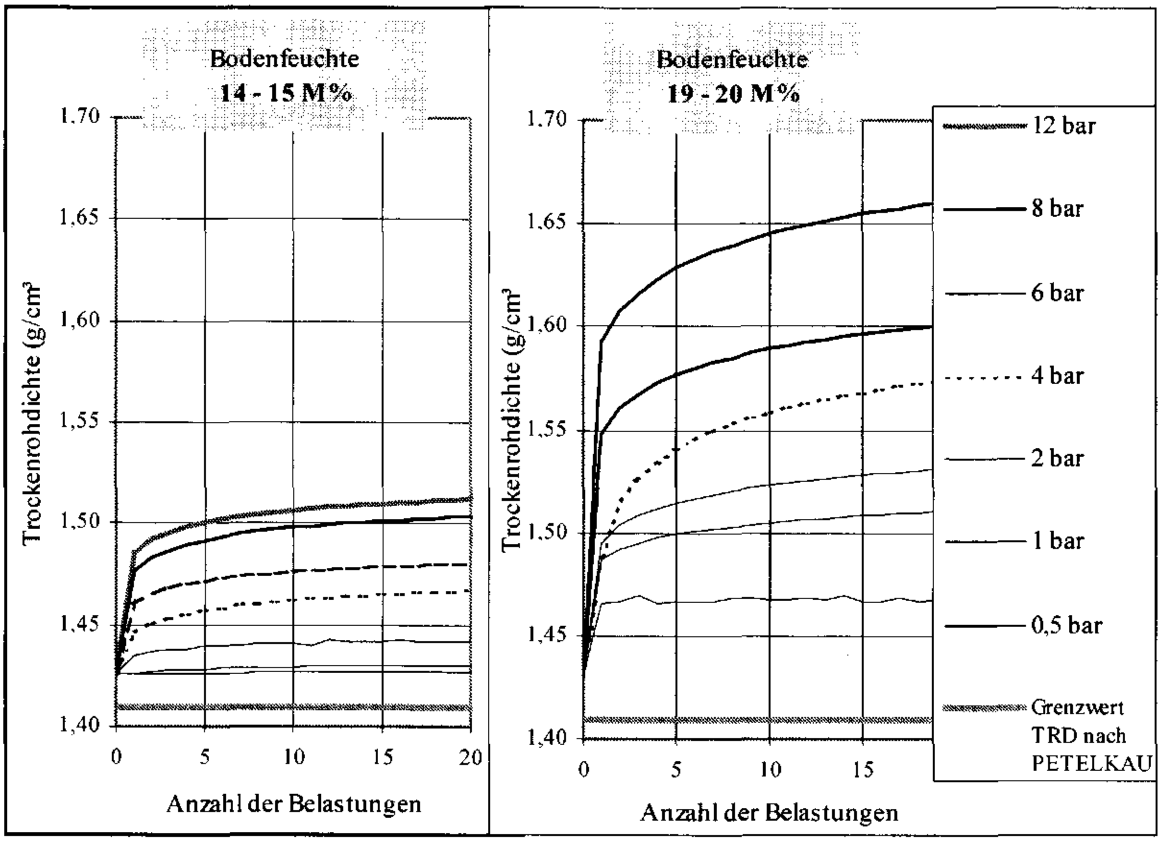

Abb. 8 Veränderung der Bodendichte (TRD) nach Druckbelastung in Abhängigkeit von der Feuchte Belastungsdauer 0,5 sec. (entspricht ca. 5 km/h), Ackerkrume Lö3, Seligenstadt/Würzburg

Die Überprüfungen von Fahrspuren unter Praxisbedingungen bestätigen eine hohe Treffsicherheit der Ergebnisse zu der beschriebenen Methode der agrotechnischen Bewertung von Landwirtschaftsreifen.

Die Belastbarkeit von Böden bei verschiedenen Verfahren der Bodenbearbeitung kann ebenfalls differenziert nachgewiesen werden. Mit bekannten Zusammenhängen der Bodenverdichtung zum Ertrag (PETELKAU) läßt sich ein Trend der positiven oder negativen Effekte des

Befahrens vorhersagen. Die Veränderung der Bodenverdichtung unter definierter Druckeinwirkung wird für typische Bodenarten ermittelt und ist nur ein Parameter zur Charakteristik des Einflusses von Fahrwerken, der aber relativ sichere Ergebnisse liefert. Die Untersuchung der Veränderung anderer physikalischer Bodenparameter (Leitfähigkeit u. a.) unter definierter Druckbelastung ist dringend erforderlich.

- **Pflanzenstreß**

Die Druckverteilung in der Kontaktfläche ist der direkte Ausgangspunkt für die Bewertung von Planzenstreß sowie dem Zugkraftverhalten. Mit systematischen Untersuchung des druckbedingten Streßverhaltens von landwirtschaftlichen Kulturpflanzen kann die zulässige Höhe des von der Pflanze verträglichen Druckes eindeutig bestimmt werden. Ergebnisse von 5-jährigen Untersuchungen der direkten Druckbelastung auf Zuckerrüben und Raps belegen, daß eine Belastungen bis 3 bar von der Pflanze ohne wesentliche Ertragsminderung (ca. 5 %) vertragen werden. Bisher konnten mit dieser Methode und der Praxisüberprüfung bei der Südzucker A. G. Empfehlungen für Fahrgassen und Anwendung von super-breiten Reifen im Zuckerrübenanbau erarbeitet werden.

Die forstwirtschaftliche Anwendung der Methode z. B. zur Schädigung der Rindenschicht von Wurzeln bei Druckbelastung und zur Reifenauswahl ist denkbar.

- **Fazit**

Mit der vorgestellten Methode läßt sich die fahrwerksbedingte Bodenbelastung im Trend bewerten und bietet für Landwirte die Möglichkeit, notwendige Maßnahmen zur schonenden Befahrung des Bodens einzuleiten. Mit der genaueren Kenntnis des zum Teil überragenden Einflusses hoher Bodenfeuchte auf das Verdichtungsverhalten der verschiedenen Bodenarten kann der Land- und Forstwirt entsprechend der territorialen und der vom Wetter abhängigen Bedingungen das Risiko schädlicher Bodenverdichtungen einschätzen oder bessere bodenschonende Reifen, Maschinen und Technologien auswählen.

Voraussetzung ist die Kenntnis der Verdichtungscharakteristik des Bodens bei kurzzeitigem Druckimpuls (Atlas der Bodenverdichtung) und die vorgestellte agrotechnische Charakteristik des Reifens (Online Reifenkatalog).

Auch für die Entwicklung von landwirtschaftlichen Reifen und Maschinen können somit detaillierte Ergebnisse zur Produktentwicklung zur Verfügung gestellt.

Die Nutzung der Ergebnisse für die Kontrolle einer bodenschonenden Befahrung der Landbewirtschaftung (Landwirtschaft) soll in einem Pilotprojekt vorbereitet werden.
Der Bezug auf weitere bodenphysikalische Parameter als der Trockenrohdichte und in Folge auf den agrotechnischen und ökologischen Effekt ist wünschenswert und angestrebt.

Die Leistungen der Projektgruppe Rad-Boden sind:

Atlas zum Druckverhalten von Ackerböden

Untersuchung des Verdichtungsverhalten von Ackerböden in Abhängigkeit von seinem Feuchte- und Strukturzustand insbesondere unter dem Einfluß der kurzzeitigen Belastung zur Einschätzung der Druckverträglichkeit des Bodens als Grundlage

* für die Risikoabschätzung der Bodenbelastung,
* für Kontroll- und förderpolitische Maßnahmen der bodenschonenden Befahrung von Ackerböden

Online-Reifenkatalog

Agrotechnische Prüfung von Reifen und Fahrwerken entsprechend der vorgegebenen Radlasten und Reifendrücke

* herkömmliche Parameter Kontaktfläche, Kontaktdrücke u. a.
* Auswirkung auf die Last- und Druckverteilung in der Kontaktfläche,
* Druckabbau im Boden (Druckzwiebel),
* Rollwiderstand, Zugkraft u. a. m.
* Einschätzung zum Deformationsverhalten und Anpassung an die Fahrbahn, zur Abschätzung des Risiko von Bodenverdichtungen mit agrotechnischen und ökologischen Folgewirkungen sowie der energetischen Aufwendungen

(Nutzung auch für die Kontrolle einer bodenschonenden Befahrung der Landbewirtschaftung)

Anlage 1

1 Liste der geprüften Reifen

Druckverteilung in der Kontaktfläche, Seitenkontur, Rollwiderstand

Radlast von 1,5 t bis max. 12,0 t in Schritten von 1,5 t,
Reifendruck bei 10*, 10, 30, 40, 50 km/h

Alliance	1.	550/60-22,5 I328	**Kleber**	47.	16,9R24 S8
	2.	550/60-22,5 I222		48.	480/70R24 S8L
	3.	600/55-22,5 I328		49.	540/65R24 Super 11L
	4.	700/50-22,5 I328		50.	480/70R34 9L
				51.	520/70R38 9L
Bandenmarkt	5.	550/60-22,5		52.	20,8R42 S9
Dnieproshina	6.	66x43.00R25 F 29	**Michelin**	53.	525/65R20,5 XS
				54.	24R20,5 XS
Goodyear	7.	7,50-16 ST		55.	16,9R24 XM25
	8.	12,5/80-18 SGL		56.	540/65R24 XM 108
	9.	24x20,5 SRS-A7		57.	620/70R26 XM27
	10.	550/60-22,5 12PR T		58.	30,5R32 XM
	11.	550/60-22,5 16PR T		59.	1050/50R32 XM608
	12.	550/60-22,5 12PR R		60.	710/70R34 XM27
	13.	550/60-22,5 12PR Rq		61.	600/65R38 XM108
	14.	16,9R24 STR		62.	230/95R44 XM25
	15.	19,5 L24 IT525		63.	270/95R48 XM25
	16.	16,9-28 ISG			
	17.	16,9R28 IT510	**Nokian**	64.	550/60R22,5 ELS
	18.	18.4R38 STG			
	19.	18.4R38 DT710	**Pirelli**	65.	16,9R24 TM200
	20.	20.8R42 STR		66.	480/70R24 TM700
	21.	30,5L32 STR		67.	520/70R38 TM700
	22.	250/80R16 STR		68.	580/70R42 TM700
	23.	280/80R18 STR			
	24.	320/70R18 IT510	**Pneumant**	69.	16-20 U27
	25.	400/70R20 FS24		70.	16-20 Rille
	26.	480/70R24 DT820		71.	18/70-20 U27
	27.	495/70R24 IT510		72.	12,4-38
	28.	540/65R24 DT820			
	29.	650/55R25 GP A-2	**Topagri**	73.	550/60R22,5
	30.	540/65R28 DT820			
	31.	480/70R34 DT810	**Trelleborg**	74.	18.4-34
	32.	800/65R32 STR		75.	500/60-22,5 TT404
	33.	800/65R32 DT820		76.	550/45-22,5 TT404
	34.	480/70R34 DT810		77.	600/50-22,5 TT404
	35.	520/70R38 DT810		78.	700/50-26,5 TT423
	36.	580/70R38 DT810			
	37.	600/65R38 DT820	**Taurus**	79.	12,4R46
	38.	650/65R38 DT820		80.	9,5R48
	39.	710/70R38 DT820			
	40.	650/65R42 DT820	**Vredestein**	81.	16/70-20
	41.	54x31.00-26 STG-6		82.	550/60-22,5
	42.	66x43.00-25 STG2			
	43.	67x34.00-25 STG-6			
	44.	67x34.00R26 STG-6			
	45.	73x44.00R32 STG XT			
	46.	73x44.00-32 STG XT			

RESEARCH AND EXPERIENCES ON AGRICULTURAL TYRES TO MINIMIZE SOIL COMPACTION

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Abstract

The problem of soil compaction caused by agricultural machinery has been studied both in laboratory experiments and field tests.

The behaviour of several agricultural tyres at various loads and inflation pressures, and when fitted to different rims, was examined. Contact area measurements on a hard surface were carried out in order to find tyre mean ground pressure. An attempt to predict tyre contact area as a function of their dimensions and working conditions was also carried out.

Field tests confirmed that, knowing tyre mean ground pressure, soil compaction mainly depends on field conditions, i.e. load-bearing capacity.

The results are encouraging and suggest that more effort should be concentrated on attempting to predict tyre mean ground pressure and soil load-bearing capacity as a function of its components, structure and moisture content.

Introduction

Soil compaction caused by agricultural machinery has been studied from the beginning of agricultural mechanization using theoretical analyses, laboratory experimentation or empirical observations on soils in the field. An example of milestones on this topic are the state of the art/review published by ASAE in 1971, written by Chancellor in 1976, by Soane et al. in 1980/1981 (a, b, c) and in 1982, and by Taylor and Gill in 1984.

More recently the increase of engine power, size and, consequently, mass of tractors and agricultural machines, in addition to intensive farming (e.g. single-crop farming), have highlighted the problems of soil structure deterioration and of the negative consequences on soil management, crop yield and environment.

Soil compaction is caused by forces. These forces may be applied by wheels, tracks, tillage tools, vibratory devices and human or animal traffic, or they may come from wetting and drying, freezing, or other natural forces (Taylor and Gill, 1984).The reaction to these forces depends on their magnitude and duration and on soil type and conditions (structure, moisture content, etc.).The result is a reduction in amount, shape, size and continuity of soil pores (Pagliai et al., 1988), with a consequent increase in soil bulk density and decrease in potential air and water movement.

Ruts and water stagnation (lack of permeability) (figs. 1, 2) are the most evident effects on soil surface (Febo and Pessina, 1988; Febo, 1991). The ground pressure exerted by a vehicle through its tyres or tracks is the main cause of soil compaction, especially in the upper layers of soil (Gasparetto et al., 1985). Subsoil compaction (meaning with this word the soil below the cultivated layer) is mainly caused by the total amount of surface load (Taylor et al., 1980; Carpenter et al., 1985; Smith and Dickson, 1990), by ploughing with the wheels in the furrow bottom and by the horizontal cutting action of some agricultural implements like plough and rotary tiller. In particular, when the soil moisture content is high and the amount of organic matter is low, a compact layer of soil (hard-pan, plough or tillage pan, figure 3) may form (Febo, 1991).

Fig. 1- Ruts and lack of plant growth caused by traffic of agricultural machinery.

Fig. 2- Water stagnation on soil surface due to soil compaction caused by agricultural machinery.

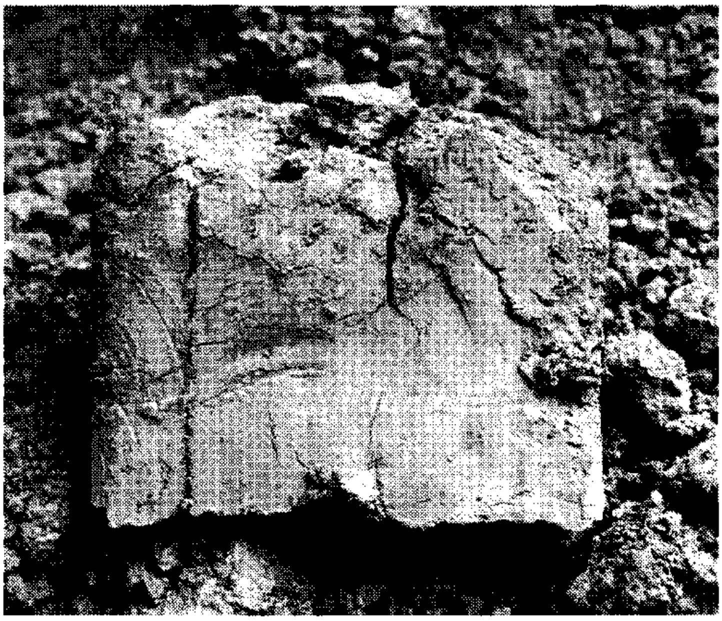

Fig. 3- Example of tillage pan on a clod artificially extracted from the bottom of the cultivated layer.

Methods

Soil compaction is mainly a function of the pressure applied to the ground surface. Therefore, ground pressure can be a good indication of the soil compaction caused by different vehicles. The pressure under a tyre varies over the area of contact, particularly if it is sinking deeply into the soil. However, if the aim is to avoid excessive soil compaction, tyres must be chosen which will prevent deep sinkage and, therefore, the mean ground pressure, at minimum sinkage, is a relevant criterion for comparison. Minimum sinkage is to be interpreted as just enough to allow full penetration of the treadbars and uniform ground contact with the carcass of the tyre, as shown in figure 4 (Plackett et al., 1987).

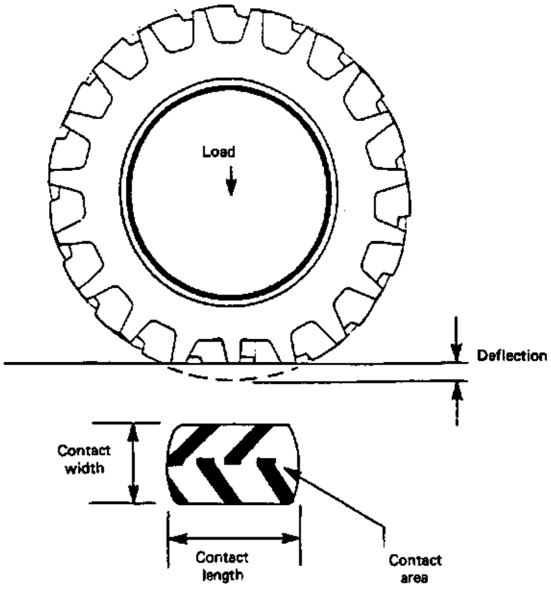

Fig. 4- Tyre deflection and contact area.

Plackett (1983; 1984) suggested measuring tyre contact area on a hard surface. A hard surface is of little interest in agriculture. However it seems to be the only way to avoid the variability of parameters such as soil components, bulk density, moisture content, etc., and to allow a comparison of the results.

When a pneumatic tyre is loaded against the ground, a contact area is formed. The size and shape of this contact area is of great interest, since its function is to transmit all of the forces developed by the tyre to the soil. When we are concerned with the amount of soil damage caused by a wheel, it is largely the vertical forces transmitted through the contact area which are of interest. If the distribution of vertical loads over the contact area is assumed to be uniform, then the mean ground pressure can be obtained by dividing the load carried on the wheel by the size of the contact area.

Loading a tyre against a soil surface often results in both the tyre and soil deflecting, with a rut being formed. However, since the aim is to minimize soil damage, the objective is to cause as little rutting as possible, and therefore simulate the case of the tyre being loaded against a hard surface. Full tread penetration is desirable, however, in order to deliver any tractive or steering force to the soil. For this reason the measurements are made on a hard surface, assuming full tread penetration, using a specially constructed rig, similar to a press.

A rig of this type has been constructed recently at the I.T.A.F. Department of the University of Palermo (Febo et al., 1997). It consists of a gantry mounted over a flat steel plate. The load is applied via two balanced hydraulic rams on to the axle fixed to the centre of the tyre rim. The load acting on the tyre is monitored by two load cells mounted at the base of each ram (fig. 5).

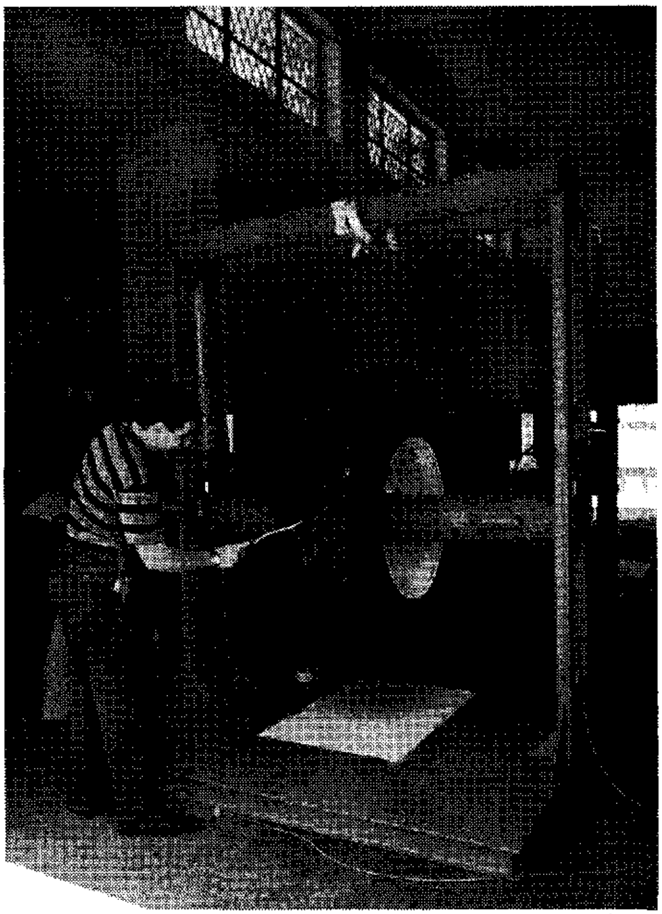

Fig. 5- Rig for measuring tyre contact area on a hard surface, constructed at the ITAF Department of Palermo University.

The contact area can be recorded by loading the tyre onto a piece of carbon paper overlaying a piece of white paper, both placed on the loading platform. Another technique is to paint the lugs with black ink and then load the tyre onto a piece of white paper placed on the loading platform.

In order to obtain the contact area of a tyre on a rigid surface, two methods can be considered. The first determines the contact area from one print. Using this method the contact area is clearly defined for a slick tyre (fig. 6.1), but for the tyres with lugs little information about the contact area can be obtained from one print as shown in figure 6.2.

The second method determines the contact area using a multiple overlay technique, whereby a number of prints are imposed onto the same piece of paper by rotating the tyre three or four times by a small amount (approximately the width of the top of the lug) between each print. An example of contact area achieved by this method is shown in figure 6.3. With this method full penetration of the lugs is assumed in order that a total area of contact for both lugs and carcass is determined. Dividing the load carried by the tyre by the contact area, a mean ground pressure can be found (Febo and Pessina, 1987).

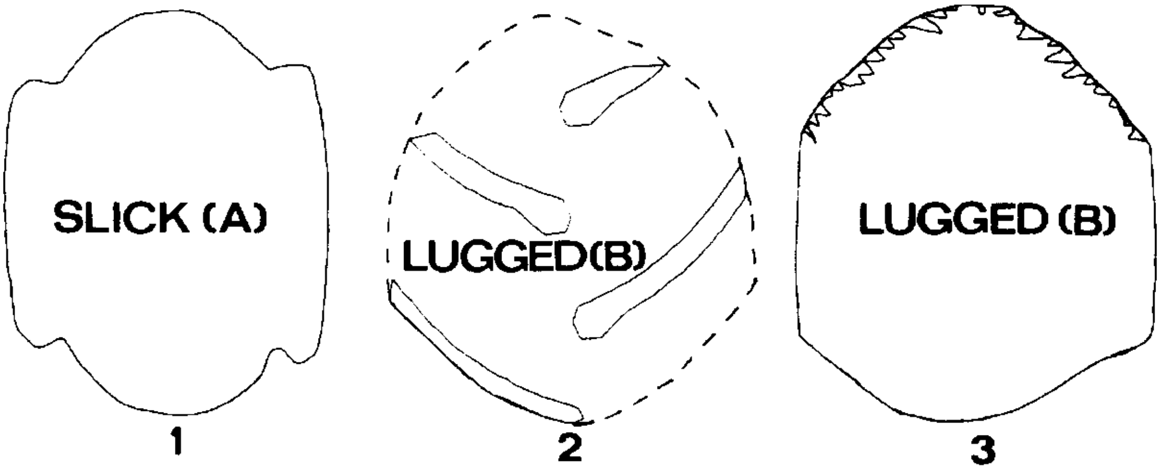

Fig. 6- Tyre contact areas on a hard surface : 1 - slick tyre, single print ; 2 - lugged tyre, single print ; 3 - lugged tyre, multiple overlay technique.

The local pressure distribution of the lugs on a hard surface was measured at the Pirelli factory using a rig similar to the press previously described. A steel sliding plate is provided with 50 aligned holes of 1 mm diameter, the gap between two of them being 3.6 mm. Each hole is connected to a small pipe blowing in compressed air. The tyre is idle on its axle and can be loaded to roll on the sliding plate. A transducer records the pressure required for the air to come out of the hole covered over by the lugs. The recorded pressure is thought to be a little higher than the real ground pressure exerted on the plate in that point. In fact, in order to come out, the air must overcome the pressure exerted by the tyre on the area surrounding the hole (Febo and Pessina, 1986).

A single-axle trailer, built on purpose by Pirelli to be pulled misaligned by the tractor, allowed soil compaction tests to be carried out with different tyres, loads, inflation pressures and field conditions. Cone penetrometer resistance was recorded to a maximum depth of 300 mm before and after one and five passes on the same wheel tracks (Gasparetto et al., 1988, 1989; Febo, 1990). Soil porosity measurements were also carried out (Pagliai et al., 1988, 1992).

Results and discussion

Laboratory tests

According to tyre manufacturers, a tyre can often be fitted on two or more different rims.

The behaviour of several tyres, including the slick carcass of a prototype tyre 520/65 R34, fitted on different rims, was examined.

Tyre side wall deflection depends heavily on the inflation pressure. It is higher at low inflation pressure with the same load. The increase of deflection with the same rim is higher between 80 and 120 kPa than between 120 and 160 kPa.

The narrowest rim gives the biggest deflection at the same load with all the inflation pressures. In fact, tyre side walls are more flexible when fitted on the narrowest rim because their position is less vertical. Bigger differences can be obviously seen in the deflection values when load increases. E.g. deflection decreases by 5% changing the rim from W 12 to W 14 at 2500 daN and 80 kPa, whilst it decreases by 8% changing the rim from W 14 to W 16 at the same load and inflation pressure. In other words,by using wider rims the same deflection can be obtained at lower inflation pressures. The tyre can therefore work better avoiding side wall stress. Figure 7 shows an example of load-deflection curves at various inflation pressures.

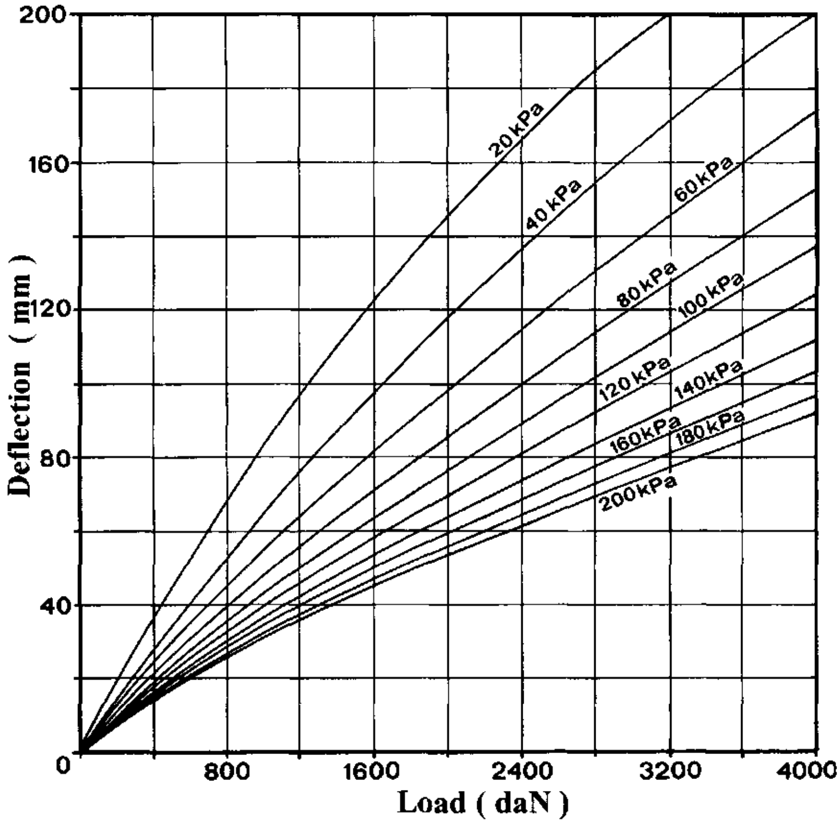

Fig. 7- Example of load-deflection curves at various inflation pressures of a 480/70 R34 radial-ply tyre on a hard surface.

Local pressure distribution under two close right and left lugs of a 520/65 R34 radial-ply tyre was measured on 17 different points at 2150 daN load and 160 kPa inflation pressure, using the steel sliding plate described above. Local pressure distribution (fig. 8) increases rapidly from the outer to the inner part of the lugs. Moreover, it is higher at the front edge of the lugs than at the rear edge, especially towards the centre of the tyre.

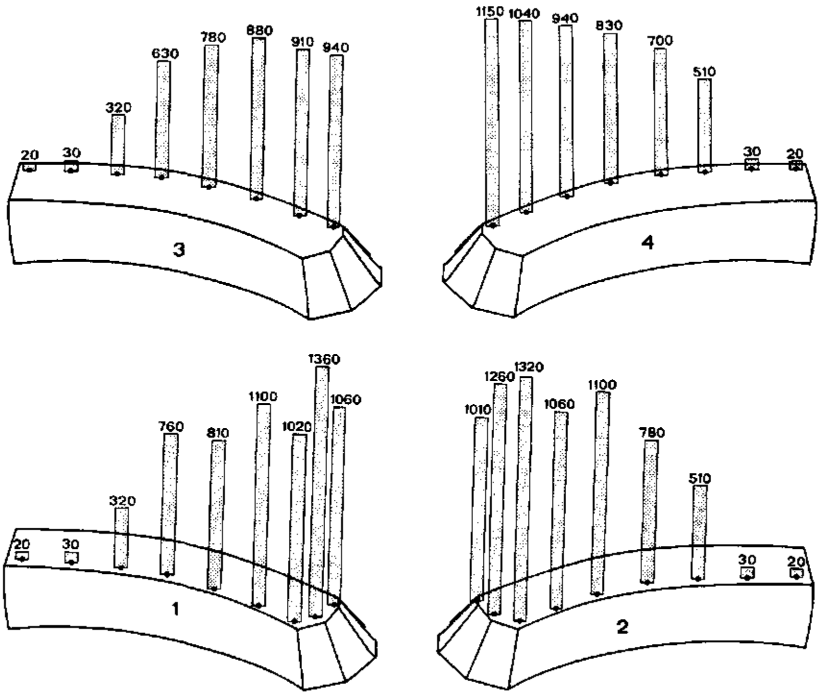

Fig. 8- Local pressure distribution (kPa) under the lugs of a 520/65 R34 radial-ply tyre loaded on a hard surface (load 2150 daN, inflation pressuse 160 kPa, rim W 13). 1 and 2 : right and left lugs front edges ; 3 and 4 : right and left lugs rear edges.

The influence of different rims on the local pressure distribution under lugs is shown in figure 9. The same tyre was fitted on W 13 and W 15 rims loaded at 2150 daN at 160 kPa. The wider rim gave a more uniform distribution with lower maximum values. The results can be explained by the different shape taken on by the tyre section, narrower with the W 13 rim.

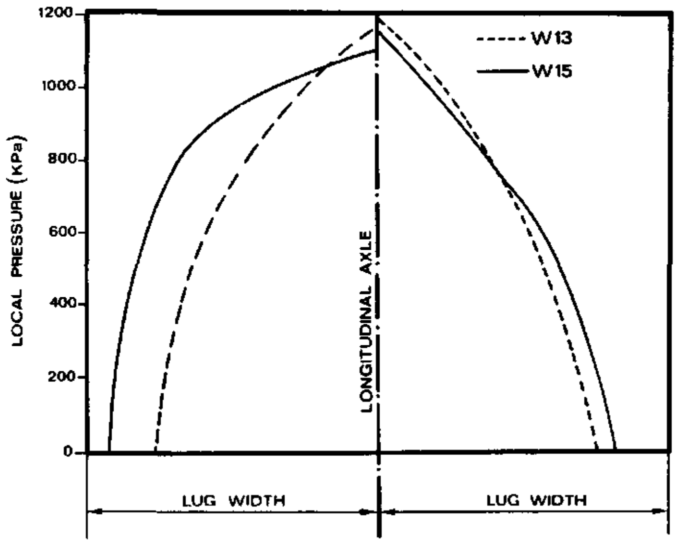

Fig. 9- Local pressure distribution under the left and right lugs of a 520/65 R34 radial-ply tyre fitted on two different rims and loaded on a hard surface.

Contact area measurements on a hard surface were carried out on several tyres with different loads and inflation pressures. Mean ground pressure was then calculated from the load on the tyre divided by the measured contact area.

Although the intensity of soil compaction is mainly a function of ground pressure and, therefore, contact area, the shape of the contact area is also important. The narrower it is, the smaller will be the total area of land compacted. A long narrow contact area is, therefore, preferable to a short wide one of the same total area. For a driving wheel this shape also produces better tractive performance. The lengths and widths of the contact areas were, therefore, also measured.

Figure 10 shows the behaviour of the shape of the contact area of a 16.9 R28 radial-ply tyre loaded at 50%, 75%, 100% and 125% of the rated load recommended by the manufacturer for the inflation pressures of 60, 100, and 160 kPa. Contact area shape from elliptical tends to become rectangular.

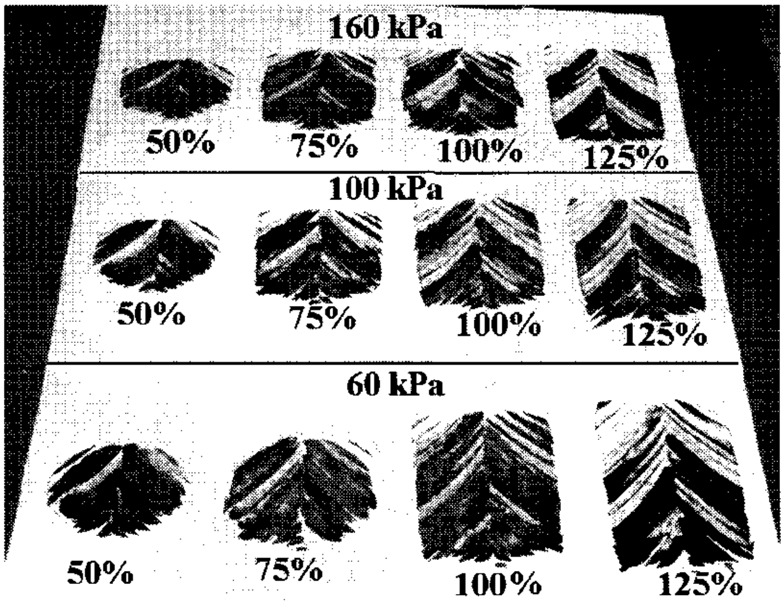

Fig. 10- Contact areas on a hard surface of a 16.9 R28 radial-ply tyre loaded at 50, 75, 100, and 125% of the rated load recommended by the manufacturer for the inflation pressures of 60, 100 and 160 kPa.

In order to predict contact width, length and area (assimilated to an ellipse), an attempt was made to relate their values measured on a hard surface to tyre dimensions (diameter and section width) and deflection under load. Load-deflection curves were drawn for one slick and two lugged radial-ply tyres at different inflation pressures to relate load and deflection. In spite of the fairly close agreement (10-15% maximum difference) found between the predicted and the measured values of contact width, length and area, it is difficult to assert that the empirical equations found can be used for all agricultural lugged tyres.

More tests need to be performed on tyres of smaller sizes, with different aspect ratio (e.g. 0.80) and especially on diagonal tyres, for which the equations were not verified. The fact that the elliptical shape of the contact area tends to become rectangular at high loads and/or with low inflation pressures, especially for radial tyres, must also be taken into account.

Field tests

Between 1986 and 1991 several tests were carried out in order to examine the influence of some design parameters and working conditions of agricultural tyres on soil compaction.

Four radial-ply tyres of very similar diameter and different section width were tested in different field and working conditions. Table 1 shows the four field conditions. Tyres characteristics and test conditions are summarized in table 2.

Table 1 - Field conditions

Field condition	Soil components			Moisture content (%)	Type of tillage
	sand (%)	silt (%)	clay (%)		
1	46	22	32	13.3	ploughed and harrowed
2	63	21	16	15.9	ploughed and harrowed
3	63	21	16	15.7	ploughed and harrowed twice
4	55	29	16	13.1	ploughed and harrowed

Table 2 - Tyres characteristics and test conditions

Tyre		Diameter (mm)	Section width (mm)	Inflation pressure (kPa)	Load (daN)	Field condition	Number of passes (n)
A	520/65 R34	1581	516	50-150	1750	1-4	1-5
B	480/70 R34	1582	472	50-150	1450-1750	1-2-3-4	1-5
C	16.9 R34	1584	427	60-160	1450-1750	1-2-3-4	1-5
D	540/65 R34	1576	556	50-140	1450-1750	2-3	1

Tyre D is a prototype.

The influence of tyre section width, inflation pressure and number of passes on soil compaction was studied, in order to determine which factors are more relevant. The influence of field conditions and position of the measurements in the tracks left by the tyres (in the tracks of the lugs or in between the tracks of two adjacent lugs) was also examined. Obviously this last study can be carried out only with a single passage of the tyre.

The degree of compaction was evaluated measuring the cone penetrometer resistance at different depths, before and after the passage of the tyres. An example of the results obtained is shown in figures 11a and 11b. Each point is the average of 20 penetrometer resistance measurements. The comparison of the two figures shows the influence of the number of passes on soil compaction, other field and test conditions being the same. A significant influence of tyre width is also evident.

In general the results showed that soil compaction, especially near the surface, decreases increasing tyre section width and is affected mainly by the number of passes and field conditions.

Less significant differences were noticed varying tyre inflation pressure. This is probably due to the fact that all tyres tested were commercial tyres (rated inflation pressure of 160 kPa) not purpose-built for working at the low inflation pressures to which they were tested (50-60 kPa). Therefore, their carcass stiffness probably has a significant influence on the ground pressure exerted.

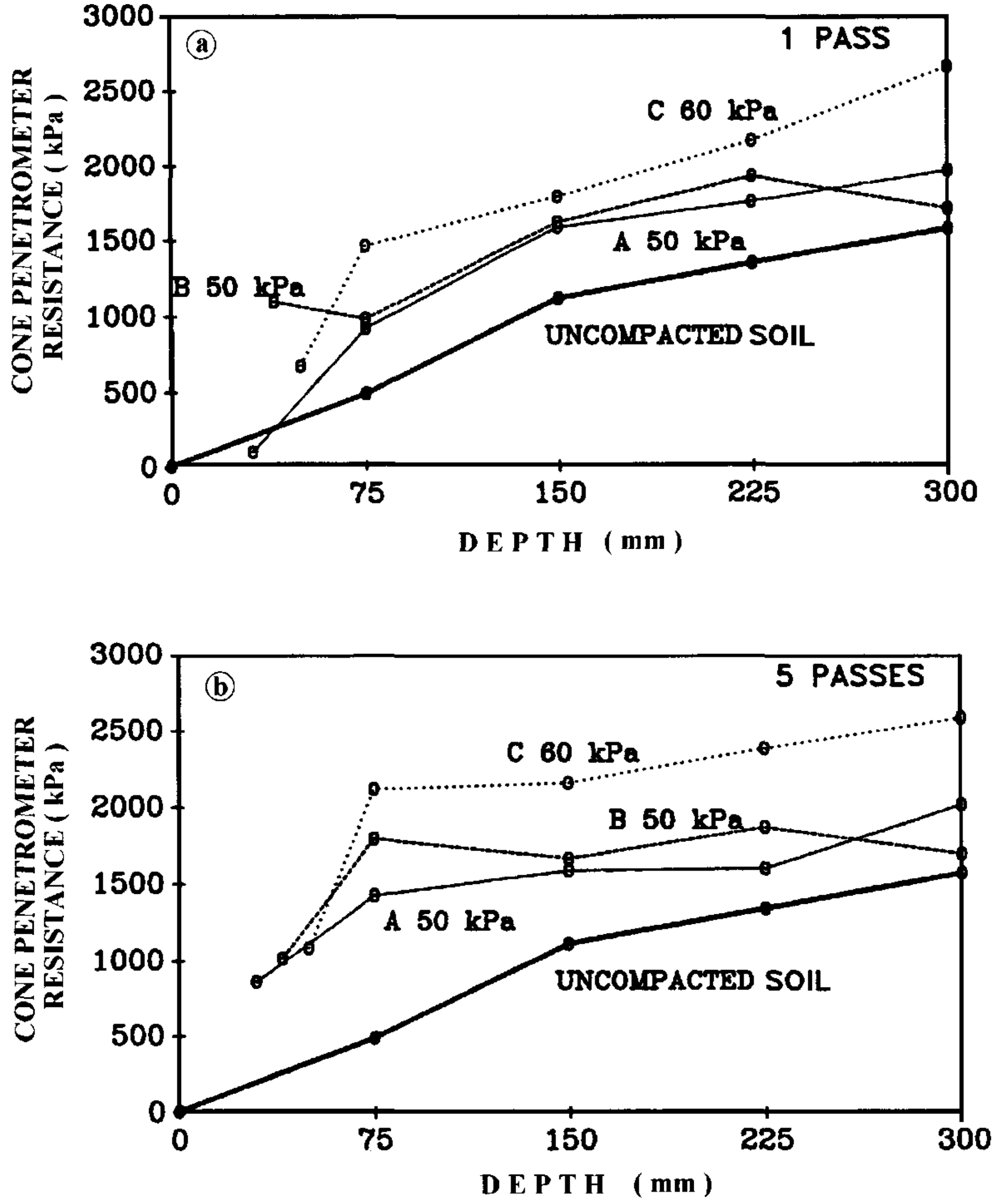

Fig. 11- Cone penetrometer resistance measurements at various depths after 1 (a) and 5 passes (b) of tyres A,B and C (see table 2) at low inflation pressures on a sandy-loam soil (field condition 4 of table 1).

Varying the position of the measurements gives higher penetrometer resistance values only in the first 100-150 mm depth when measuring in the tracks left by the lugs. An explanation for this phenomenon might be the smoothing action of the lugs on the soil surface and the breaking and rising of the soil between two adjacent lugs.

Porosity measurements were also carried out during some of the above mentioned tests (Pagliai et al., 1988, 1992). A good correlation between soil porosity and penetrometer resistance measurements was always found.

Conclusions

The results of the laboratory tests suggest that more effort should be concentrated on attempting to predict tyre mean ground pressure, predicting their contact area as a function of their dimensions and side wall deflection under load at various inflation pressures. Perhaps side wall deflection could also be predicted as a function of the load index and inflation pressure recommended by the tyre manufacturers.

Field tests confirm that knowing tyre mean ground pressure, soil compaction mainly depends on field conditions, i.e. load-bearing capacity. The task of predicting soil load-bearing capacity (and, therefore, soil compaction) as a function of its components, structure and moisture content is the most difficult one. Nevertheless this is the goal toward which soil compaction studies should be directed in order to prevent or at least minimize its negative consequences.

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OCCURRENCE, EXPERIENCES AND RESEARCH ON SOIL COMPACTION IN ITALY

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Introduction

Environmental degradation is one of the most serious problems in Italy, mainly due to antropic activities, but also to the nature and variety of its landscapes. Italian territory is roughly represented by 41.6% of hills, 35.2% of mountains and 23.2% of plains. From the pedological point of view we can stress that there is a wide variety of soil types ranging from the podzols in the Alps to soil with vertic characters in the South of Italy. The more representative orders according to the Soil Taxonomy are the Entisols, Inceptisols and Alfisols. Unfortunately in Italy a Soil Survey is lacking and to date we have only a soil mapping at one million scale. A complete cartography at 250.000 scale for the whole Country does not exist. As a consequence soil thematic maps dealing with the risk of physical soil degradation are not available. A few maps, dealing with the suitability of soil for landspreading of liquid manure or with the risk of water pollution, are available only for some areas of the North of Italy. As far as soil degradation is concerned, only the erosion problems have been investigated, on a small scale in specific research projects. Soil compaction is practically ignored with respect to its importance as one of the major factors responsible for environmental degradation.

Occurrence

Although under evaluated, soil compaction is present in all cultivated soils. The plains are generally formed by alluvial soils rich in silt and clay and are intensively cultivated, in many cases with monocultures (wheat, maize, sugar beet, etc.). Moreover in Italy, farmers are used to ploughing soil very deeply (40-50 cm) and only in latter years those farmers who are generally enlightened and more sensitive to environmental problems have been considering alternative tillage systems more compatible with the protection of natural resources. The abandoning of traditional farming rotations and adoption of intensive monocultures, without application of farmyard manure to the soil, has decreased the organic matter content in Italian soils with evident deterioration of soil structure. In fact, the main consequence of long-term intensive cultivation is the degradation of soil structure. Compaction is one of the most significant aspects of such a degradation, also because trends in agricultural engineering over the last few decades have resulted in machines of a bigger size and weight. Besides the compaction due to wheel traffic, in these plains a compact layer at the lower limit of cultivation (plough pan, **fig. 1**) is widespread. Such subsoil compaction suddenly interrupts the continuity of the pore system in the vertical direction, drastically reducing drainage and root development. Such a compact layer is completely under evaluated even though it is responsible for field flooding following heavy rain (**fig. 2**).

Soil compaction is even more significant in cultivated hilly soils. Most of the soils of the Italian hill terrain are developed on Pliocene marine clays and are characterized by poor structure stabilty. The downhill tillage system causes soil erosion which, in many cases, takes place in the tracks left by the wheels.

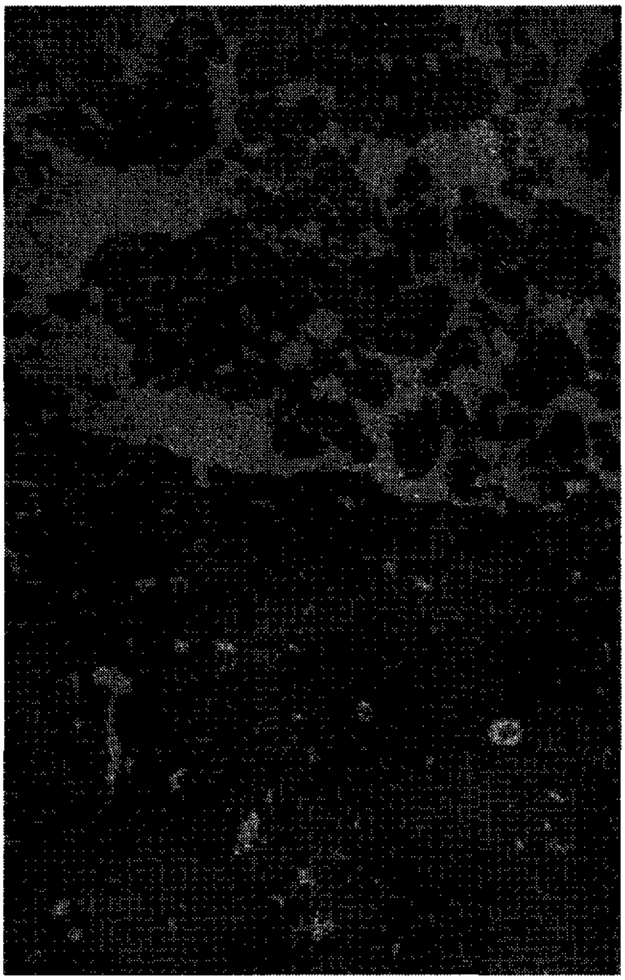

Fig. 1 - Macrophotograph of a vertically oriented thin section from the 380-440 mm layer of a loam soil continuously ploughed to a depth of about 400 mm. In this case, plain polarized light pores appear white. The formation of a compact layer at the lower limit of cultivation (subsoil compaction) causing a discontinuity of soil porosity is evident.

A large part of the mountain area is covered by forest. Fire has often been considered as a characteristic phenomenon for the forest ecosystems in the Mediterranean area and its effect on the vegetation is dramatically evident. In recent decades the frequency of fire has increased throughout the Mediterranean area. In the same period in this area accelerated soil erosion has became an increasingly serious problem. It is generally attributed to changes in hill slope run-off characteristics, resulting from changes in the vegetation cover and in the topsoil characteristics brought about by man, mainly through intensive agriculture, deforestation and ever increasing forest and shrub fires. This is one of the major processes causing land degradation and leading to losses of nutrients. In such a situation the traffic of machines for the management of the forest has caused a heavy soil compaction thus leading to an increase of surface runoff and erosion.

Fig. 2 - An example of field flooding caused by soil compaction after heavy rain.

Research experiments

Italian investigation into soil compaction is almost entirely reported in the individual papers of Febo, Pagliai and Pessina. Schematically, such an investigation can be summarised as follows.

Field experiments

- Evaluation of the effect of different types of tyres and tracks on soil compaction with different types of soil and soil conditions. Influence of load, inflation pressure, number of passes on the same wheel track and soil condition on soil compaction
- Evaluation of the effect of different types of tyres and tracks on soil erosion
- Soil compaction in paddy fields
- Type of tools used for soil tillage (laser levelling, plough, harrow, chisel)

Laboratory experiments

- Agricultural tyres contact area measurements on a rigid surface. Mean ground pressure measurements of various tyres varying load, inflation pressure and rim.

Soil parameters investigated

- Bulk density
- Saturated hydraulic conductivity
- Penetration resistance
- Soil porosity (Soil pore system: microporosity, measured by mercury intrusion porosimetry; macroporosity, characterized by image analysis on soil thin sections prepared from undisturbed samples)
- Aggregate stability

- Surface runoff
- Soil erosion

Crop properties
- Crop yield
- Root density

Final considerations

Results reported in the individual papers show that soil compaction is a serious problem and effectively causes damage to soil in terms of soil porosity and infiltration and limiting root growth.

Specific studies on subsoil compaction are completely lacking, even though it could be the main factor responsible for the periodical field flooding in the Italians plains when heavy rains are distributed over a short period of time.

SOIL COMPACTION RESEARCH IN IRELAND

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Abstract

Research on soil compaction has been limited. The results of two sets of experiments are presented - 1. the effects of deep loosening and subsequent cultivations on soil characteristics and sugar beet growth (1981-83); 2. the effects of forage harvesting traffic on soil conditions, grass growth and nitrogen removal (1991-94).

1. Twelve experimental sites were laid down to ascertain the effect of autumn deep loosening in alleviating soil compaction and improving sugar beet performance. Four sites showed significant root and sugar yield increases, six showed no significant differences, while two gave significant decreases in yield on deep-loosened plots. Negative and negligible yield responses to deep loosening were largely explained by recompaction of autumn loosened soil by excessive tillage traffic during seedbed preparation the following spring. Deep loosening decreased the percentage of forked roots on all sites where there was a yield response to the operation. Seedbed preparation methods studied included powered rotary cultivator, disc harrow and springtine cultivation on deep-loosened and non-loosened soil. It was found that beneficial loosening effects were severely reduced following the action of ploughing and seedbed cultivation. Recompaction was greatest where several cultivation passes were necessary for seedbed preparation. The recompaction effect was reflected in the low yield response of sugar beet to deep loosening.

2. There were two sites in the grass harvesting compaction experiment - one on a wet land site at Kilmaley and the other on a lower rainfall site at Oak Park. Soil strength, as measured by shear vane tests, varied significantly and consistently with intensity of wheel ground contact pressure. Conventional traffic increased cone penetrometer resistance relative to low ground pressure. Soil bulk density, air-filled porosity and hydraulic conductivity were negatively influenced by increasing traffic intensity.

   Total annual forage yields were always lower on the conventionally trafficked than either the LGP or the zero traffic plots except in the first year at Oak Park. The yield increases over the conventional ranged from -2.5% (Oak Park 1992) to +17% on the LGP and +15% to +48% on the zero traffic plots.

   Total nitrogen uptake was clearly related to traffic treatment, particularly on the Kilmaley site. In 1993, the total N removal on the Oak Park 1 site was 8.4% and 11.8% higher on the LGP and zero traffic areas than the conventional; in 1994, the corresponding values were 11.6% and 11.0%. At Kilmaley, reduced traffic increased offtake significantly compared with the conventional, the figures being 11.2% and 36.9% in 1993 and 24.8% and 55.3% in 1994 for the LGP and zero traffic, respectively. The 1994 figures represented an increased removal of 52.3 and 116.4 kg ha^{-1} nitrogen.

1. SOIL COMPACTION – SUGAR BEET CULTIVATION

Introduction

Tractor and equipment weights have increased over the years, with greater potential for causing subsoil compaction. Subsoiling or deep loosening has been the traditional method of dealing with this compaction, particularly on tillage soils. Indeed, on some farms, subsoiling is almost a routine operation, being rotated around the farm over a period of years. Some experiments reported large increases in crop yield following deep loosening (Braim *et al.*, 1984; Stone, 1982; Unger 1979). Sugar beet is particularly sensitive to soil compaction, as severe root forking can result, reducing yield potential and causing increased tare problems. A series of soil management experiments for sugar beet was conducted in south-east Ireland over the period 1982-84. These studies investigated the effect of soil physical properties, autumn deep loosening and spring seedbed cultivations on sugar beet growth and yield.

Methods

Deep loosening treatments were imposed on four different sites in each of three autumns, 1981-83. Each autumn, three test sites were located on Grey Brown Podsolic soils which had developed soil compaction and weak structure; the fourth site each year was on a Brown Earth. The Brown Earths had a higher yield capacity than the Grey Brown Podsols. Mean annual rainfall was about 800 mm. Experimental details are given in other publications (Larney, 1985; Larney *et al.*, 1986; Larney *et al.*, 1989).

Results

Deep loosening gave small but non-significant decreases in the proportion of forked roots on most of the sites. The effects of deep loosening on root yield varied with site and soil type. Eight sites showed yield increases due to deep loosening, four of which were significant (Table 1). Positive response was obtained on the well structured soils, indicating that deep loosening may be beneficial even when there are no apparent soil structural problems. There was no response on two sites and there were significant yield decreases on two sites.

Table 1. Root yield (t ha^{-1}) on deep loosening treatments at 12 study sites, 1982-84

	Control	Paraplow	Armer Salmon	McConnel	F-test
1982					
Ashfield	25.1	28.8	-	-	NS
Churchtown	37.5	35.9	-	-	*
Donabate	47.3	47.1	-	46.7	NS
Ferns	46.9	52.5	53.9	-	**
1983					
Hollymount	50.7	55.4	53.4	-	*
Athy	47.6	47.8	47.2	-	NS
Oak Park	39.9	35.9	-	35.9	*
Fenagh	58.3	61.3	60.6	-	NS
1984					
Busherstown	55.4	58.3	57.7	-	*
Paulstown	50.1	-	53.2	50.5	*
Maganey	44.0	44.5	-	45.6	NS
Pump Field	42.7	44.6	45.4	-	NS

*, ** = Significant at 0.05 and 0.01 levels, respectively
NS = not significant

Soil measurements in 1983 on four sites indicated machine induced compaction on three sites and natural compaction (fragic horizon) on the fourth. Cone penetrometer (12.83 mm cone) measurements were used to characterise soil conditions following deep loosening, ploughing and seedbed preparation. The differences between the loosened and unloosened control plots were significant on the three plots where penetrometer measurements were carried out after loosening [Figure 1(a)-(c)]. Deep loosening was effective in reducing soil strength significantly to depths approximately twice the depth of ploughing. Cone resistance was measured again in June 1983 after the beet crop was established. The loosened layer had almost disappeared on the Athy and Oak Park sites [Figure 1(d) and (f)]. At Oak Park, there were no significant differences between the loosened and control at any depth; in fact, at shallow depths (0-200 mm) the deep loosened treatment was slightly more compact than the control. At Hollymount, the deep loosened soil was significantly less compact than the control at depths from 280-420 mm [Figure 1(e)]. The loosened plots on the Fenagh site were significantly looser than the control over the depth range 280-420 mm but the cone resistance values at depths below 300 mm were very high because of the fragic nature of the B horizon.

The obliteration of the loosening effects by the cultivation operations was directly related to the number of passes for seedbed preparation. At Fenagh and Hollymount, where only one or two cultivation passes were required, the deep loosening effects were largely preserved. At Athy and Oak Park, the high number of passes necessary for seedbed preparation (four and five, respectively), coupled with the presence of plastic soil layers at cultivation time, resulted in almost complete cancellation of loosening effects. Cone penetrometer resistance provided a useful measure of changes occurring due to ploughing and seedbed preparation on deep loosened soils.

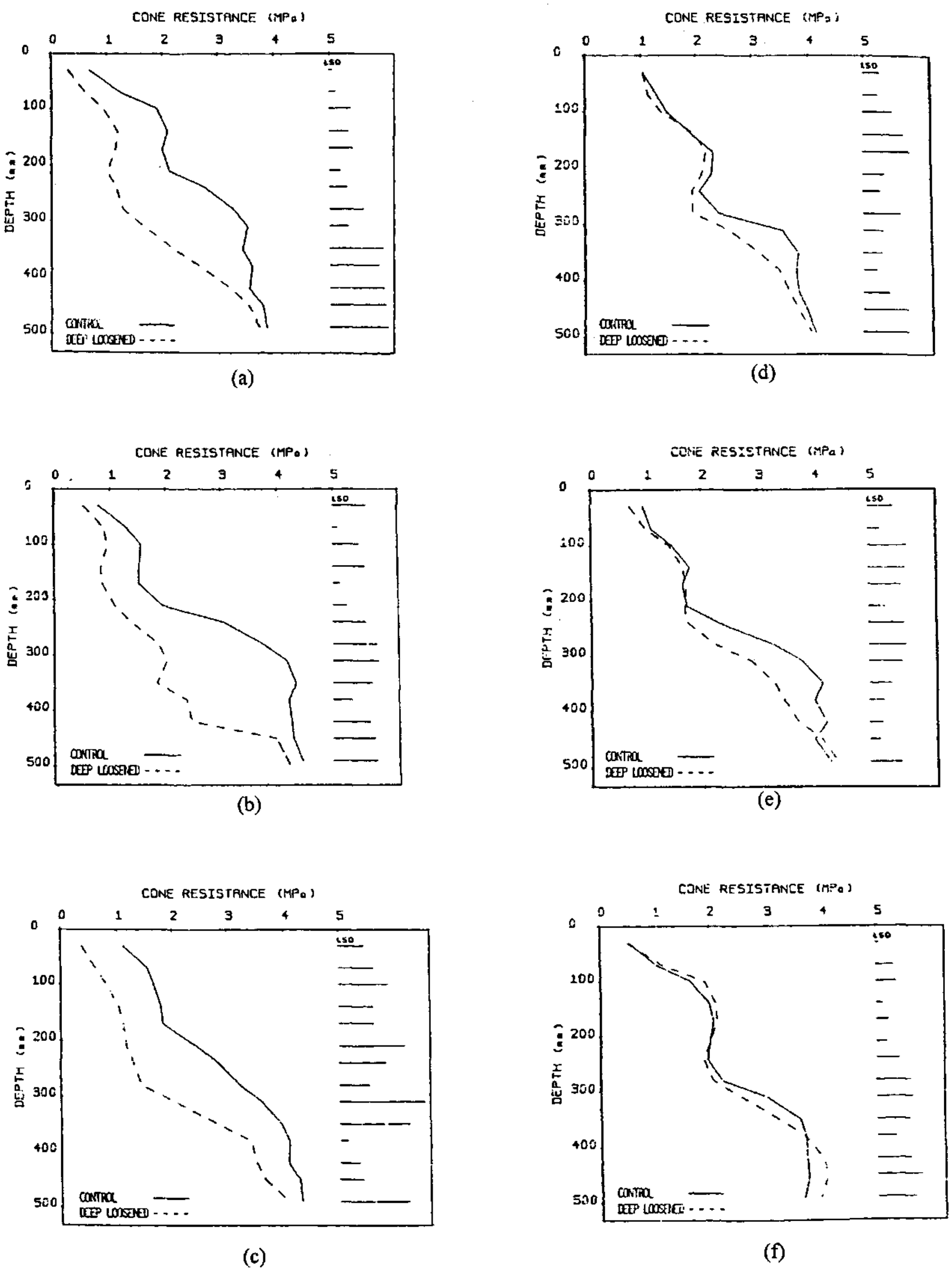
2. GRASSLAND COMPACTION

Introduction

Wheel traffic applied when soil is moist causes soil compaction and consequently less favourable growing conditions for plants. Most research has shown that damage to grassland by wheel traffic has a strong negative effect on herbage dry matter yield (Douglas *et al.*, 1991; Frost, 1988a and b). Traffic activity on grassland includes fertilizer and slurry spreading, rolling, and, most intensive from a wheel coverage viewpoint, harvesting and transport of grass.

Methods

Experiments conducted in Ireland from 1991-94 studied the effect of different harvest systems on soil conditions, crop production and nitrogen removal. There were two sites: 1. Oak Park - on clay loam soil with good drainage; 2. Kilmaley - also on a clay loam top soil but with a high silt content. The soil is described as a heavy textured, poorly drained, surface water gley with a weakly structured A horizon. The long-term annual rainfalls at the sites were 763 and 1,341 mm for Oak Park and Kilmaley, respectively.



(a) (d)

(b) (e)

(c) (f)

Figure 1 Cone resistance readings at 3 sites after subsoiling and after subsoiling, cultivation and sowing operations, Athy (a) and (d), Hollymount (b) and (e), Oak Park (c) and (f)

The experimental plots were subjected to one of three traffic treatments during the course of the trial. Only traffic associated with grass harvesting was considered in the main experiment. The traffic treatments were: *Conventional traffic (C):* The plots were subjected to traffic similar in terms of wheel/tyre equipment and axle loads to commercially-used silage harvesting equipment in the site regions; *Low-ground-pressure traffic (LGP):* The plots were subjected to similar traffic to (C) but the machinery was fitted with larger tyres operating at much lower inflation pressures; *Zero traffic (Z):* These plots were not subjected to any harvesting traffic.

In the case of the C and LGP treatments, the traffic was applied after the plots were cut at each harvest date, i.e. three times per year. The only other traffic received by the plots was from a tractor spreading fertilizer, which crossed the plots at two locations three times each year. The actual harvester etc. which would normally be used on farms were not driven over the plots. Instead 'traffic systems' to simulate the tractor, harvester and trailers with matching weights and wheel arrangements were used to apply the loads to the soil, with the same wheeling pattern as the traffic being simulated. Different systems were used at the two sites as the axle loads and traffic patterns were chosen to be representative of grass harvesting systems used in the site regions.

At Oak Park, a high capacity metered-chop harvesting system using a mower, self-propelled forage harvester and large capacity trailers and associated tractors was simulated. Tractors and trailers were ballasted to give the required axle loads of the component machines in the system. The effect of the wheels on a trailed mower was not considered significant and these were not simulated in the traffic treatments.

Details of axle loads, tyre sizes and inflation pressures used at the Oak Park site are given in Table 2. For the first cut traffic treatments in May 1992, the trailer axle load was restricted to less than 6,000 kg as larger axle loads were considered excessive as part of the first traffic application following reseeding. For the conventional traffic, standard tyres inflated to the tyre manufacturers recommended pressure for the loads being carried were used. Larger tyres operating at lower pressures were selected for the LGP traffic. Very wide section tyres ('Terra Tires') capable of operating at inflation pressures as low as 35 kPa were selected for use on the tractor and self-propelled harvester components of the system. A tandem axle trailer bogey was constructed and fitted with wide section Trelleborg tyres capable of operating at inflation pressures as low as 80 kPa.

Table 2. Axle loads, tyre sizes and inflation pressures for traffic treatments at Oak Park

				Conventional		LGP	
Simulated operation	Machine	Axle	Axle load (kg)	Tyre size	Inflation pressure (kPa)	Tyre size	Inflation pressure (kPa)
Mowing	Tractor	Front	1400	9.0-16	170	20.0-16	35
		Rear	3500	16.9-34	90	43.0-25	35
Harvesting	Self-propelled harvester	Front	5500	23.1-26	100	43.0-25	50
		Rear	2500	12.0-18	140	20.0-16	100
Trailer transport	Tractor	Front	2000 (1500)[1]	9.0-16	280	20.0-16	69
		Rear	3500 (3300)[1]	16.9-34	90	43.0-25	35
	Trailer	-	8000 (5400)[1]	18-19.5	400	500-22.5T[2]	80

Notes: 1: Axle loads for 1st cut restricted (see text)
2: Tandem axle

At Kilmaley, a lower capacity direct-cut side-mounted harvesting system, using smaller capacity trailers, was simulated. Details of axle loads, tyre sizes and inflation pressures used are given in Table 3. The novel trailer designed as part of this project was used as part of the LGP traffic system. The individual axle loads used for the LGP traffic differ from the conventional loads as the purpose-built LGP trailer had a different loaded weight distribution but the total load imposed by the three axles in each traffic treatment was the same. The tractor and silage trailer were fitted with standard tyres for the (C) treatment. For the LGP traffic, very wide-section tyres were used on the tractor. Dual tractor traction-type tyres (Michelin) were selected for the LGP trailer. These are capable of carrying an axle load of 6,000 kg at 50 kPa inflation pressure. Their large diameter reduces rolling resistance on soils of low bearing strength. It was considered that these tyres would be more acceptable in farm practice than very wide section single tyres of similar load-carrying capacity.

Table 3. Axle loads, tyre sizes and inflation pressures for traffic treatments at Kilmaley

			Conventional			LGP		
Simulated operation	Machine	Axle	Axle load (kg)	Tyre size	Inflation pressure (kPa)	Axle load (kg)	Tyre size	Inflation pressure (kPa)
Harvesting And Transport	Tractor	Front	1200	9.0-16	150	1000	20.0-16	35
		Rear	4000	16.9-34	110	4950	43.0-25	40
	Trailer	-	5200	9.00-20D[1]	400	4500	16.9-24D[1]	50

[1] Dual wheels

Because of the very wet soil conditions at Kilmaley at the time of the third harvest in 1992, the traffic loads applied and method of application were modified. It was considered that if the usual trailer traffic loads were applied, severe wheel rutting and sward damage would have occurred limiting the usefulness of the site for the remainder of the project. Consequently, trailer traffic was not applied; both traffic treatments consisted of the tractor only, with the appropriate tyres (conventional or LGP) fitted. The front and rear axle loads of this treatment were 1,200 kg and 4,000 kg, respectively.

The traffic treatments were applied to the plots at each cutting date immediately after the grass was removed with the mower/weigher. Traffic patterns applied during normal field harvesting were simulated by driving the vehicles on the plots a number of times using appropriate bout widths corresponding to normal field usage. At Oak Park, where an effective bout width of 2.6 m for the individual traffic operations (mowing, harvesting and trailer transport) was used, each plot received traffic wheelings equivalent to one pass of each vehicle combination. At Kilmaley, a direct cut system involving just one vehicle combination (tractor, harvester and trailer) with an effective bout width of 1.2 m was simulated. This required four passes of the vehicles to generate the complete traffic pattern.

The following soil measurements were made:

Water content: For the duration of the experiment, samples for drying were collected using a 40 mm diameter gouge auger at three depth ranges 0-100, 100-200 and 200-300 mm, close to the time the harvest traffic treatments were being applied and soil strength measurements being made. These were dried for 24 hours at 105°C. One sample set (3 depths) was taken from each plot at each site.

Bulk density: Bulk density measurements were made at each site with a Shire soil bulk density meter after the traffic treatments had been applied at each site. The Shire meter utilizes a high resolution gamma ray transmission and a photon detector system to measure differences in wet bulk density. Dry bulk density was calculated from wet bulk density using the gravimetric water content determined from the augered samples.

Soil dry bulk density and volume of air-filled pores were calculated for the 0-75 mm depth from core samples of known volume. Three samples were taken from each plot.

Soil strength: Soil strength measurements were made on a number of occasions during the reporting period. Two measures of soil strength were used: (i) shear vane; (ii) cone penetrometer. Readings were taken at two depths with shear vane - centred at 40 and 120 mm at 10 locations on each plot. The measuring points were located at 1-metre intervals on two 5-metre transects across the plots. A hand-held Pilcon shear vane instrument fitted with 29 x 18 mm vanes was used. The cone penetrometer measurements were made at 10 locations per plot with similar layout to that used for the shear vane. The instrument was a Bush recording penetrometer fitted with a 30° cone, 12.8 mm base diameter. Fifteen readings were taken at each location at pre-set depth intervals of 20 mm from 0 to 300 mm.

Hydraulic conductivity: Effective hydraulic conductivity into the soil through the undisturbed soil surface was measured in September 1992 at one position per plot on each site using a tension infiltrometer method.

The following crop measurements were made:

Yields: Total forage yields and dry matter production were measured at each of the three harvests in each of the years 1992-94. Yields were obtained by harvesting complete plots using a modified trailed mower-conditioner to which a weighing box was attached, into which the harvested grass was thrown. The weighing box was mounted on four strain gauge load cells which gave a read-out of the total weight of material from the plot. Representative samples were taken from this grass for subsequent dry matter and quality analysis.

Nitrogen uptake and grass quality: Samples of grass were taken from each plot for nitrogen content measurement (crude protein) and for dry matter digestibility (DMD) analysis.

Results

Soil strength: Strength measurements - shear vane and cone penetrometer - were made on a number of occasions during the experiment.

The shear vane measurements, at both 40 and 120 mm depths, displayed a consistent pattern at both sites from an early stage. The shear strength was consistently and significantly lower on the LGP traffic treatment than on the conventional, while the zero traffic plots gave the lowest readings, although these were not always significantly different from the LGP values (Table 4). There were variations in the absolute values of shear vane readings which were related to soil water contents but the relativities between the treatments did not vary. Higher shear strength values were recorded at the 120 mm than the 40 mm depth on the Kilmaley site.

Table 4. Soil shear strength measurements - Oak Park post 3rd harvest 1992

Depth	Shear strength (kPa)			
(mm)	Conventional	LGP	Zero traffic	F-test
40	47.37	41.42	34.18	***
120	59.33	46.32	40.25	***

*** = Significant at 0.001 level

Cone penetrometer measurements showed similar trends to the shear vane readings, with consistently higher values from the conventional traffic plots than the low ground pressure or zero traffic areas [Figure 2(a) and (b)]. Penetration resistance was measured to 300 mm depths and the differences extended to at least this depth.

Bulk density: Soil bulk density measurements were taken with a Shire bulk density meter to 360 mm depth at each of the sites (Kilmaley - October 1993, Oak Park - May 1994). The trends are shown in Table 5 for Kilmaley and Figure 3 for Oak Park.

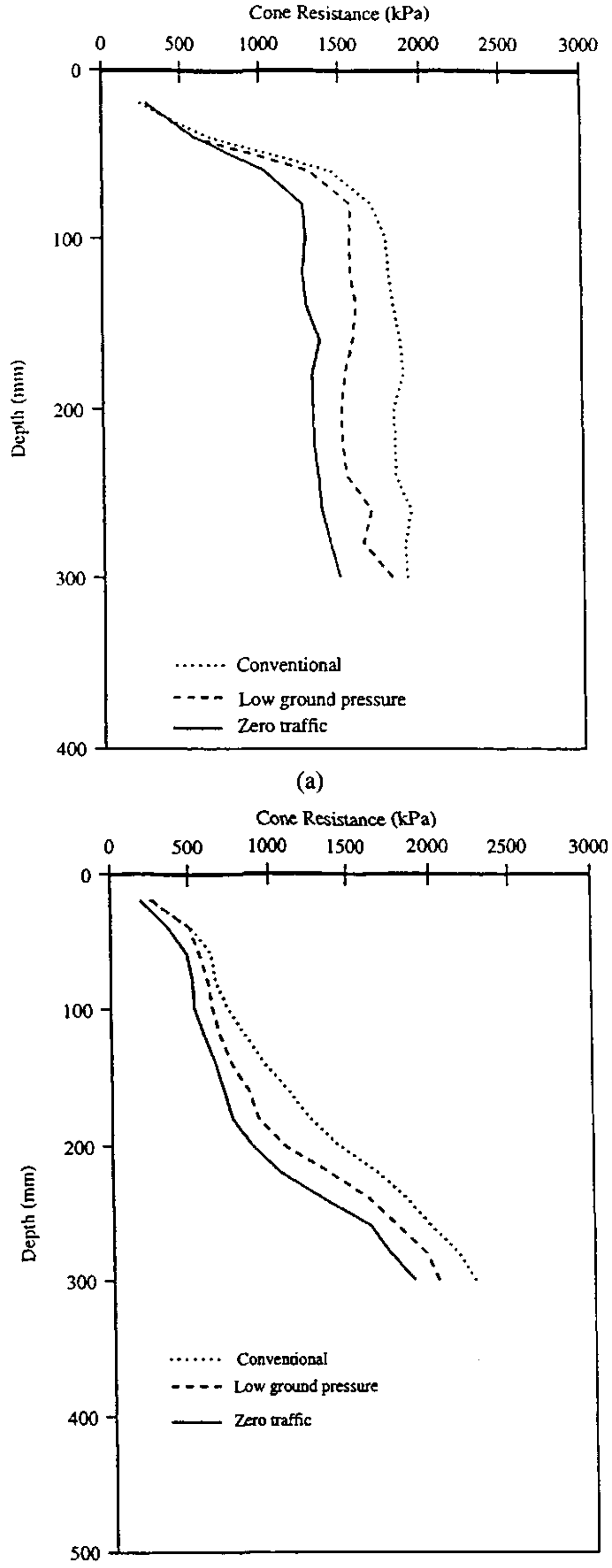
At Kilmaley, there was a sharp increase in bulk density with depth on all treatments due to the nature of the soil. The conventional and LGP plots had similar bulk density values and both were higher than the zero traffic areas.

In the measurements made in May 1994, at the Oak Park site, the zero traffic plots had lower bulk densities than the other two treatments at all depths to 300 mm; there was little difference between the LGP and conventional traffic treatments [Figure 2].

Table 5. Soil dry bulk density values at 3 depths - Kilmaley site, post 3rd harvest - October 1993 (Mg m^{-3})

Depth	Traffic treatment		
(mm)	Conventional	LGP	Zero traffic
60	0.73	0.76	0.65
150	1.11	1.04	0.93
270	1.42	1.44	1.34

Bulk density and porosity (core samples): Core samples for bulk density and porosity measurements were taken from the Oak Park site in April 1993 and from the Kilmaley site in April and October 1993 and April 1995. The results of the April 1993 measurements are given in Table 6. At Oak Park these indicate the increase in bulk density with the varying degrees of compaction and the differences were highly significant. In line with this there was a reduction in the volume of large pores (air filled pores) with increasing bulk density.



(a)

(b)

Figure 2 Penetrometer cone resistance at (a) Oak Park and (b) Kilmaley, post 1st harvest 1993

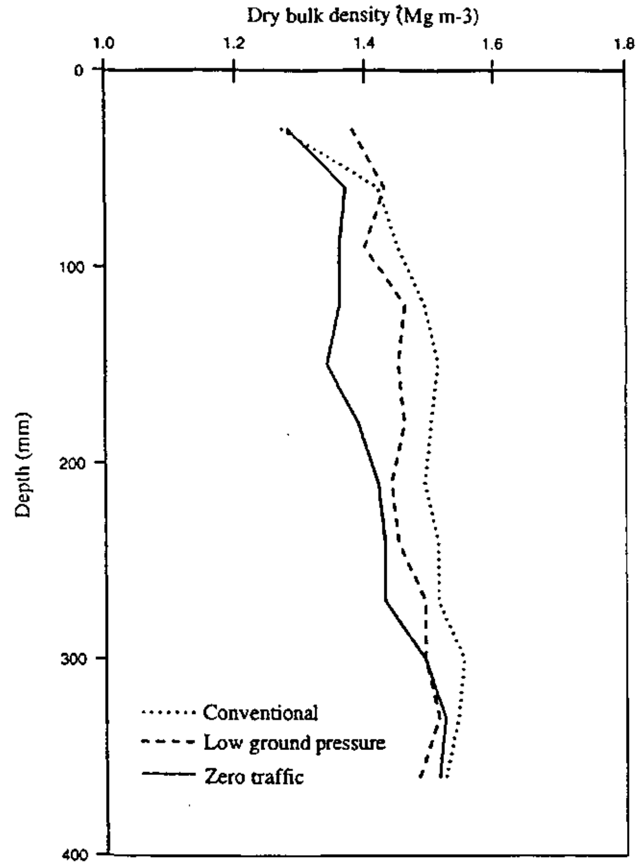


Fig. 3 Soil dry bulk density at Oak Park – pre 1st harvest May 1994

Table 6. Dry bulk density, air-filled porosity and volumetric water content at 0-75 mm depth - pre 1st harvest 1993 (all sites)

Traffic treatment	Dry bulk density (Mg m^{-3})	Air-filled porosity (% v/v)	Volumetric water content (%)
		Oak Park	
Conventional	1.518	6.5	34.3
LGP	1.471	9.2	33.3
Zero	1.401	12.9	34.3
F-test	***	***	*
		Kilmaley	
Conventional	0.666	6.8	63.4
LGP	0.612	8.7	64.6
Zero	0.618	9.7	64.3
F-test	NS	NS	NS

*,*** = Significant at 0.05 and 0.001 levels, respectively
NS = not significant

There were no significant differences in bulk density, air-filled porosity or water content at the Kilmaley site, but the trends in the porosity values were similar to the other sites. The bulk density values for the zero traffic and the LGP treatments were very similar and slightly lower than those on the conventionally trafficked plots.

Hydraulic conductivity: The effective hydraulic conductivity of the soil at Oak Park was reduced on the LGP and conventional traffic treatments compared with the zero traffic (Table 7). At Kilmaley the conductivities were low on all treatments and differences were not significant but the trend was towards reducing conductivity with increasing traffic intensity.

Table 7. Hydraulic conductivity (mm min^{-1}) - September 1992

	Oak Park	Kilmaley
Conventional	1.02	0.61
LGP	1.53	1.00
Zero traffic	3.74	1.53

Crop yields: The first traffic treatments were applied in May 1992 to the Oak Park and Kilmaley sites at the time of the first grass harvest, so the yields (Oak Park - 6.610 t ha^{-1} DM; Kilmaley - 5.991 t ha^{-1} DM) taken at that stage are only an indication of crop growth and do not show any treatment effects (Table 8). The yields of dry matter were quite high from all treatments for the second harvest at Oak Park, but there were no significant differences between the treatments. At Kilmaley the LGP and zero traffic plots yielded substantially more (14.4% and 23.0%, respectively) than the conventionally trafficked plots. At the third harvest in 1992 there were small but significant differences between the treatments at Oak Park; the LGP treatment giving the lowest yield and the zero traffic the highest. The yield differences between treatments were not significant at Kilmaley for this harvest.

In 1993, the dry matter yields were high, with the Oak Park and Kilmaley zero traffic areas producing over 15 t ha^{-1} of dry matter. There were significant differences in dry matter yields at all sites and all harvests except the first harvest on the Oak Park site. The total yield figures on the Oak Park site showed that there were small but significant increases in yield on the LGP and zero traffic plots (4.2% and 6.8%, respectively) compared with the conventionally-trafficked plots.

At Kilmaley in 1993, there were consistent highly significant yield differences between treatments with the trend towards increasing yields from conventional to LGP to zero traffic. The total yields were 9.7% and 32.0% higher on the LGP and the zero traffic, respectively, than on the conventional traffic plots.

In 1994, the yield patterns of 1993 were maintained. At the Oak Park site, LGP and zero traffic areas produced 8.1% and 8.9% more dry matter than the conventional, while at Kilmaley the corresponding figures were 17.0% and 36.8%.

Nitrogen content in forage: In 1992, measurements of nitrogen content in the forage were made only at the second harvest and the differences between treatments were small at both the Oak Park and Kilmaley sites. However, in 1993 when samples from all three harvests were assessed, there were significant differences at six of the nine harvest/site events. The trend was always in favour of the less compactive treatments. At the Oak Park site, the total nitrogen uptake was 8.4% and 11.8% higher on the LGP and zero traffic plots, respectively, than on the conventional. Similarly, on the Kilmaley site the total N in the forage was 11.2% and 36.9% higher on the LGP and zero traffic plots than on the conventional (Table 9).

At each site the nitrogen content and the total yield of dry matter were higher at the first cuts so that the total nitrogen utilization was much higher in spring, particularly at Kilmaley where the nitrogen uptake was 3-4 times greater in the first cut forage compared with the subsequent harvests.

In 1994, the nitrogen uptake at Oak Park tended to mirror the dry matter production patterns, with the biggest differences occurring in the first cut and the total uptake for the year being almost identical on the LGP and zero traffic treatments, both of which had higher uptakes than the conventional traffic treatment (Table 9). There was no difference in uptake between treatments at the third harvest. At Kilmaley, there were substantial differences in N uptake between treatments at each harvest and the trends were always the same with increased uptake corresponding with lower traffic intensity and less soil compaction.

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Table 8. Dry matter yields at each harvest and total annual yield 1992-1994

	1992		1993		1994	
	Oak Park	Kilmaley	Oak Park	Kilmaley	Oak Park	Kilmaley
1st harvest						
Conventional	-	-	5.367	7.055	3.990	3.181
L.G.P.	-	-	5.453	7.617	4.495	3.890
Zero	-	-	5.490	8.466	4.772	4.625
F-test	-	-	NS	***	***	***
2nd harvest						
Conventional	5.149	4.109	4.555	2.345	4.609	4.122
L.G.P.	5.029	4.702	4.912	2.808	4.955	4.371
Zero	5.369	5.056	5.130	3.255	4.794	4.493
F-test	NS	**	*	***	NS	NS
3rd harvest						
Conventional	4.156	4.397	4.180	2.340	3.983	2.196
L.G.P.	4.041	4.349	4.338	2.449	4.133	2.852
Zero	4.260	4.758	4.436	3.772	4.111	3.875
F-test		NS	*	***	NS	***
Total						
Conventional	9.305	8.506	14.103	11.740	12.492	9.499
L.G.P.	9.070	9.051	14.703	12.874	13.583	11.113
Zero	9.629	9.814	15.056	15.493	13.678	12.993
F-test			*	***	***	***

*,**,*** = Significant at 0.05, 0.01 and 0.001 levels, respectively
NS = not significant

Table 9. Nitrogen removed in forage 1992-1994 (kg/ha)

	1992		1993		1994	
	Oak Park	Kilmaley	Oak Park	Kilmaley	Oak Park	Kilmaley
1st harvest						
Conventional	-	-	141.4	183.1	100.8	79.1
L.G.P.	-	-	146.2	197.1	123.6	99.4
Zero	-	-	144.1	226.8	133.2	121.7
F-test	-	-	NS	*	***	***
2nd harvest						
Conventional	106.3	91.6	86.6	45.5	125.1	86.2
L.G.P.	106.0	107.1	104.2	53.5	138.7	103.5
Zero	107.4	117.9	116.6	66.5	130.2	115.7
F-test			*	*	NS	***
3rd harvest						
Conventional	-	-	80.1	38.4	100.0	45.2
L.G.P.	-	-	83.3	46.4	101.4	59.9
Zero	-	-	83.4	72.3	98.3	89.5
F-test	-	-	NS	*	NS	***
Total						
Conventional	-	-	308.0	267.0	325.9	210.5
L.G.P.	-	-	333.8	297.0	363.7	262.8
Zero	-	-	344.3	365.6	361.7	326.9
F-test	-	-			***	***

*,**,*** = Significant at 0.05, 0.01 and 0.001 levels, respectively
NS = not significant

LABORATORY PENETROMETER MEASUREMENTS TO CHARACTERISE SOIL STRENGTH

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Introduction

Compaction by agricultural machines changes the soil strength of the plow layer. Crusting of the surface soil layer occurs because of desintegration of soil aggregates under the impact of raindrops and hardening by sunshine and wind.

This change in soil strength by compaction or crusting can affect soil aeration, mechanically resist root growth and seedling emergence and reduce water infiltration causing ponding water on flat surfaces and surface and subsurface runoff and erosion on sloped surfaces.

Already decades ago attempts were made to characterise soil crusting in terms of its strength in the modulus of rupture test (Richards, 1953). But when relating the soil strength to root growth, the application of laboratory results from Richard's technique to field conditions seemed doubtful (Lemos and Lutz, 1957). A more realistic approach to the understanding of the factors affecting soil surface impedance is the direct measurement of the mechanical resistance with a penetrometer. Penetrometer resistance is regarded as the best available measure of soil impedance to root growth (Bengough and Mullins, 1990) and relations between soil strength and root elongation of different crops were determined. A value of 2 - 2.5 MPa is often cited as a critical penetration resistance (cone index) beyond which plant root elongation is severely restricted (Taylor, 1971).

Some studies deal with the use of penetrometers in order to estimate crust strength in relation to shoot growth. Taylor et al (1966) determined the relationship between crust strength and emergence of corn, onion, barley, wheat, switchgrass and rye seedlings by means of a laboratory penetrometer. A slight decrease in emergence percentage was observed for crust strengths in the range of 0.6 - 0.9 MPa, with no emergence occurring above the 1.2 - 1.8 MPa range.

The critical crust strength which prevents emergence depends on crust thickness and soil wetness as well as on plant species and depth of seed placement. Hanks and Thorp (1956, 1957) reported that crusts limited emergence of wheat, grain, sorghum and soybeans, especially at the lower moisture contents. At a constant moisture content the seedling emergence decreased with increasing crust strength although some seedlings emerged even when the crust strength was a high as 0.14 MPa.

Obviously, the critical crust strength which prevents emergence depends on soil wetness and on crust thickness as well as on plant species and depth of seed placement (Hillel, 1972). Comparison of results from different investigations is difficult if not impossible if different types of penetration probes and different test procedures are used.

The effect of probe type, base area, cone angle as well as moisture content, aggregate size and penetration speed on the penetration resistance was investigated under laboratory conditions by La Woo-Jung et al (1985). As the penetrometer resistance depends on the size and geometry of the probe, the root or seedling resistance can be estimated by using probes with a geometry similar to this of roots or seedlings.

Callebaut et al (1985) used a motor-driven needle-type penetrometer in order to determine the critical crust strength of salsify (Scorzonera hispanica) during a field experiment. A range of different crust strengths was established by treating a sealed soil surface, formed under natural rainfall conditions, with soil stabilisers. They observed that the penetration resistance of a needle was negatively affected by the water content and positively by the density of the soil surface layer. Seedling emergence of salsify was negatively correlated with the penetration resistance, the critical resistance being 0.037 MPa.

At the Department of Soil Management and Soil Care, University of Ghent, Belgium, an electrically operated penetrometer was constructed with the possibility of using a needle or different shaped cones.

The penetrometer

The penetrometer T-5001, manufactured by J.J. Lloyd Instruments Ltd, Southampton, England is schematically illustrated in figure 1. The moving crosshead can be equipped with different types of penetration probes. The maximum crosshead displacement is 1100 mm. Penetration resistance of soil columns with a maximum length of 50 cm can be measured. Crosshead speeds from 5 to 500 $mm.min^{-1}$ can be established and the applied force can range from 0.05 to 5000 N. The penetration resistance can be recorded for every 0.1 mm depth through the soil profile.

Laboratory experiments

Effect of cone geometry

It is known that the penetration resistance depends to a large extent on the cross-sectional area A of the probe used. Usually, penetration resistance is measured using a cone with an angle of 60° and a cross-sectional area of 1 cm^2.

A comparison was made between the soil-surface strength measured with a needle probe with a cross sectional area of 1.43 mm^2, a standard cone 60° and A : 100 mm^2 and a cone 60° and A : 26.4 mm^2.

The relationships between the probes and for a range of moisture contents are illustrated in figure 2. It can be seen that an increase in the cross-sectional area of the probe results in a decrease of the penetration resistance per unit surface area of the probe. However, this decrease is not proportional to the increase of the cross-sectional area. The penetration resistance measured with the needle is about 4 and 3 times greater than when measured with the standard cone and the smaller cone, respectively. This is not reflected in the ratio between the cross-sectional areas of the needle and the two other probes, being 1:70 and 1:80, respectively.

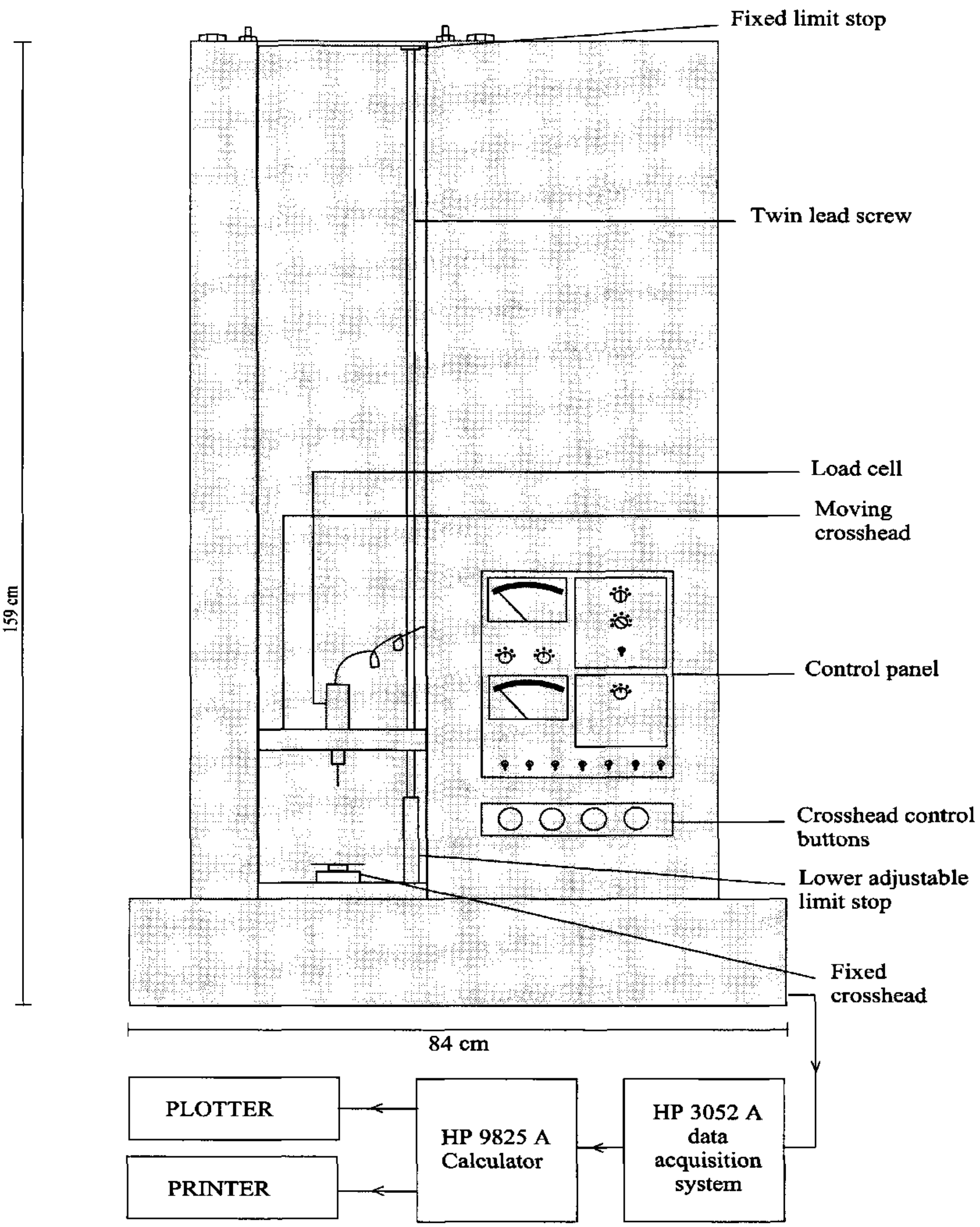

Figure 1. Schematic view of the penetrometer

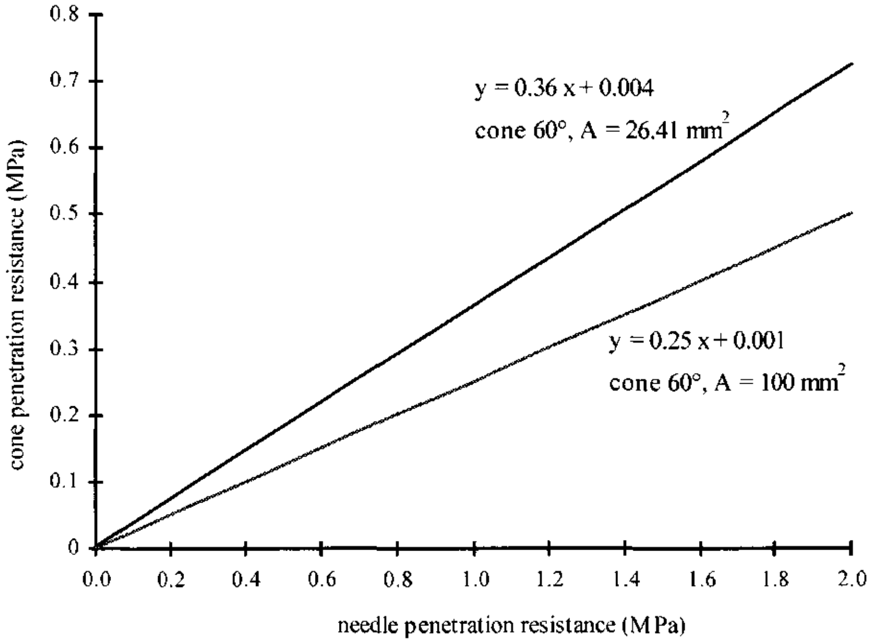

Figure 2. Relationship between the resistance to penetration of a cone and a needle

Effect of moisture content and bulk density

In order to detect the effect of soil surface properties, bulk density and water content on the penetration-resistance of a needle, cylinders (h = 4 cm, □ = 7.6 cm) were filled with the aggregate fraction 0.5 - 5 mm of a loamy sand. Packing was done by hand, up to bulk densities of 1.37 g cm^{-3} and 1.04 g cm^{-3} and wetting was performed by capillary rise. The cylinders were subjected to an artificial rainfall of 40 $mm.h^{-1}$ so that the soil surface became sealed. Penetration resistance at intervals of 0.1 mm over a depth of 15 mm were measured at three water contents (11 %, 22 %, 31 % w/w). Different water contents were obtained by drying out after rainfall. The effect of water content and bulk density on needle penetration resistance in a surface-sealed soil is illustrated in figures 3 and 4. In a sealed soil, at low bulk density (1.04 g cm^{-3}) no effect of water content was observed in the upper 5 mm. At a higher bulk density (1.37 g cm^{-3}) the effect of water content was reflected in marked differences in penetration resistance. Thus, in dense soil the effect of water content is stronger than in loose soil.

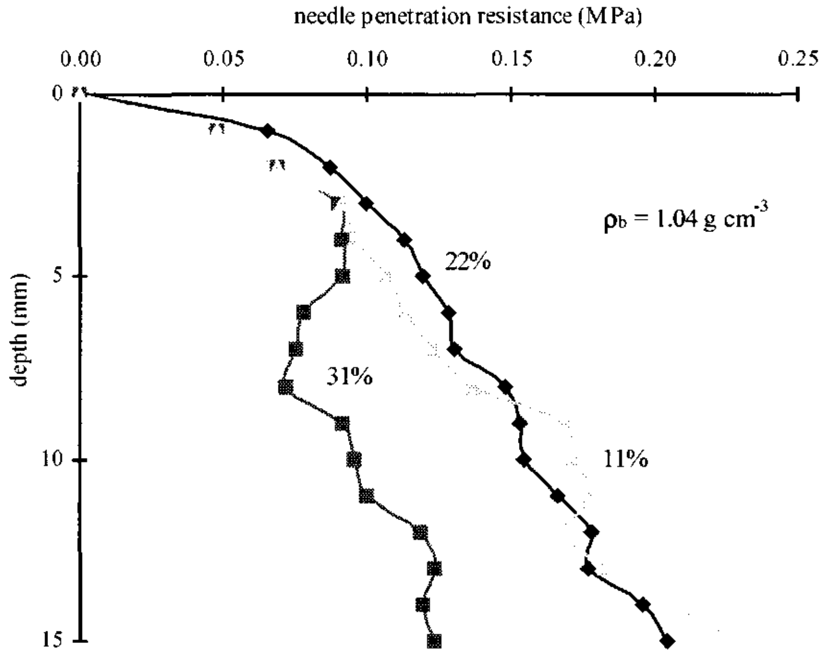

Figure 3. Effect of water content on penetration resistance of a needle in a surface-sealed loamy sand soil (aggregate fraction 0.5 - 5.0 mm)

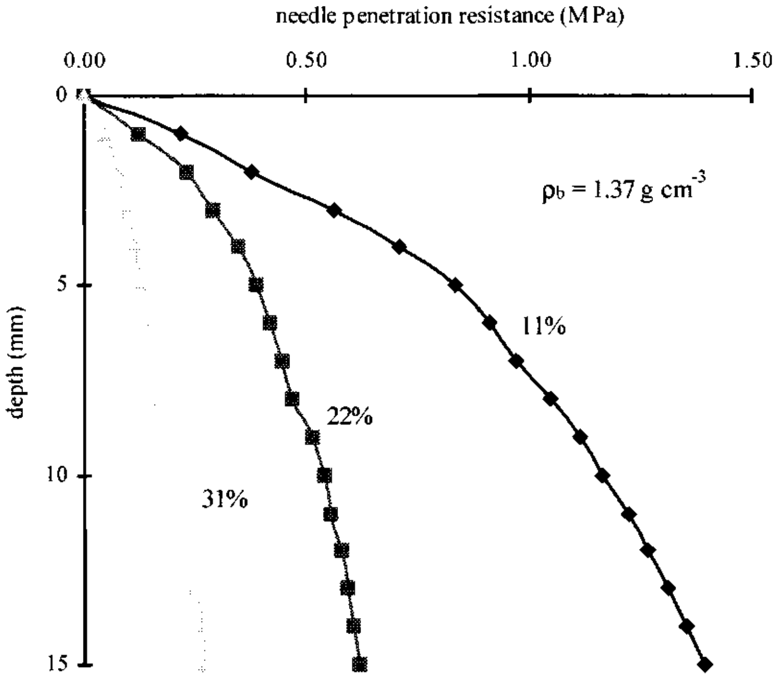

Figure 4. Effect of water content on penetration resistance of a needle in a surface-sealed loamy sand soil (aggregate fraction 0.5 - 5.0 mm)

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INPUT PARAMETERS FOR SOIL MECHANICAL PROPERTIES - THEORY AND FIRST APPROACH -

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Abstract

Soils are usually structured and unsaturated and differ in mechanical strength depending on internal properties like texture, structure and type of aggregates, clay mineralogy, ionic composition, water content and/or pore water pressure, organic carbon, predrying history, and external factors like intensity and kind of stress, stress history. Stress propagation e.g. due to wheeling occurs always threedimensionally and changes soil structure and functions if exceeding the precompression stress value as a measure for soil type dependent soil strength by soil deformation processes. The coupled stress-strain relationship can be determined by SST (Stress State Transducer) and DTS (Displacement Transducer System) measurements and can reveal severe differences in soil deformation behaviour. Tillage effects on soil strength and soil deformation can be verified both by the stress components as well as by differences in soil movement in x and z direction and can be used to also predict longterm sustainability aspects. The effect of wheeling with different machines e.g. during harvesting, plowing or seeding on stress dependent soil displacement, changes in soil structure, and in ecological site properties like aeration, amount of plant available water, root penetration and nutrient uptake efficiency can be also derived from mechanical properties like soil strength and stress propagation pattern. The possibility to prepare pedotransferfunctions on soil mechanical properties in order to lateron derive corresponding soil maps and recommendations for site and soil type dependent application of machines will be also described by various types of models applicable for such purpose.
Finally a first evaluation of the informations defined in the submitted papers will be given.

Keywords: texture, structure, strength, stress, strain, precompression stress, air permeability, hydraulic properties, mechanical properties, modeling, pedotransfer-functions

Introduction

It is well known in the literature, that soils as three phase systems undergo an intensive alteration in their physical, chemical, and biological properties both during natural soil development as well as during anthropogenic impact processes like soil plowing, sealing, soil erosion by wind and water, soil amelioration, soil material excavation and refilling of devastated land.
Oldeman (1992) as well as Soane and van Ouverkerk (1994) have intensely pointed out that about 20% of total soil degradation in the world can be defined as induced by soil compaction, while even only in Europe about 33 Mha of arable land are already completely devasted by non-site-specific wheeling and tillage processes. In agriculture, soil compaction as well as soil erosion by wind and water are classified as the most harmful processes which do not only end in a reduction of the productivity of the site but which are also responsible for groundwater pollution, gas emission and higher requirement of energy input in order to gain a comparable crop yield. Apart from the irreversibility of such degradation processes also changes in physical, chemical and biological soil processes affect the properties of the other components in ecosystems as for example filtering and buffering capacities for groundwater, recharge or CH_4-pollution of the atmoshere due to anaerobic processes in soils. Furthermore, there are several papers available which also report a more pronounced erosion by wind and

water, because the seed bed preparation results only in a very weak soil bed with nearly any internal soil strength but this material can lateron be more easily transported both by wind and water. In addition Boone and Veen (1994), Lipiec and Simoto (1994) and Stepniewski et al. (1994) argue that due to complete homogenization of this seedbed pore system also the gas, water and heat transport into and out of the soil are also prevented. This is especially true if, because of the non-site specific site treatment extreme changes of properties between the soil horizons exist which prevent the transport processes very extremely.

In the following, various processes shall be described which determine soil compaction and stress/strain distribution as well as possibilities to quantify mechanical properties and to derive pedotransferfunctions are described.

Determination of mechanical parameters

Soils consist of the solid, liquid and the gaseous phases and depend on the degree of soil development. Chemical, physical and biological processes further alter the site properties as well as their functions. In various scientific disciplines the differentiation between capacity and intensity parameters and functions is made to either define basic material properties or to quantify material functions. The latter include the definition of well defined limits (validity of the material properties, e.g. whether or not there are elastic or plastic changes due to mechanical loading) and the derivation of induced changes in physical, chemical and biological functions.

„Capacity" methods

Capacity methods or analysis quantify material properties which are classified as constant but which therefore - in case of application under in situ situation - differ to a great extent according to the surrounding conditions.

If e.g. mechanical properties for various kinds of mineral or organic particles under well defined conditions have to be compared, the following methods can be used:

Table 1: Methods determining soil physical properties

Method	Dimension	Soil Condition
• Atterberg test Consistency test	water content (%, w/w)	homogenized soil
• Proctor test	water content (%, w/w) bulk density (g cm^{-3})	homogenized soil single aggregate
• Mean weight diameter	(-)	partly homogenized soil samples
• Wet sieving Percolation Irrigation	length (cm)	single aggregates

Soil consistency

Atterberg test

Consistency limits of homogenous soil material are defined as a function of water content θm and are related to soil strength properties. The results are also used to predict the workability of soil.

- Liquid limit

The liquid limit is defined as the water content θm at a certain amount of energy applied to the soil (= 25 strokes) in the Casagrande apparatus. In order to obtain the water content at exactly 25 strokes the completely homogenized soil material will be watered to distinct water contents. Each set of samples will be homogenized, placed in a special bowl and V shape trenched from top to bottom. Thereafter the sample will be pushed up and down by the special equipment continuously and the amount of strokes counted. As soon as the trench has been closed for 1 cm, the water content θm must be determined. This test will be repeated at the minimum 4 times (starting from the dry end to the wetter part) and the water content (mass base) versus log number of strokes calculated in order to derive the water content at 25 strokes. The greater the clay content, the ionic strength or the valency of ions, the organic matter content, or the more dominant are the 3 layers minerals, the greater the water content at the liquid limit.

- Plasticity limit

The plasticity limit is defined as the water content θm (by mass) when homogenizd soil samples start to crack just by rolling it to a diameter of less than 4 mm.

- Plasticity value

The difference between the water content θm at the liquid limit and the plasticity limit is called „Plasticity value". It is often used as an index for workability of a soil. The higher the plasticity value the more sensitive are the soils for plastic deformation; the smaller the difference the quicker they can be wheeled etc. without further soil deformation. There are several attempts described in the literature to correlate the plasticity value to soil strength. The higher the plasticity value, the smaller is the angle of internal friction for sandy soils. (Kezdi 1969; for more detailed informations see Hartge and Horn 1991, Kretschmer 1997, Klute 1986) In principle such test only informs about the mimimum strength values .

Proctor test

The Proctor test is recommended as a standard test mainly for homogenized soil material in order to define the effect of water content θm, of organic and mineral composition of soils on soil compactability. Optimal bulk density (ρ_{opt}) and the optimum water content (W_{opt}) for maximum compactability of the soil sample at a given energy applied to the sample (3 x 25 strokes by a hammer with a defined compaction energy i.e. defined falling height and weight) are determined, after a series of soil tests have been performed at different water contents.

The coarser the soil sample, the higher is the Proctor bulk density value at a smaller water content W_{opt}. Sandy soils have higher values than silty, or clayey soils, while the latter ones require a higher water content θm_{opt} at the optimum bulk density (ρ_{opt} = proctor density). The more pronounced the uneveness of the grain size distribution, i.e. the more mixed soils are, the higher the Proctor density at higher water content θm.

Aggregated soil samples either react like coarser soil material (= i.e. the Proctor (bulk) density becomes higher at a smaller optimal water content θm (= θ_{opt}) in case of very strong aggregates, or if aggregates themselves will be destroyed during the test, the Proctor density becomes smaller but the water content increases compared to the corresponding data for the completely homogenized material.

Mean weight diameter

Aggregate stability is often determined by wet sieving and percolating or irrigating packages of aggregates under water. The soil samples will be wetted to a given pore water pressure and thereafter sieved through a set of sieves from 8 to 2 mm diameter. The difference between the aggregate size distribution at the beginning and after sieving under water for e.g. 5 min by up- and downward movement can be calculated as the mean weight diameter at nearly water saturation. The result gives a qualitative hint about aggregate strength.

A larger average diameter after sieving under water means a higher stability of the aggregates.

Penetration resistance

The resistance of soil samples against any kind of soil deformation will be determined by various kinds of penetrometer devices. The most simple ones consist of an iron stick with a small diameter (e.g. less than 0.5 cm) and a defined tip shape. Very often, the cone angle equals 30 degree in order to simulate root properties or earthworm shapes. The penetrometer can be either pushed into the ground by a constant weight of a falling hammer or it can be driven by a motor at constant speed. The various readings can be either cm pentration depth per hammer stroke, or the more sophisticated penetrometer readings give depth depletions of stresses which have to be overcome by the pentrating bodies. In the literature an enormous amount of papers define both the optimal design and construction of the penetrometer itself in order to reduce wall friction effects with increasing depth, the most adjusted stress sensor reading system, speed effects on the readings etc. Predominantly the data are correlated to root growth, earthworm activity , or tillage effects. With respect to root growth there are several hints that exceeding 2 MPa results in a reduction of root growth to the half, while exceeding 3 MPa results statistically in no root growth. However, tillage effects may increase the critical stress value to more than 3.5 MPa and such readings are further affected by the kind of the pore system and of the kind of soil structure. Furthermore a penetrometer needle is not flexible as it is true for roots, which may choose the plaines of weakness for root growth. Thus, penetrometer readings quantify the resistances mostly in the vertical direction. In addition, the penetrometer readings only integrate all hindering effects but are not applicable to differentiate between the various reasons for such values. Even if there are many papers available which based on statistical approaches inform about the effect of increasing bulk density and/or increasing water content on the penetration resistance, is the possibility to extent such data for planning or to derive further measures for land management is very limited.

Another approach to apply such penetrometer readings is for creating maps of derived properties (e.g. the definition of sites with a given strength irrespective from where it originates). The data can be interpreted by means of statistical variogram approaches, fractal analyses or simply by "it is different at the various locations".

Other methods

- Bulk density

The bulk density of soil samples will be often used as a first hint for soil strength which may be true for completely homogenized and/or sandy soils without any structure. However bulk density describes only mass per volume but gives no information about the distribution of the solid in a given constant volume. Thus the interpretation of such data is very much limited as soon as soils are structured or/and unsaturated. There is no link between strength and bulk density in aggregated soils nor is it possible to derive further properties from such data apart for the seedbed or newly reameliorated sites.

- Structure stability in alcohol/water mixtures.

For more detailed informations about this very qualitative method see Hartge and Horn (1991) or Burke et al. (1986)

Determination of „intensity“ parameters

Soil formation including aggregate development always changes both physical and mechanical properties and therefore requires the exact definition of validity limits if properties should be quantified. This is true, because in situ soil formation processes have to be linked to surrounding internal and external conditions (climatic, mechanical, physical, hydrological, or chemical aspects) which coincides with a needed detailed analysis. E.g. all properties like soil strength, stress attenuation and changes in soil structure or pore systems are material functions (with well defined and quantified limits) as it is true for water and ion fluxes, gas exchange and accessibility of exchange places for cations.

Consequently in order to deal with dynamic properties of soils, stresses, strain and strength definitions have to be given at first in order to lateron also define the limits of the material functions with respect to the application of external stresses applied.

Stress Theory

- Definitions

Before discussing methods of stress measurement in the field and in the laboratory as well as factors influencing compactability, it is appropriate to differentiate between several terms used to define dynamic compressive properties. These definitions have been taken from Kezdi (1969), Bradford and Gupta (1986), Hartge and Horn (1991), Fredlund and Rahardjo (1993).

Forces applied to the soil are to be related to an area. The force per unit area is defined as stress.

Stresses working along the surface will also induce stresses in the soil, which may result in a three dimensional deformation of the soil volume or will be transmitted as a rigid body. The mechanical behavior of a soil (i.e. the volume change and the shear strength behavior) can be described in terms of the state of stress in the soil.

Strength

Soil strength data quantify mechanically based material functions and depend on internal parameters like grain size distribution, kind of clay minerals, kind and amount of adsorbed cations, the content and kind of organic substances, aggregation induced by swelling and shrinking, stabilisation by roots and humic substances, bulk density, pore size distribution and pore continuity of the bulk soil and of single aggregates, water content and/or water suction (Horn, 1981, 1988).

- Stress state

The number of stress state variables required to define the stress state depends primarily upon the number of phases involved. The effective stress σ' for saturated soils has often been regarded as a physical law. This stress component can be defined as a stress variable for saturated conditions and defines the difference between the total and the neutral stress u_w which equals the pore water pressure:

$$\sigma' = \sigma \pm u_w \qquad (1)$$

The effective stress σ' is transmitted via the solid particles, the neutral stress (u_w) via the liquid phase.

Stresses in unsaturated soils are transmitted via the solid, liquid and gaseous phase. Thus, eqn. (1) becomes:

$$\sigma' = (\sigma - u_a) + X\,(u_a - u_w) \qquad (2)$$

where u_a = pore air pressure, u_w = pore water pressure, and X = a factor which depends on the degree of saturation of the soil. At pF = -oo, X = 1, while at pF 7, X = 0.

For sandy, less compressible and non-aggregated soils, X can be calculated by

$$X = 0.22 + 0.78\,Sr \qquad (3)$$

where Sr = degree of saturation. For silty and clayey soils, the values of the parameters in eqns. (1) and (2) depend on soil aggregation, soil pores arrangement and strength, and on hydraulic properties and must be well quantified. Thus the material function of the components in structured soils is only valid as long as the internal soil strength is not exceeded by the externally applied stresses and changes if e.g. aggregates are destroyed during soil deformation and hence the structure properties reduced to mainly texture dependent ones.

STRESS THEORY

In the present discussion on sustainability especially soil compaction is repeatedly mentioned to be the main threat in agriculture which has to be prevented (Soane and van Ouwerkerk 1994, Horn et al. 1995).

The extent of soil deformation can be predicted by stress strain processes and by the proportions of stress components to each other. In the absence of gravitational and other body forces stresses in soils as three phase systems must be differentiated in three normal stresses and six shearing stresses acting on a cube, of which the shearing forces can be reduced to three because of equilibrium. Therefore, three normal stresses (σ_x, σ_y, σ_z) and three shearing stresses (τ_{xy}, τ_{xz}, τ_{yz}) must be determined to define the stress state at a point (Nichols et al. 1987, Horn et al. 1992, Harris and Bakker 1994). The stress state can be desribed completely by a symmetrical tensor:

$$\begin{bmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{xy} & \sigma_y & \tau_{yz} \\ \tau_{xz} & \tau_{yz} & \sigma_z \end{bmatrix}$$

As for all symmetrical tensors it is always possible to find a coordinate system, in which the tensor becomes diagonal. In this principal axis system the stress tensor simplifies to

$$\begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{bmatrix}$$

with principal stresses σ_1, σ_2 and σ_3. For a more simple characterisation of the stress state two invariants of the stress tensor are often used, the mean normal stress MNS and the octahedral shear stress OCTSS (see also Koolen 1994):

$$\mathrm{MNS} = \tfrac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3)$$

$$\mathrm{OCTSS} = \tfrac{2}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}$$

- Stress propagation

Each stress applied to soils will be transmitted to deeper depths threedimensionally and may alter physical, chemical and biological properties if the internal mechanical strength is exceeded. Kind of external forces applied, time dependency and number of compaction events can either change properties up to deeper depths by divergency proccesses or a given structure i.e. soil strength will be destroyed by shear forces (i.e. kneading). The latter case may result in a complete homogenization and normal shrinkage behaviour. (Horn 1988).

Stress propagation theories are rather old and have been often modified and more adjusted to in situ situations. The fundamental theories of Boussinesque are only valid for completely elastic material, while Fröhlich (1934) or Söhne (1953) (both cited in Horn 1988) defined

their approaches by including elasto plastic properties through the introduction of concentration factor values.
The more complete description of the models is given by Koolen and Kuipers (1985),or Horn et al. (1994), Bailey et al. (1992), Johnson and Bailey (1990).

Strain Theory
Every change of the stress state results in a soil deformation. Usually the plastic (= irreversible) portion and the total amount of this strain strongly increase, if the stresses exceed the internal soil strength. Analogous to stress, strain can be designated as normal strain ε_x, ε_y, ε_z and shear strain ε_{xy}, ε_{xz}, ε_{yz}, the strain is described completely by the symmetrical strain tensor:

$$\begin{bmatrix} \varepsilon_x & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{xy} & \varepsilon_y & \varepsilon_{yz} \\ \varepsilon_{xz} & \varepsilon_{yz} & \varepsilon_z \end{bmatrix}$$

In the corresponding principal axis system the strain tensor reduces to

$$\begin{bmatrix} \varepsilon_1 & 0 & 0 \\ 0 & \varepsilon_2 & 0 \\ 0 & 0 & \varepsilon_3 \end{bmatrix}$$

The strain tensor includes a complete description of the local soil deformation. For example the volumetric strain ε_{vol} can be calculated as (note that the trace of a tensor is invariant under coordinate transformations)

$$\varepsilon_{vol} = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 = \varepsilon_x + \varepsilon_y + \varepsilon_z$$

Furthermore, the strain components and their proportions depend on the internal and external parameters and require the determination of all components mentioned in a threedimensional volume.

Stress/strain processes
Generally mechanical processes in soils are described by the stress-strain-equation:

$$\begin{bmatrix} \sigma_x(\vec{x},t) & \tau_{xy}(\vec{x},t) & \tau_{xz}(\vec{x},t) \\ \tau_{xy}(\vec{x},t) & \sigma_y(\vec{x},t) & \tau_{yz}(\vec{x},t) \\ \tau_{xz}(\vec{x},t) & \tau_{yz}(\vec{x},t) & \sigma_z(\vec{x},t) \end{bmatrix} = f \begin{bmatrix} \varepsilon_x(\vec{x},t) & \varepsilon_{xy}(\vec{x},t) & \varepsilon_{xz}(\vec{x},t) \\ \varepsilon_{xy}(\vec{x},t) & \varepsilon_y(\vec{x},t) & \varepsilon_{yz}(\vec{x},t) \\ \varepsilon_{xz}(\vec{x},t) & \varepsilon_{yz}(\vec{x},t) & \varepsilon_z(\vec{x},t) \end{bmatrix}$$

The function f defines soil properties. In case of non linear isotropic elastic properties the matrix notation reads as follows:

$$\begin{bmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{xy} & \sigma_y & \tau_{yz} \\ \tau_{xz} & \tau_{yz} & \sigma_z \end{bmatrix} = \frac{E}{1+v} \cdot \begin{bmatrix} \varepsilon_x - \varepsilon_m & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{xy} & \varepsilon_y - \varepsilon_m & \varepsilon_{yz} \\ \varepsilon_{xz} & \varepsilon_{yz} & \varepsilon_z - \varepsilon_m \end{bmatrix} + \frac{E}{3 \cdot (1 - 2 \cdot v)} \cdot \begin{bmatrix} \varepsilon_m & 0 & 0 \\ 0 & \varepsilon_m & 0 \\ 0 & 0 & \varepsilon_m \end{bmatrix}$$

where E = Young's modulus
υ = Poisson's ratio
$\varepsilon_m = \frac{1}{3} \cdot (\varepsilon_x + \varepsilon_y + \varepsilon_z) = \frac{1}{3} \cdot \varepsilon_{vol}$

Definition of deformation in soils

Assuming soil as a continuum soil movement is described as a translation field $\vec{d}(\vec{x},t)$ the local properties of which are usually characterized by three parts of its spatial derivative

$$\nabla \circ \vec{d} = \begin{bmatrix} \frac{\partial}{\partial x} d_x & \frac{\partial}{\partial x} d_y & \frac{\partial}{\partial x} d_z \\ \frac{\partial}{\partial y} d_x & \frac{\partial}{\partial y} d_y & \frac{\partial}{\partial y} d_z \\ \frac{\partial}{\partial z} d_x & \frac{\partial}{\partial z} d_y & \frac{\partial}{\partial z} d_z \end{bmatrix}$$

1. rotation

$$\operatorname{rot}(\vec{d}) = \nabla \times \vec{d} = \begin{bmatrix} \frac{\partial}{\partial y} d_z - \frac{\partial}{\partial z} d_y \\ \frac{\partial}{\partial z} d_x - \frac{\partial}{\partial x} d_z \\ \frac{\partial}{\partial x} d_y - \frac{\partial}{\partial y} d_x \end{bmatrix}$$

2. compaction/decompaction = divergence = volumetric strain

$$\varepsilon_{vol} = \operatorname{div}(\vec{d}) = \nabla \cdot \vec{d} = \operatorname{tr}(\nabla \circ \vec{d}) = \frac{\partial}{\partial x} d_x + \frac{\partial}{\partial y} d_y + \frac{\partial}{\partial z} d_z$$

3. shearing

$$\varepsilon_s = \frac{1}{2}\left(\nabla \circ \vec{d} + \left(\nabla \circ \vec{d}\right)^T\right) - \frac{1}{3}\operatorname{div}(\vec{d}) \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

While rotation does not result in any deformation nor in changes in properties of the soil volume (except the rotation of the principal axis system of any anisotropic material property), volumetric strain and shearing result in a deformation (Fig. 1).

Thus, soil deformation is a more complex process than only a reduction in volume. The latter one which is the same as volumetric strain expresses just one degree of freedom, whereas deformation at constant volume (shearing) summarizes 5 degrees of freedom. Although it is useful and well defined to distinguish between shear and compaction/decompaction processes as they typically show very different effects, all deformations in soils are combinations of both of them utilizing the full range of 6 degrees of freedom.

Compression refers to a process that describes the increase in soil mass per unit volume (= increase in bulk density) under an externally applied load or under changes of internal pore water pressure. External applied static or dynamic loads can be specified as vibration, rolling, trampling etc., while internal forces per unit area may be pore water pressure or water suction caused by a hydraulic gradient.

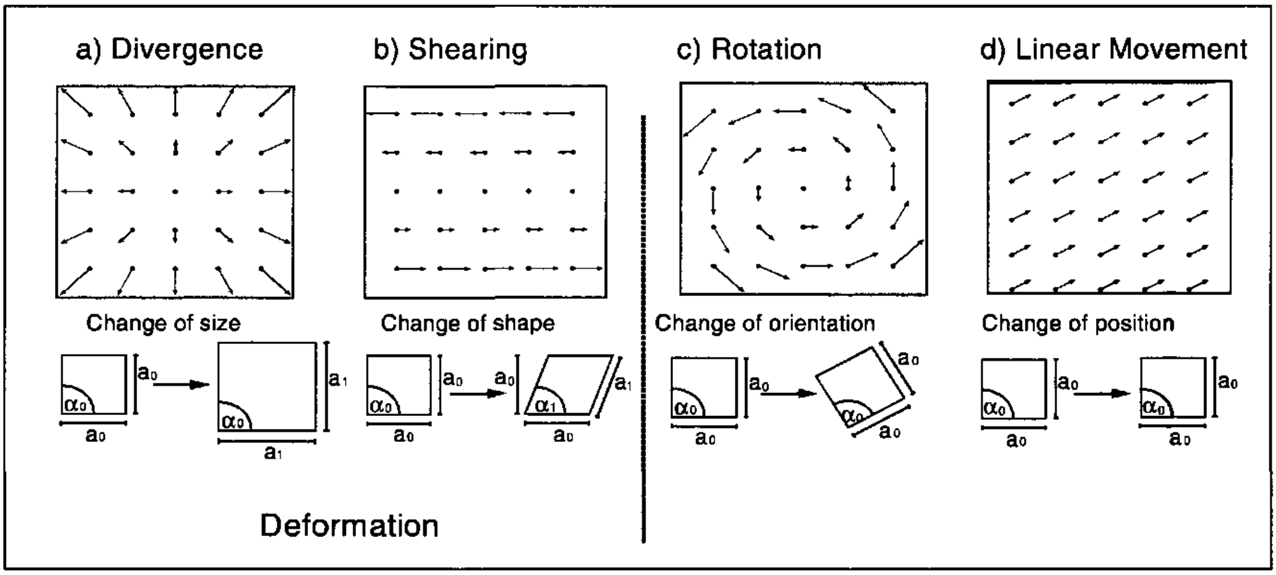

Fig. 1: Particle - displacment - fields (2-dimensional) in a continuous soil - body. (from Kühner, 1997)

In saturated soils, compression is called consolidation, while in unsaturated soils, it is called compaction. Consolidation, therefore, depends on the drainage of excess soil water according to the hydraulic conductivity and hydraulic gradient. However, during compaction also less compressible air will be expelled according to the air permeability, pore continuity and water saturation in the whole profile. Consolidation tests are therefore mainly used in civil engineering, e.g. in road construction, and have only limited application to agricultural soils.

Soil compressibility is defined as the resistance against volume decrease, when the soil is subjected to a mechanical load. Thus, it is described by the shape of the stress-strain curve. Compaction tests are used both for laboratory and for field soil compression characterizations. In the laboratory, soil compaction refers to the compression of small soil samples, whereas in the field it refers to the three-dimensional change in bulk density, change in pore size distribution, or in the strength parameters of an elemental soil volume up to deeper depths and distances from the loading area (Gräsle and Nissen 1996) Compaction tests in the laboratory are very common. In order to avoid friction effects between the cylinder wall and the sample itself, the optimum length ratio of the diameter to height of the cylinder should be ≥ 5. Compaction tests are carried out with homogenized or completely undisturbed bulk soil samples at different pore water pressure values (i.e. water suction). Additionally, even single naturally formed aggregates are compacted in order to determine their strength. (Baumgartl 1991)

Compactability is the difference between the initial bulk density and the maximum density to which a soil can be compacted by a given amount of energy and a defined water content.

- Methods of Measurement

Some of the most common methods used to quantify soil mechanical parameters under in-situ and laboratory conditions will be described in the following.

Stress measurements under in-situ conditions

Stress distribution

Stress distribution measurements in undisturbed soil profiles during wheeling the soil at different speeds, with different loads and contact areas reveal the kind and intensity of soil strength, stress attenuation, or soil deformation. In unsaturated soils, the pore water pressure at the time of loading further affects these parameters.

One of the major problems with respect to lateron validate compaction models is the installation of the sensors in the soil. The determination of soil stresses requires the installation of pressure sensors in different depths and distances from the perpendicular line in the soil. As soon as the original soil structure is disturbed due to excavation, installation of the sensors and the refilling of the soil, the obtained data only describe the stress pattern for ± homogenized or artificially mixed soil material. Thus, only in nonaggregated sandy soils no great differences between the values obtained after various kinds of installation can be expected. In aggregated soils, however, soil structure requires the very precise sensor installation in completely undisturbed soil from the side in well defined directions in order to then derive octohedral normal and shear stresses.

The pressure sensor is a extrinsic body which has different deformation properties compared to the soil material. If the pressure sensor itself is weaker than the soil, the registered stresses will underestimate the real stresses at that depth. If, however, the pressure sensor stiffness exceeds that one of the surrounding soil, stresses concentrate at the more rigid transducer body and, therefore, overestimate the real soil stresses. Table 2 informs about different types of stress transducers.

Tab. 2: Different types of stress state transducers (taken from Bolling, 1986, modified)

Principle	Material	Size	Deformation	Measured Values	Calculated Values	Author	Year
pneumatic	rubber	cylinder	plastic	soil stiffness	-	Kögler	1933
hydraulic	rubber	disk	plastic	1 defined stress	-	Söhne	1951
hydraulic	steel	disk	elastic	1 defined stress	-	Franz	1958
hydraulic	rubber	sphere	plastic	mean normal stress	-	Blackwell	1978
hydraulic	silicon	cylinder	plastic	mean normal stress	-	Bolling	1984
strain gauge	silicon	sphere	plastic	mean normal stress	-	Verma	1975
strain gauge	steel	disk	elastic	1 defined normal	-	Cooper	1975
strain gauge	aluminium	disk	elastic	1 defined normal	-	Horn (1980)	1980
strain gauge	steel	cube	elastic	3 defined normal	-	Prange	1960
strain gauge	aluminium	quarter	elastic	6 defined normal	$_{1,2,3}$ $_{xy,yz,xz}$	Nichols et al (1987) Horn et al (1992) Harris& Bakker (1994)	1987
strain gauge	aluminium	sphere	elastic	6 defined normal	$_{1,2,3}$ $_{xy,yz,xz}$	Kühner (1997)	1997

Plastic bodies as pneumatic or hydraulic cylinders, balls or discs, made by silicone or rubber (Bolling, 1984; Blackwell, 1978) change their volume according to the applied stresses. Prior to the measurement, the pressure cells have to be filled with water or air and thereafter prestressed with up to 80 kPa. However, the pre-pressure influences the stress-strain modulus of the sensor and, therefore, the measured pressure value (Horn et al. 1991). Theoretically, the sensor elasticity should be the same as that one of the surrounding undisturbed soil volume, which is nearly impossible to obtain. Generally, plastic sensors tend to behave weaker than the soil and stresses will be underestimated.

The plastic stress transducer indicates an average normal stress. The direction of stresses can not be identified if cylindric or spheric transducers are used. The shear stresses cannot be determined.

When rigid bodies are used as stress transducers, piezoelectric materials or strain gauges (Nichols et al 1987, Horn 1980) are applied on diaphragm material made out of aluminum or steel. As compared to the plastic stress transducers, it is not possible to match the stress-strain modulus of the rigid transducer with the surrounding soil. The optimum ratio of the transducer stress-strain modulus to that one of the soil is suggested by Peattie and Sparrow (1954) to be 10 or greater.

The determination of the stress distribution in „normal soils" values has been described amongst others by Horn (1981, 1989), Burger et al. (1987), van den Akker et al. (1994), Blunden et al (1994), and Horn et al. (1994) based on stress distribution measurements in soils by strain gauges. Ellies et al. (1995, 1996), Ellies and Horn (1996) also proofed the applicability of such technique for vulcanic ash soils which behave very different compared with the „normal" mineral soils. Horn (1995) summed up the physical/mechanical properties of deep loosened soils and also quantified the effect of wheeling on stress distribution in those heterogenous soil systems compared to corresponding untreated i.e. normally tilled and/or wheeled soils.

Horn et al. (1995), Kühner et al. (1994), and Kühner (1997) have quantified the stress distribution under various in situ conditions and Horn (1997) defined stress and strength conditions for soils under different landuse systems. Blunden et al. (1992, 1994), Kirby et al. (1997), Trein (1995), Kühner (1997), van den Akker et al. (1994) describe various further aspects of stress distribution and attenuation in soils and define both soil protection strategies as well as soil engineering approaches. The stress distribution in partly deep loosened (slit plow technique) soils is also described by Horn et al. (1997). Olsen (1994) calculated the mean stress values for various contact areas at constant concentration factors and concluded that even only a slight increase in moisture content or an increase in the contact area always resulted in an intensive increase of the concentration factor value.

The measurements and calculations of Blunden et al. (1992, 1994), Kirby et al. (1997), Trein (1995), van den Akker et al. (1994) were only based on measurements of the vertical component of the stresses applied to the soil, and they calculated the missing data by modelling in order to predict stress state in soils. However, such approach can only verify processes which are assumed to dominate in homogenous soil systems (like in the seedbed), while the stress distribution analysis in unsaturated structured soils is a more complex problem with many multi-disciplinary processes operating in an interactive fashion. Especially if the long term stability of soils involves materials which are unsaturated, non-linear, hysteretic and their composition is changing with time or if during tillage operations physical and partly also chemical properties are altered including the complete deterioration of soil structure, stress propagation will be more complex.

Consequently, the determination of stress paths requires the determination of all stress components at a single point by SST (Stress State Transducer) systems (6 normal stresses on three mutually orthogonal planes and three others, non-orthogonal planes). Based on the continuum mechanics theory, octohedral principle and shear stresses can be partly measured and partly calculated for a cube, cut from the continuum. It has also to be emphasized that such stress propagation can't be handled as it would be possible for parent soil material. (i.e. completely homogenized or as stiff material like in soil mechanics)

Strain determination

In principle the determination of soil strain is well described in the literature (Koolen and Kuipers 1985, Hartge and Horn 1991). One of the earliest systems to determine the complete volumetric strain path during wheeling under in situ conditions was that of Gliemeroth (1953), while those of e.g. McKibben and Green (1936), Hovanesian (1958), Gill and vanden Berg (1967), Van den Akker and Stuiver (1989), Okhitin et al. (1991) could be only used to determine the changes in the position of installed particles (coloured sticks, spheres etc) to their original position. Apart from the complete disturbance of at least the adjacent soil volume during installation also missing sensors in the various positions or the impossibility to characterize the movement of the sensor during deformation prevents the complete calculation of the strain path under in situ conditions and to predict the consequences for physical properties under in situ conditions (Erbach et al. 1991, Bakker et al. 1994). Consequently, Kühner et al. (1994) described a new soil „Displacement Transducer System“ (DTS), which can be installed in the undisturbed soil volume prior to wheeling experiments and records the kind of stress induced movements of soil particles (see also Pytka et al. 1995). If 4 DTS systems are installed in soils at various positions and distances from the rut not only the strain path but also the volumetric strain matrix can be quantified.

Stress - strain determination

The stress/strain apparatus is described by Kühner (1997) and consists of a SST sensor block, which is connected to a mobile measuring device in order to determine the movements in the x and z directions. The recording of combined data will be done by a data logging system with a frequency of approx. 40/s for stresses and the same for the displacement of the sensor in both directions.

Strength measurements of undisturbed samples in the laboratory

Measurements of soil strength

The determination of soil stability parameters requires measurements under well defined soil conditions. Therefore, these measurements are mainly performed in the laboratory (Tab. 3).

Tab. 3: Methods determining soil strength

Method	Dimension	Derived	Soil Condition
uniaxial compression	pressure (Pa)	-	homogenized soil single aggregates structured bulk soil
confined compression test	pressure (Pa)	precompression stress (Pa)	homogenized soil structured bulk soil
trixial test	pressure (Pa)	cohesion (Pa) angle of internal friction (°)	homogenized soil structured bulk soil single aggregates
direct shear test	pressure (Pa)	cohesion (Pa) angle of internal friction (°)	homogenized soil structured bulk soil single aggregates

Uniaxial compression test

The uniaxial compression test is used to define the pressure, at which the soil sample starts to fail at a given water content. One defined vertical normal stress (σ_1) is applied to the soil sample, while the stresses on the planes mutually perpendicular to the σ_1-direction ($\sigma_2 = \sigma_3$) are zero. The uniaxial compression test is as well used to determine the tensile strength of single aggregates (crushing test).

Confined compression test

The soil strength relationships of undisturbed or homogenized soils and of single aggregates are quantified in the confined compression test. In contrast to the uniaxial compression test, stresses in the confined compression test in the σ_2 and σ_3 direction are undefined. (= rigid wall of the soil cylinder). Both the time and the load dependent alteration of soil deformation is quantified and the slope of the virgin compression line (i.e. the compression index), as well as the transition from the overconsolidated to the virgin compression line (i.e. the precompression stress) determined. The precompression stress is defined as the stress value at the transition of the less declined recompression curve to the virgin compression line. The latter straight line part has a steeper slope if plotted on a semi - logarithmic scale.There are several methods available to determine the precompression stress. One of the most frequently used is that one of Casagrande (For more detailed information see Bölling 1971)

Triaxial test

Undisturbed cylindrical soil samples are loaded with increasing vertical principle stress σ_1, while the horizontal principle stresses $\sigma_2 = \sigma_3$ are defined and kept constant throughout the test. Shear stresses occur in any other plane than in the planes of the principle stresses. The shear parameters: cohesion and angle of internal friction can be determined from the slope of the Mohr's circles envelope.

However, number of contact points, strength per contact point and the pore geometry affect the obtained triaxial test results. Various kinds of triaxial tests can be separated:

In the consolidated drained test (CD), the soil sample will be equilibrated with the mean normal stresses prior to the increase of the vertical stress σ_1 and the pore water can be drained off the soil sample when the volume reduction exceeds that one of the air filled pore space. Therefore, the applied stresses are assumed to be transmitted as effective stresses via the solid phase.

However, measurements of Baumgartl (1989) showed an additional change in the pore water pressure even during very long lasting triaxial tests under "drained and consolidated" conditions depending on the hydraulic soil properties. Thus, shear speed and low values of hydraulic conductivity, high tortuosity and small hydraulic gradients affect the drainage of excess soil water and the effective stresses (see also Horn et al. 1995)

In the consolidated undrained triaxial test (CU), pore water can not be drained off the soil during vertical stress increase. Thus, high hydraulic gradients occur and the pore water reacts as a lubricant with a small surface tension value. Thus, in the CU test, the shear parameters are much smaller and the pore water pressure values are much higher compared to those in the CD test.

The highest neutral stresses and therefore the lowest shear stresses can be measured in the unconsolidated undrained test (UU), where neither the effective stresses nor the neutral stresses are equilibrated with the applied principle stresses in the beginning of the test.

Thus, the shear parameters: cohesion and angle of internal friction are highly influenced by the compression and drainage conditions during the triaxial test. In terms of questions about strength of agricultural soils under running wheels, texture, pore water pressure (i.e. water suction) and kind of aggregates as well as soil structure mainly affect the preference for a specific test.

Direct shear test

At the direct shear test, the kind and the direction of the shear plane is fixed. The shear plane is assumed to be only affected by normal and shear stresses. The normal stress is applied in vertical and the shear stress in horizontal direction.

Similar to the triaxial test, the values of the shear parameters: cohesion and angle of internal friction are influenced by the shear speed and the drainage conditions for a given soil.

Examples on soil mechanical processes

Soil strength

In soils under load only the air and water-filled soil volumes are affected, both with respect to a total volume reduction and/or to changes in the pore size distribution, water saturation and gas exchange. The extent of soil deformation at a given stress depends on soil strength, particle mobility and rearrangement as well as on the mobility of gas and water in the inter- and intra-aggregate pores. The pore continuity has to be considered, too.

The mechanical strength can be quantified by stress/strain measurements which result in precompression stress values. (Horn 1981, 1988)

In homogenized soil substrates, compressibility is the higher

- the greater the clay content at given bulk density values,
- the smaller the bulk density values at given texture,
- the smaller the amount of organic material at comparable grain size distribution,
- the wetter the soil is.

At given internal parameters, aggregation and due to the above mentioned tillage effects always result in higher strength. (Fig. 2)

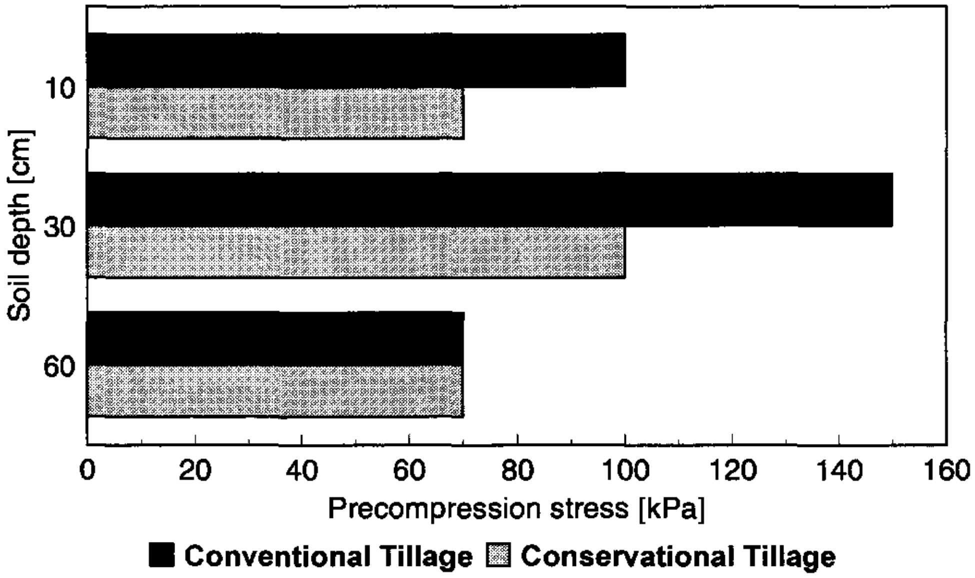

Fig. 2: Precompression stress [kPa] in different soil depths of a Luvisol derived from loess under conventional and conservational tillage systems at a pore water pressure of -6 kPa. (from Wiermann, 1998)

The „natural“ soil shows the effect of clay migration on strength decline in the Al horizon and strength increase due to aggregate formation in the Bt horizon of a Luvisol derived from loess. The corresponding soil under conservation tillage is stronger than the conventional tillage site. The latter shows a significantly reduced strength in the A horizon due to a too intensive homogenizsation during seedbed preparation and a very pronounced plowpan layer (expressed as anthropogenically induced strength increase by compaction in the Al horizon as well as in the deeper soil. Especially processes like the yearly ploughing and the tractor traffic create such very strong plough pans and plough layers with precompression stress values like the contact pressure of the tractor tyre or even higher due to lug effects (up to 300%). In all three soils always the anthropogenic parent material was weakest. The precompression stress values in the plow pan layer resemble the contact area pressure of the tractor tyre and persist for at least more then 30 years as it was verified at various sites worldwide. (Horn 1986, 1997)

With respect to predict soil strength it has been proved very often that under the same climatic conditions and soil use, the precompression stress values mainly differ because of differences in aggregation, texture, and pore water pressure values. Consequently, each soil type can be classified by structure dependent precompression stress values which is a material function defined by several physical parameters.

Soil deformation due to stress distribution and propagation in the profile

At a given soil texture stress propagation is the more intensive, the less aggregated, the wetter and the less dense the horizons are. The bigger the load, the larger the contact area at a given contact area pressure, the deeper is the stress propagation. The pattern of the stress equipotential line differs depending on soil strength, kind of loading, contact area and contact area pressure and is quantified as a concentration factor. The stronger the soil at a given external stress applied, the smaller the value while in weak, wet and loose soils the concentration factor can reach approximately the value 9. Furthermore, the stress distribution pattern in the soil is not only different for the lugs and the area in between the lugs, but it is also affected by the stiffness of the carcass (Horn et al., 1987). Thus, there are no well-defined unique stress equipotential lines in soils (Horn et al., 1989) but the concentration factor values must be related to precompression stresses in comparison with the stresses applied, the contact area for a given soil texture. (DVWK 1995) The effect of speed of wheeling on stress distribution has also to be considered.

If e.g. normal stresses are determined as a function of the number of wheeling events, it can be shown for different sites that with increasing wheeling frequency the measured vertical stress in the upper soil horizon clearly becomes smaller, because due to soil strain repeated external loadings induce a pronounced increase in bulk density, elasticity and shear strength. These stronger soil horizons on the one hand attenuate the external stresses more completely, on the other hand their increased elasticity and stress dependent deflection result in a further deformation of the deeper and still weaker soil horizons. Thus, additional soil loadings induce a further increase in the precompression stress values of the deeper soil horizons. Owing to progressive stress attenuation this effect fades out at greater depths (Horn et al. 1995)

If complete stress field is determined during a wheeling event, it can be shown that apart from the major vertical and horizontal stresses also mean normal and octahedral shear stresses show complete different pattern as detected in conservation and conventional tillage plots. Although the physical and chemical properties are the same, the stresses determined at single depth are much greater at the conventional site as compared to the conservationally tilled one (Fig. 3).

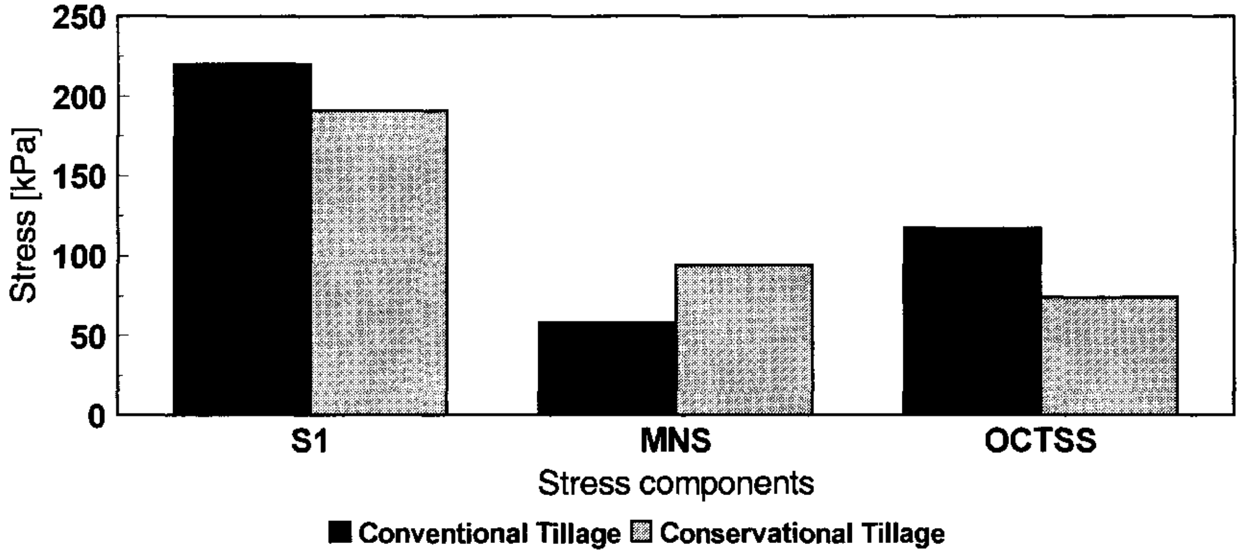

_Fig. 3: Effect of wheeling with a load of 5 Mg on changes in the stress components at 10 cm depth in conventional and conservational tilled soils at a matric potential of -6 kPa. S1 = vertical major stress, MNS = mean normal stress, OCTSS = octahedral shear stress. (from Wiermann, 1998)

In addition these stresses affect also soil particle displacement, volumetric strain and particle rearrangement. Thus soil strength can be either increased due to compaction or decreased because of destruction of existing aggregation due to process of shearing. During soil loading the stress components can vary as well as the ratio between mean normal and octahedral shear stress. Repeated wheeling a Luvisol derived from loess at constant water content during a single day results in a pronounced decline of the horizontal major stresses while the major vertical stress relatively gets bigger. Thus the concentration factor values will increase due to this more pronounced vertical stress distribution and each loading consequently also results in a smaller proportion of effective mechanical stress to hydraulic stresses. Finally also the bulk density values can decline especially if at a given water content stress induced smaller hydraulic conductivity prevents a quick drainage and results in an intensive soil kneading. (Horn et al. 1995)

Stress induced soil strain processes

Stresses can be either completely attenuated in a given soil volume, if the external stress is smaller than the internal soil strength. However, if the applied stress exceeds the internal strength, a further soil deformation occurs. The latter example can either result in a volume constant displacement or deformation or in a soil compaction (Kühner et al., 1994; Pytka et al., 1995). These differentiations also underline, that soil deformation and soil deformability are much more complex processes than a simple compaction and compactability. Especially if the shearing (e.g. due to kneading) occurs, a volume constant complete deterioration of the pore system and -functions occurs and result in a severe change in ecological properties.

In order to differentiate between these processes, e.g. both the rut depth and the vertical movement of a given soil volume below the rut in agricultural or forest soils must be known. How far soil strain during wheeling occurs and to which extent various tillage treatments (conventional/conservational) influence soil deformation at a given pore water pressure and kind of tractor is shown in Fig. 4.

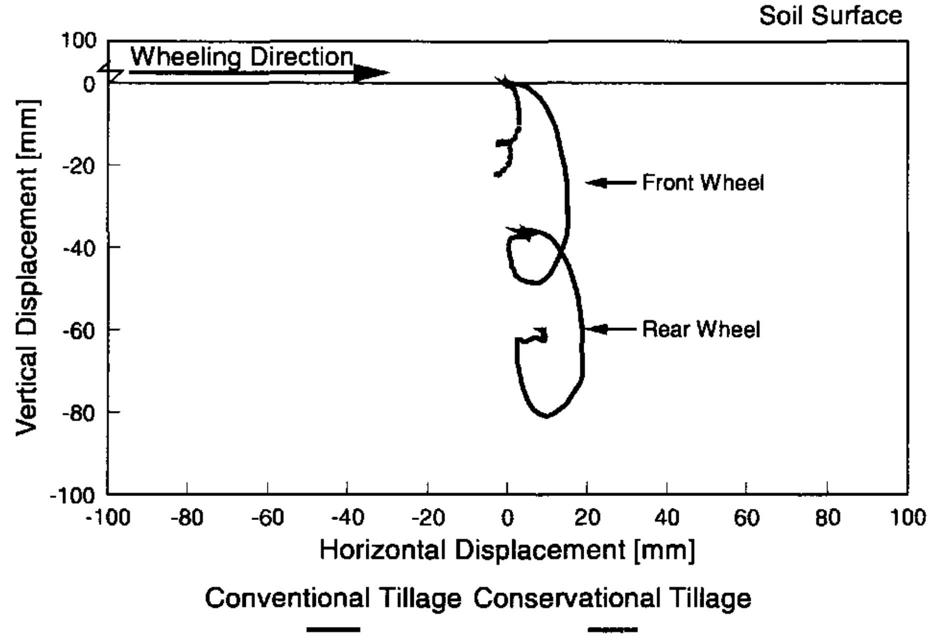

Fig. 4: Vertical and horizontal soil displacement, induced by a wheel-load of 5 Mg, in a Luvisol derived from loess at a pore water pressure of -6 kPa for conventional and conservational tilled plots. (from Wiermann, 1998)

In the conventionally tilled soil, a tractor passage (front/rear wheel) results in a very pronounced vertical displacement (up to 8 cm and horizontal forward and backward placement of up to 20 cm), while these soil deformations are not that intensive in the conservation tillage plot. A maximum vertical displacement of less than 4 cm after 2 wheeling events could be detected and also the horizontal displacement is much less pronounced. The more pronounced the aggregate formation, the stronger the soil is the less pronounced are the processes of aggregate deterioration during displacement and the alteration of pore systems due to infilling of aggregate bits or particles in the inter-aggregate pore systems.

Nevertheless, it has to be pointed out that all stresses which cannot be attenuated and which exceed the internal soil strength result in a further soil volume and function alteration, even if the amount of not attenuable applied stresses varies for different soil types, land use, tillage systems, and environmental conditions.

Models: characteristics and classification

General remarks

Each soil deformation induced by stress and strain processes can be explained either by translation and rotation or by divergency and shear processes. Consequences of such processes on environmental properties can also be defined and used as an environmental impact model (O'Sullivan and Simota 1995)

In principle models can be classified as *deterministic* or *stochastic* approaches.

Deterministic models are based on precise definitions and relationships among the variables but don't take into consideration any variability in the field. Stochastic models, however, also include the variability in the field and the uncertainty. Consequently, deterministic models are easier to apply under in situ situations but are less realistic while the consideration of soil and stress variability in the field also informs about statistical terms. (e.g. standard error)

According to O'Sullivan and Simota (1995) another differentiation can be also made: *Mechanistic* models attempt to simulate the processes occuring in a system, whereas *empirical* models only define relationships between inputs and outputs but are not interested in defining the ongoing processes. Additionally it has to be mentioned that both types of models can be either deterministic or stochastic.

Because mechanical and physical properties in unsaturated soils undergo seasonal changes and their properties also depend on the kind of landuse and tillage practice as well as on soil development over the time Wheeler and Karube (1996) describe in their review about constitutive modelling the existing differences concerning their applicability. They reviewed several constitutive models for the mechanical behaviour of unsaturated soils by also including the relationships between stress, strain, strength and water content and subdivided the models in elastic or incrementally elastic models or elasto plastic models The main limitations of elastic models are apparent from the assumption of a unique state surface linking void ratio to net stress and suction which is only true for completely homogenized material i.e. homogenized seedbed or if stresses exceed by far the precompression stress value. Further changes in physical properties due to swelling and shrinkage including hydraulic hysteresis in the soil water characteristic curve and the influence of this on mechanical behaviour can not be included in elastic models. However, because these changes are especially essential for the topsoil due to tillage processes which always results in a complete disturbance of soil structure (see also Horn et al. 1994) such approach is not useful for agricultural purposes. The authors conclude after the revision of approx. 20 different models that strictly elastic models should be used only when all soil elements within the problem under analysis will undergo either monotonic loading or monotonic unloading and soil constants have to be measured for all conditions (which is difficult to achieve). Even for the stress paths involving only monotonic loading, elastic models have several weaknesses. Apart from the ignoration of the swelling induced changes in physical properties in the soil throughout a growing period, and the changes in pore size distribution and shear strength throughout the structure regain, there are no links included between shearing and volume changes.

As a consequence of these disadvantages more generalized elastoplastic critical state constitutive models for unsaturated soils have been developed, which also include plastic strains and the link between volumetric and shear behaviour.According to Wheeler and Karube (1996) such models for non expansive unsaturated soils are reasonably well validated, while mechanical processes in highly expansive clay soils are until now not to be modelled.

Type of models to determine tillage effects

Empirical model (statistical approach: Regression analysis to predict soil strength and stress distribution)

Soil strength is defined as precompresion stress value while stress distribution can be predicted by concentration factor values as material functions for given soil conditions. The precompression stress value has been repeatedly measured or predicted by various methods and approaches (see: Horn 1981, Horn 1989, Veenhof and McBride 1996, Hakansson and Reeder 1994, Mc Bride and Joosse 1996, Nissen and Gräsle 1996, Gräsle and Nissen 1996, and Horn et al. 1994,1995,1996).

Several of these authors suggest to determine soil strength of a soil profile up to approx. 1 meter and to compare these data with the strength and tractor dependent stress propagation by including site and equipment dependent concentration factor values. Based on about 80 data sets for arable soil profiles with complete physical properties Horn et al. (1989), Nissen (1998) have developed regression equations to predict stress distribution effects on soil strength as well as the consequences of exceeding the precompression stress value on changes in physical properties like air capacity, plant available water content or hydraulic conductivity throughout the total soil profile. In Germany such approach is now recommended to quantify the effect of soil formation and/or soil disturbance by tillage tools as well as to define the strength changes due to wheeling (= compaction) or deformation by shearing (i.e. ploughing). The manual for the application of such approach is published by DVWK (1995), and stress and strength dependent changes of physical soil parameters in the virgin compression load range can be predicted according to DVWK (1997).

If e.g. the effect of ploughing or of wheeling on top of a weak seedbed or if the wheeling effect in the ploughpan layer on changes in air capacity etc. in the deeper soil horizons are considered as a function of internal strength or stresses applied exceeding the precompression stress value, the following equations can be used:

In Table 4 the values of the empirical parameters depend on grain size distribution, aggregation, pore water pressure etc..

Tab. 4: Changes in air capacity (AC) due to wheeling or plowing in the consecutive soil horizons at given initial soil physical properties

wheeling, topsoil (seedbed): clayey, silty loam (Ut3) at pF 1.8
$a_0 = 53.73$; $a_1 = -23.38$; $b = 7$
plowing, deeper soil horizons: prism, Lt3 (very clayey loam), at pF 1.8
$a_0 = 29.04$; $a_1 = 15.27$; $b = 5$

The precompression stress value as a function of texture, structure and hydraulic properties can be derived according to Lebert (1989), Nissen (1998) and DVWK (1995) by specific equations and can be also applied to derive corresponding strength maps for regions, states or countries. (for more details see: DVWK, 1995; van den Akker, 1997)

Other empirical models to predict tillage effects (e.g. wheeling or ploughing) relate e.g. penetration resistance to soil strength or the pattern of penetration resistance values to stress distribution (Döll, 1989; Lerink, 1994; Canarache, 1990). Watts et al .(1996 a, b) define the vulnerability of soil structure to tillage effects by readily dispersive clay fractions. It has however to be mentioned, that all these regression analysis´ or indirect tests do not consider any physical process which are mentioned. Attempts to relate soil strength to the liquid or plasticity limit (Atterberg) data for various soil properties can only be used as a very rough hint if only substrate dependent properties will be compared. (for more complete informations see Kretschmer, 1997). Structure effects, strain and shear processes, previous shrinkage and virgin drying effects on soil strength are not included nor can they be quantified or differentiated with respect to their impact on changes in soil properties.

Mechanistic models

Mechanistics models always assume that soils are homogenous, isotropic and continuous. Especially if tillage effects with intensive soil disturbances of soil structure throughout the growing period have to be modelled with respect to changes in physical properties (like pore size distribution and derived ecological parameters or mechanical strength). The mathematical calculation procedure can be further distinguished in analytical or finite element approaches.

- Analytical models

Analytical models e.g. for the quantification of stress propagation in soils are relative simple tools to determine the stress distribution under wheel loads.They are based on the assumptions that soils are homogenous, isotropic, semi infinite and ideal elastic.The original definition of texture dependent concentration factors or the many indirect relations between strength and physical properties (see Kezdi 1969) however are only valid for strong pore systems which are never available in A and B horizons of arable or forest soils and even for natural i.e.

undisturbed soils they aren´t to be expected. These idealistic ideas about soil properties are even more unrealistic if due to tillage events a further reduction in mechanical strength is obtained and if throughout the year a particle rearrangement due to swelling and shrinkage occurs. Consequently, disturbance during tillage, wheeling, ploughing or harvesting alters the internal soil strength parameters as well as the concentration factor values which have to be related to specific site conditions and external e.g. machinery conditions. (see also DVWK, 1995). Shear and divergency processes always lead to an additional weakening of the calculated results. Nevertheless analytical models are successful applied to predict soil stresses with „sufficient“ accuracy (Hammel, 1994; Gupta and Raper, 1994; Gupta and Allmaras, 1989; van den Akker, 1994) and can be used to examine the bearing capacity of subsoils (i.e. at depths where a sufficient internal strength is available.)

- Finite element model (FEM)

In Finite element models, which include plastic deformations, the behaviour of soil under stresses is modelled in a better and a more realistic way than in analytical models. Richards (1992) has described in great detail the advantages of finite element modelling of coupled processes in unsaturated and/or swelling soils. Even if Youngs modulus and Poisson´s ratio have to be determined and even if these data are changing continuously throughout the deformation in the virgin compression stress range such models are most useful and their results more reliable than those obtained with analytical models. (Gupta and Raper, 1994; Kirby et al., 1997; Kirby and O´Sullivan, 1997; Kirby, 1994; Gräsle et al., 1996).

- Example to validate the FEM approach

In order to proof the capability of the FEM approach, SST data from a wheeling experiment at a conservation tillage plot (Horsch system = shallow chisellingup to 8 cm, Luvisol derived from glacial till) as well as the above mentioned parameters for 3 soil horizons were taken and the measured stresses and strain compared with those which had be predicted by the FEM technique. (for more detailed information see Kühner, 1997) If only the mechanical parameters of 3 soil horizons are taken at given rut depth and stresses applied, no good agreement could be obtained between the measured and the calculated data with increasing depth.

However, if mechanical data are included in the calculation at a given depth of 20 to 40 cm where in former days (last ploughing had been carried out 8 years ago) plowing had been carried out and where the shear strength and bulk modulus data are different from those of the adjacent soil horizons, than a reasonable good agreement between the measurement and model prediction can be obtained.

Conclusions

The determination of soil strength in order to quantify ecological processes require mechanical and physical methods. The determination of stress/strain behaviour results in precompression stress values as a measure for internal soil strength. Soil deformation after exceeding the precompression stress value is induced by divergency and shear processes but depend on internal as well as external parameters. The quantification and/or the prediction of mechanical properties and processes can be either carried out by empirical regression analysis or by more detailed analytical or deterministic models.

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SOIL TECHNOLOGY STRATEGIES FOR MAIZE PRODUCTION UNDER GRADED FURROW IRRIGATION

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Abstract

To become competitive, Portuguese maize producers under furrow irrigation must maximise the economical profitability of the crop by increasing production and reducing costs, attending to the national and international environment protection constraints.

As a result of a study conducted during 1995-1997 in the Ministry of agriculture Antonio Teixeira Experimental Station (INIA), Portugal, were developed four different soil technologies which include reduced tillage and band application of fertilisers and pesticides that can be the appropriate answers to those requests.

Introduction

Maize is at the moment, the most solid arable crop in Portugal, with about 215 000 hectares being planted every year. The production shows a deficit related to consumption of around 800 000 tons which permits the farmers not to face commercial problems. However, farmers are concerned with the current changes in EU agriculture and GATT policies and strategies for cost reduction, energy saving and environmental protection are starting to be implemented.

Furrow irrigation is the traditional process of applying water to the crop (that in our climate is absolutely necessary), and remains a very important procedure. More recently the introduction of simplified and automated water distribution techniques raised the interest for such irrigation method, allowing the reduction of labour and water and energy consumption.

Despite the previous, furrow irrigation is still limited to fields that can be submitted to precision levelling, only achieved with the use of laser controlled equipment. These include as fields suitable for the application of this irrigation process, the majority of river valleys where in fact is concentrated the greatest part of the commercial maize production, mainly the Tejo and Mondego Valleys, in the south and centre of Portugal.

The objective of this study was the development of integrated mechanisation systems for maize production under furrow irrigation. The three year research program was successfully accomplished by the definition of four different environmental friendly soil technologies which include reduced tillage and band application of fertilisers and pesticides.

Soil cultivation strategies

Conventional maize production systems make use of a mouldboard plough for primary cultivation. Secondary cultivation is performed by means of several disc harrowings, although it is being observed that this operation has the tendency to be replaced by the work of a pto-driven rotary harrow for seedbed final preparation.

In these systems P and K fertiliser and herbicides are broadcasted before final superficial cultivation (seed-bed preparation) followed by flat drilling. All this field operations are therefore isolated in the establishment system. Mouldboard ploughing could remain in the new soil technologies as a way to deal with the farmers conservative attitude, but spring cultivators for high speed work or power driven rotary cultivators combined with simultaneous drilling must be used, after a single passage with a disc harrow, for seedbed preparation.

As alternatives to mouldboard ploughing in which the soil is totally tilled two new technologies based on reduced tillage can be introduced: subsoilling the crop row only and chiselling the row and the middle of the inter-row.

Seedbed preparation can be in both performed by a pto driven rotary cultivator, which has proved to be the best way to deal with residues as refereed by Jorge et al. (1997).

These soil tillage systems must all be equally balanced in terms of work width for soil compaction purposes.

The introduction of reduced tillage techniques can only be well managed if we are able to control soil compaction. An easier way to do that is to develop a proper traffic control strategy, which means that the soil cultivation sets (tractor + implement), must always follow the same tracks (Carmona, 1997).

Under furrow irrigation the ideal situation is to make the coincidence between tractor tracks and furrows. This condition can be reached balancing the width of the implements with inter-row distance.

On reduced tillage techniques the absence of enough moisture for crop emergence must be expected due to dry conditions in the seed zone during spring time. This disadvantage can be overcame throughout a ridge forming operation which should be combined with fertiliser application, allowing furrow irrigation for seedling after bed drilling. For this purpose, the tractor must be fitted with narrow tires to avoid any compaction over the ridges, solution that can be used as well for post drilling herbicide band application..

Procedure

The study was conduced during the 1995 to 1997 irrigation seasons (summer) at the Ministry of Agriculture Antonio Teixeira Experimental Station, located in Coruche (Sorraia Valley), Portugal.

Figure 1. Schematic localisation of the experiment site in Portugal and in the Sorraia Valley.

The soil, a fine textured of low permeability silt loam (Fluvisol) usually flooded during Winter, was described by Sousa (1990).

Treatments were designated (Pires, 1998) as:

C1: L × G × TMR × Se - Mouldboard ploughing (L) followed by a disking (G), a spring cultivator fitted with two "packer" rollers (TMR) and flat drilling.

C2: L × G × (Rt + Se) - Mouldboard ploughing (L) followed by a disking (G), a pto driven rotary cultivator fitted with a packer roller (Rt) and flat simultaneous drilling (Se).

A1: S × Rt × Se - Subsoilling (S) the crop row followed by pto driven rotary cultivator fitted with a packer roller (Rt), ridges forming, and bed drilling (Se).

A2: S × Ch × Se - Chiselling (Ch) the row and the middle of the crop inter-row followed by pto driven rotary cultivator fitted with a packer roller (Rt), ridges forming and bed drilling (Se).

The experimental design was one way completely randomised with fix effects and three replications. Each treatment had 6.0 m × 110 m and contained eight 750 mm spaced crop rows on a 0.1 % grade.

The experimental site was previously stalks shredded and disked for winter weeds control.
In treatments C1 and C2 fertilisers (N, P and K) and herbicides (atrazine + metolachlor) were broadcasted after disking and mixed with the soil by the spring cultivator or the pto driven rotary cultivator. Fertiliser application levels were 50 kg ha^{-1} N; 140 kg ha^{-1} P and K. Herbicides were sprayed at a rate of 1200 g ha^{-1} for atrazine and 1700 g ha^{-1} for metolachlor (Primextra 500 FW).

In treatments A1 and A2 bed (ridge) and furrows were formed with a double mouldboard bedder. Fertilisers were spread in front of each bedder body and moved with the soil to the top of the ridges. With this operation 50 kg ha^{-1} of N and only 100 kg ha^{-1} of P and K were applied.

Herbicides were sprayed after drilling, before seed emergence, in bands over the ridges, which allows an application of only 900 g ha^{-1} of atrazine and 1100 g ha^{1} of metolachlor.
Mouldboard ploughing was performed at a depth of 250 mm to 300 mm, chiselling at about 300 mm and subsoilling at 400 mm.

Irrigation was applied through flexible pipe with slide valves for adjustable orifice size. Individual furrow inflow rates were set at 0.5 L s^{-1} for all the season and in all treatments the total amount of water applied was 360 mm.
The Cone Index values (soil strength) were obtained using a hand operated *Bush* recording electronic penetrometer. The measurements were made on the crop row zone in all treatments of the same replication when plants were at 4 - 5 leaf stage.
In each crop row zone, were recorded 15 points aligned in the middle of the crop row and in two parallel lines 140 mm apart. The crop row zones were located 10 m away from the upstream headland.

In treatments C1 and C2, when plants were in the 5 - 8 leaf stage, the same double mouldboard bedder was used to form the irrigation furrows while 200 kg ha^{-1} of N fertiliser (urea) was being applied to the plant row.

In treatments A1 and A2 the same equipment was used to rebuild plant row ridges and apply the same N fertiliser at the same rate.

For all treatments the same FAO 500 maize hybrid (Pioneer Cecilia) was used.

Grain yield for each treatment was determined by hand harvesting: 6 × 16.7 m row samples and adjusted to 14.5 % moisture content.

Soil cultivation field operations were all performed by the same 4WD tractor at the same engine speed.

Time requirement and fuel consumption were measured by an electronic fuel measurement device - ECONOTEST, installed in the injection engine system.

Results and discussion

Cone Index profiles obtained in the spring 1997, after three years of soil cultivation over the same places, are showed in Figure 2.

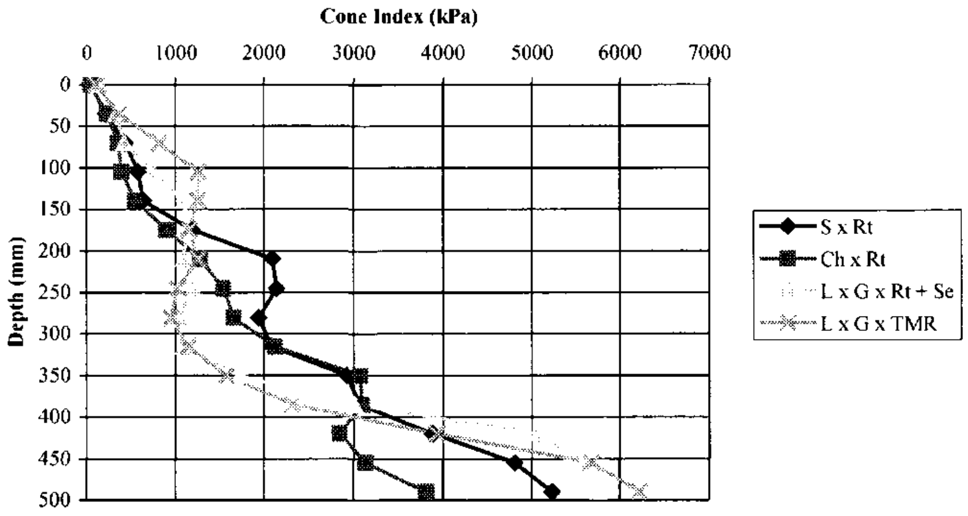

Figure 2. Average Cone Index (soil strength) vs depth in the ridge, for all treatments.

Up to 400 mm depth approximately the zone with the highest root density, it's possible to identify two different soil strength behaviours. In the layer 0-200 mm, corresponding to the height of the ridges, the cone index values are higher in the treatments where a mouldboard plough was used (flat drilling), as it would be expected.

In the layer 200-400 mm, higher strength values (about 1000 kPa more) are observed in the treatments that used the subsoiler and chisel, as expected too.

Grain yields (Table 1) were not however affected by these different soil conditions, which is mainly due to the fundamental role of the irrigation water. If a proper water management is achieved, which is always possible, subsoilling only the crop row zone or chiselling the crop row and the middle of the inter-row zone , are both good soil alternative technologies to the traditional mouldboard ploughing to maize production under graded furrow irrigation. These strategies also allow by the other hand, timely crop establishment and fuel savings as showed in Table 1, reducing soil cultivation costs.

Table 1. Treatment effects on soil preparation time required and fuel consumption for crop establishment, and grain yield.

Treatment	Time ($h\ ha^{-1}$)	Fuel consumption ($L\ ha^{-1}$)	14.5% moist. yield ($t\ ha^{-1}$)
C1: L × G × TMR	3.41	39.88	13.55
C2: L × G × Rt+Se	4.26	61.25	12.98
A1: S × Rt	1.95	33.70	13.71
A2: Ch × Rt	2.09	36.32	13.20

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THE COMPACTIVE ACTION. INITIAL CONDITIONS, MODELLING, AND IMMEDIATE EFFECTS

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Abstract

Research results of the author and related work from MSc students on subsoil compaction have been reviewed. It concerns the various soil conditions that running gear of off-road vehicles can encounter, the soil stresses and strains underneath running gear, and immediate effects of these stresses and strains on the soil. The immediate effects concern soil qualities that are of direct importance to crop production and farming.

Introduction

It is generally accepted that subsoil compaction is mainly caused by the tyres of wheeled vehicles and the undercarriages (tracks) of track-laying vehicles. Most research concerned tyres, but the results for tyres may be applied to tracks. A tyre of a travelling vehicle engages soil with a given, initial, condition. As soon as a soil volume is influenced by a moving tyre, the soil is increasingly loaded and deformed. As the wheel axle is moving ahead and is passing the soil volume, the influencing will start to decrease at a given moment, and will stop when the wheel heads the soil volume a certain distance. Residual stresses may remain after the wheel passage. The soil - wheel interaction as described above, will be referred to as the compactive action. The process of loading and deformation, to which the soil volume is subjected during the compactive action, generally changes the soil properties significantly.Many soil properties change, but attention is focussed to properties that relate to crop growth and farming. The "new“ soil condition that comes into existence immediately after the compactive action may change as time proceeds, due to soil external and internal events, like soil water redistribution, aging etc. Attention is limited to the immediate effects.

Initial conditions

The initial condition of a soil is completely determined by the situation “in micro”, and may be described by its strength-determining or micro-factors (Koolen and Kuipers, 1983). Apart from the shape and type of the solid particles, these are:

Micro-factors:
-number of particles per unit of volume,
-spatial distribution of particles,
-water content as a percentage of total volume,
-water distribution,
-bonds between particles (other than by water potential),
-distribution of these bonds.

The micro-factors vary in the course of time by vehicle-induced compaction, suction equilibration, suction thixotropy, drying, wetting,freezing, thawing, effects of flora and fauna, and tillage effects.

It is very difficult to prepare soil samples for laboratory experiments in such a way that field conditions are sufficiently matched. Three categories of laboratory soil preparation may be distinguished:

Categories of laboratory soil preparation:
-compaction at the moisture content at testing,
-compaction in a rather wet condition, followed by drying,
-compaction at a relatively low moisture content, followed by wetting.

The first method (compaction at the moisture content at testing) is simplest and is followed most frequently. Unfortunately, this method can only simulate a small part of the soil conditions that occur in agricultural practice. A number of preparation methods exist for obtaining puddled samples. Micro-factors depend on soil type. However, in general, strength variations in time are more spectacular than between soil types. Extreme values of strength properties will be more frequent in problem soils, such as blowing sands, weak peat soils, or sticky clay soils. For a farmer, soil type is a given factor which he cannot change, whereas he is able to control his soils strength variations with time to a certain extent.

Soil mechanics models usually do not need microfactors, but macroscopic mechanical properties of the soil. The relation between the mico-factors and the macroscopic properties for unsaturated soils may use the concepts of total stress, pore pressure and effective stress, together with an apparent degree of saturation χ. Klaij (1975) measured χ-values through unconfined compression tests at known water tensions, assuming that cohesion was zero. He also performed uni-axial compression tests on wet, but initially unsaturated, soils. These tests were so quick that water was not expelled out of the soil. During such tests soil water tension may change into a positive pressure. Klaij measured these water pressures, and the total lateral stress. Kimman (1987) measured shear strength and water tension under field conditions in two soils at two depths. He also ran laboratory shear tests at different water tensions under different consolidation and drainage conditions. In addition to the microfactors that are listed above, it might be necessary to consider the soil air pressure (Swinkels, 1982).

Soil stress – strain behaviour at low stress levels, or in a first part of a more severe loading, is usually considered to be elastic. Realistic values of elastic modulus E and Poisson's ratio ν for agricultural soils are hardly available. Barneveld (1994) mentionned the values $E = 2.20$ MPa and $\nu = 0.45$ for wet, dense, clayey soil having an air content of 5%. These values have been derived from triaxial tests of Dawidowski and Koolen (1987). Realistic values of of the lateral earth pressure at rest K_0 are also hardly available for agricultural conditions. Klaij (1975) measured effective K_0 values for 4 different soil types at different loading and water content levels. A classic way to describe plastic behaviour without hardening uses the concepts of cohesion c and angle of internal friction ϕ. Koolen (1977) presented c and ϕ values for a number of soil types at different conditions. Cohesion c at three water tension levels was measured after precompaction at a range of water contents (Koolen, 1978). Middel (1969) studied the loading rate dependency of the cohesion. A simple test to find a loading level at which plastic hardening starts (known as consolidation stress) is the uniaxial compression test. For this test, Dawidowski and Koolen (1994) describe software that can be used to determine a consolidation stress from the measured stress – strain curve. In agriculture, it might be better to call this stress an equivalent precompaction stress instead of a consolidation stress, because agricultural soils are usually unsaturated, and water contents may have changed beween initial compaction and further compaction. Application of the method to samples from a tractor rut showed ageing effects and effect of speed in the uniaxial compression tests. In a pilot study by our laboratory (Koolen and Kuipers, 1989) of fall ploughed loam soil, equivalent precompaction stress was measured in early spring when the ploughed layer was still very wet. The equivalent precompaction stress was found to be 24 kPa at a soil water content of 33.5% by weight. Samples were 50 mm in height and 77mm in width. Standard deviation of the equivalent precompaction stress was found to be 80 kPa.

Plastic behaviour with hardening (soil compaction) may be measured by simple uniaxial compression tests (Koolen, 1974), or by triaxial tests. Using uniaxial compression tests, Koolen (1978) studied the effect of water content at precompaction on the compactibility of soil in further compaction. Soil water tension between precompaction and further compaction was adjusted to pF = 2.7. The effect of the precompaction water content on porosity after further compaction did not fade out by the further compaction. It is generally accepted that plastic hardening in triaxial tests is well-described by the so-called Critical State Soil Mechanics (CSSM). Following the principles of CSSM, a number of soil models are available now. Very wet, clayey, dense soil cannot be compacted, but may be deformed at near-constant volume. This deformation shows, in addition to plasticity, viscous behaviour. For such soils, Wevers (1972) tried to model stress – strain relationships that were measured in unconfined compression tests at different strain rates. Dawidowski and Koolen (1987) performed triaxial tests on very wet, clayey, dense soil at different cel pressures and strain rates, and found that the results could be modelled as a Bingham material. A Bingham material is characterized by a threshold value ξ and a coefficient of viscosity η. Values of ξ and η are given for Wageningen silty clay loam with a porosity of 45%, at initial water tensions of 1 and 3 kPa.

Finding appropriate mechanical properties for practical applications is often difficult. One may prefer the use of measurements like cone index tests (so-called characterization processes (Koolen and Kuipers, 1983)). Combining different characterization processes may increase prediction accuracy. Tijink and Koolen (1985) combined cone test, shear vane test and a test using a falling weight in seeking to improve accuracy of the prediction of tyre rut depth and tyre-induced soil compaction. Combining the cone test and the falling weight test improved prediction accuracy. Combining cone test and shear vane test appeared not to give additional accuracy, because these two tests are highly correlated to each other. Appropriate mechanical properties may also be derived from known values of other mechanical properties, because there is much interdependency between mechanical properties. Koolen and Vaandrager (1984) present a number of relationships, for instance, the relationships among cone measurements at different cone tip angles and base areas. Often, soil profiles are not homogeneous or include non-soil material, for instance, plant roots. Field observations of mechanical properties show spatial variability. Blanken (1987) found a low variation in soil properties when these were measured in a rut, and a large variation when these were measured in vertical planes across ruts. The measured soil properties were: prevailing water content, water content at field capacity, porosity, air permeability, hydraulic conductivity, penetration resistence, tensile strength. The prevailing equivalent precompaction stress ("apparent" consolidation stress) of a soil profile varies with depth. Konijn (Koolen and Kuipers, 1989) took samples at different depths of the 20 – 60 cm layer of a loam soil after potato harvesting and measured the equivalent precompaction stress on the samples at field water contents. The measuring results clearly showed that there was a plough pan, its pore space and air content at time of sampling being 39 – 40% and 6 – 8%, respectively. Vegetation roots may reinforce soil (Koolen, 1996). Liu (1994) presented a few cyclic loading tests on fine beech and larch roots (1 – 5mm ϕ). Elastic as well as plastic strains were observed during each loading cycle. When a test included nonzero dwell times at the force reversal points, during which root length was fixed, root stress appeared to change during the dwell times. This change was a relaxation for the upper reversal points and a strength recovery (stress increase) for the lower reversal points. His root tests showed features of fatigue failure that are known in materials science. Makarova et al. (1998) measured axial stress – strain relationships of fine roots of beech and larch in loading to failure and in cyclic loading. It was observed that water was expelled out of the roots during the tests. Water loss, failure stress, and failure strain depended on root diameter. General curve shapes did not. The results of cyclic loading tests with upper reversal stresses well below estimated failure stress were presented by a Young's modulus of elasticity and incremental plastic strain for each loading cycle. Young's modulus was, relatively, low and incremental plastic strain was, relatively, high for the first loading cycle. The incremental plastic strains in cyclic loading tended to decrease with increasing root diameter. Very little is known about the shear stress that can be developed at the soil – root interface.

Modelling

Modelling the compactive action has resulted in very many models that differ widely. Such models often starts from wheel parameters and properties of the soil profile, and provide the course of soil stresses and strains during the compactive action.

Well-known, simple, wheel parameters are size and shape of the contact area and the mean normal stress in the contact surface, all at zero rut depth. Kurstjens (1993) measured these parameters for a great range of agricultural vehicles at wide ranges of tyre size and tyre inflation pressure. De Brouwer (1995) measured these parameters on three tractors and a trailer that are used in wet nature reserves. Medema (1994) measured the parameters for a range of forestry vehicles using mobile measuring equipment. The soil – tyre interface situation at zero rut depth is mainly determined by wheel load and tyre inflation pressure. Taking into account tyre inflation pressure, the ever-existing shear stresses in the soil – tyre interface, and the tyre carcass stiffness, it may be stated that the level of major principal stress in the soil near the soil – tyre interface equals twice the tyre inflation pressure (Koolen et al., 1992). The situation is more complicated for nonzero rut depths. Prediction of rut depth is known to be very dificult. Combining cone measurements with measurements of the sinkage of a falling weight resulted in prediction improvement (Tijink and Koolen, 1985). It is difficult to replicate soil conditions. As this is a serious drawback in tyre – soil interface experiments, de Jong (1986) tried to find a material that behaves as soil, but can be controlled better. He performed triaxial tests and single-wheel tests on several material. Stress distribution under tyres did not change much when soil was replaced by a polyetherfoam.

Traditionally, modelling includes the assumption of elastic soil behaviour. Kurstjens (1993), using a simple spreadsheet, calculated stresses in the soil profile under tyres for measured, as well as for assumed tyre – soil interface conditions. This study included uneven contact stress distributions and lug effects. Koolen et al. (1992) calculated these stresses for realistic levels of stress near the tyre – soil contact surface, and verified the calculation results for a large range of agricultural vehicles with different tyre sizes and inflation pressures. The calculations applied to zero rut depth, low drawbar pull, deflecting tyres, and "average" tyre carcass stiffnesses. Changes in stress distribution for deviating conditions may be estimated. Hendrison (1990) applied the method to logging operations in forestry.

With the development of the Finite Element Method, a new generation of models is coming available. For this generation, modelling is not limited to simple contact stress conditions, axisymmetric or plane strain, homogeneous soil profiles, and/or elastic soil behaviour. PLAXIS (Finite Element Code for Soil and Rock Plasticity) , which is a Dutch FEM for civil engineering problems, models soil compactibility with a specific set of soil parameters. This set is known as the PLAXIS clay model. This model shows great resemblence with the CSSM model. It needs the following soil parameters.

Parameters of the PLAXIS clay model:

- Young's modulus of elasticity
- Poisson's ratio
- a modified compression index
- a modified swelling index
- preconsolidation stress

- cohesion
- angle of internal friction
- angle of dilatation
- coefficient of lateral earth pressure.

The above set of PLAXIS parameters has not been measured on agricultural soils. The Auburn Compaction model, developed at the National Soil Dynamics Laboratory in Auburn, Al (USA), uses the following parameters.

Auburn Compaction Model:
- 4 parameters (A, B, C, D) that describe the relationship beween bulk density and stress state (octahedral normal stress and octahedral shearing stress)
- initial bulk density
- a plastic flow yield coefficient

The set of parameters of the Auburn Compaction Model has been measured for four agricultural soils by the National Soil Dynamics Laboratory. C.T. Petersen (Section of Soil and Water and Plant Nutrition of the Department of agricultral Sciences of the Royal Veterinary and Agricultural University, Frederiksbeg, Danmark) developed a model with the following parameters.

Petersen Model:
- slope of the normal consolidation line on log – linear plot
- specific volume specified by the normal consolidation line at stress = 1kPa
- slope of projection of the critical state line on log – linear plot on plane of zero deviatoric stress
- critical specific volume specified by critical state line at stress = 1kPa
- slope of the projection of the critical state line on the mean normal stress – deviatoric stress plane
- intercept on deviatoric stress axis of the projection of the critical state line on the mean normal stress – deviatoric stress plane
- slope of swelling line on log – linear plot
- preconsolidation stress

Petersen measured these parameters on many agricultural soils at many conditions of water content and bulk density. A combined effort of the Scottish Centre of Agricultural Engineering and the Department of Agricultural and Environmental Science of the University of Newcastle, both in the United Kingdom, resulted in a soil model with the following parameters.

UK Model:
- slope of the normal consolidation line on log – linear plot
- specific volume specified by the normal consolidation line at stress at 1kPa
- slope of projection of the critical state line on log – linear plot on plane of zero deviatoric stress
- critical specific volume specified by critical state line at stress = 1kPa
- slope of the projection of the critical state line on the mean normal stress – deviatoric stress plane
- slope of swelling line on log – linear plot

These UK Model parameters have been measured on a number of agricultural soils at different water contents. The PLAXIS software is an advanced Finite Element Method, and available at our laboratoty. As measuring the PLAXIS parameters is expensive and time consuming, van den Boogaert and Koolen (1997) developed a computer programme that can estimate the PLAXIS values from parameter sets of the Auburn Compaction Model, the Petersen Model, and the UK model, which are available for agricultural soils at different conditions.

The effects of given field operations on a given piece of land were modelled by recognizing that severely compacting field operations may be divided into spring operations and autumn operations, and that main variables are tyre inflation pressure and soil water content during the compactive action (van Oorschot, 1986). For these variables, the effects of the traffic events were measured on one piece of land with different crops during a period of time, and expressed in so-called Moisture (gravimetric soil water content) – Pressure (tyre inflation pressure) – Volume (soil porosity) diagrams extended with the resulting soil qualities that are listed below.

Extended M-P-V diagram:
- air content at field capacity
- penetration resistence at field capacity
- saturated hydraulic conductivity
- dry strength

Such diagrams provide good insight into the role of tyre inflation pressure and field soil water content.

Stienstra (1976), in an attempt to develop a simple laboratory test that loads soil like a wheel does, reasoned that tractor tyre effect on soil near the tyre is similar to the effect of a uniaxial compression test of 4 bar. This stress is clearly higher than tyre inflation pressure, in order to account for aspects like: tyre carcass stiffness, loading rate differences, shear stresses in the soil – tyre contact surface, differences in minor principal stress levels, soil – cylinder wall friction in the uni-axial compression test. Van der Heide (1977) developed a deformation test with penetrating needles that can be used to deform wet clayey soil in a controlled way. Lerink (1990) developed for the same purpose a test in which a known soil volume in a soil layer is alternately deformed under a downward moving piston and by a downward moving annulus on top of the surroundings of the soil volume. Huibers (1976) measured levels of vibration parameters on the undercarriage of a crawler tractor and designed an experimental set-up that could subject soil samples to the same levels of vibration parameters. Hofstra (1982) subjected samples to cyclic loading and varied time length and soil conditions between subsequent loadings.

Immediate effects

Often, the immediate effect of a compactive action is expressed in terms of soil porosity after unloading and (short term) recovery of porosity. The degree, and mechanism of porosity recovery after compaction is highly dependent on loading parameters and soil condition (Swinkels, 1982). Resilience is primarily caused by spring action of needle-shaped material in the case of peat, and by pressure in isolated soil air bubbles in the case of wet clay. A compactive action not always results in a porosity reduction. Steinbusch (1993) deformed wet dense clay soil in a triaxial cell and equilibrated the deformed samples to given levels of water tension afterwards. He found that such procedure can increase porosity for a range of cell pressures at which triaxial deformation was performed. Huibers (1976) subjected soil samples to vibrations like crawler tractors impose. Uneven stress distribution in the soil – track contact surface seemed to have a larger negative effect on porosity than the vibrations. So-called wet compaction is much more damaging than dry compaction. Dry and wet compaction can be discovered from photograph's (van Oorschot, 1986). Heiner (1994) tested a sensor that may provide a real-time wet compaction detection. M-P-V diagrams, extended with resulting soil qualities are very useful. Koolen (1978) presented such a diagram, extended with the resulting water content at field capacity and the specific ploughing resistence at given water tension levels. Undisturbed samples of a dry compacted, wet, clayey soil were deformed in a triaxial cell at different water tension levels and strain rates to different final strains (Dawidowski and Koolen, 1987). This loading action influenced porosity, hydraulic conductivity, water content at field capacity, air permeability, shrinkage upon drying, and dry stregth. The resistence against deformation was described by a threshold value and a coefficient of viscosity. After spherical markers of steel were placed in a soil volume this soil volume was driven over by a tyre (Tijink et al., 1988). The tyre was suddenly removed from the soil surface when it was above the markers region, and the new positions of the markers were measured. By this procedure, the course in time of the volume changes, principal strains, principal strain directions, and rigid body rotations could be found. In addition, sum of incremental strains of a soil element was determined. It appeared that such sums are much larger than could be expected from the difference between initial and final element shape. Kerckhaert and Medema (1992) measured the effect of reinforcement by tree roots on the stress diminution with depth below tyres. The effect can be large, but decreases with number of passes when the tyre pass is repeated. The reinforcement effect may have disappeared after 3-5 passes, due to root failure, permanent root elongation, and reallocation of soil near roots. Biopores and –canals may be destroyed by compactive actions. This was found in laboratory experiments (de Groen,1988) and in strain field calculations (Barneveld, 1991). Compactive actions change the soil water content – soil water tension relationship (Raats, 1960; Horstink, 1985; Blanken, 1987), and the coefficient of oxygen diffusion (Steinbusch, 1993). When a compactive action changes the coefficient of oxygen diffusion, the oxygen regime of the soil profile will change. The simulation programme OX-SI has been written, which can calculate steady state oxygen concentrations in the soil air from vehicle-induced changes in the coefficient of oxygen diffusion and from the oxygen consumption by vegetation roots and the soil itself (Stol and Koolen, 1997). Measuring coefficient of oxygen diffusion is time consuming and expensive. Alternatively, this quantity may be derived from air permeability tests (Steinbusch, 1993). Soil penetration resistence that has to be overcome by roots will also change by a compaction action. A measure for this is the soil cone index. Changes of cone index due to loading actions has been measured by Schoenmakers (1984) and, in the laboratory, by Blanken (1987). Cone index is also a measure of wheel slip percentage. Blanken (1987) studied soil shrinkability as affected by compactive actions. Damian (1983) studied the reaction of soil aggregates upon a static two bar load. The following properties were taken into consideration: porosity, soil water tension, plasic deformation creep, collapse, aggregate stability. Compactive actions may be repeated several times. The time intervals between successive actions may differ, and drying/wetting cycles may occur in such intervals. The effect of interval length and drying/wetting cycles between compactive actions has been studied by Hofstra (1982) and Koolen (1976) under laboratory conditions.

Conclusion

The paper reviews a small part of the studies on modelling compactive actions, on soil conditions that such actions encounter, and on immediate effects of such actions. If all studies that are known are considered, it must be concluded that our knowledge on these subjects is still fragmentary, and needs to be extended.

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HOW TO INVESTIGATE THE MUTUAL INFLUENCE OF SOIL ANIMALS AND SOIL COMPACTION

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Abstract

Soil compaction is a problem of modern agriculture with many aspects. The damage of the pore system by the compaction process affects soil animals strongly. The variety of soil animal taxa, the differences in their biology, and the different scales on which the micro-, meso-, macro- and megafauna is acting require a lot of methods to evaluate the mutual influence between soil and fauna. This paper gives a review about the methods we used in our investigations.

Introduction

Today arable land is endangered by increasing loads of heavy machinery which can cause soil compaction in topsoil and subsoil. Under wet conditions even comparatively small axle loads of 2.5 tonnes can result in compactions which damage the pore space of the soil in a way the most faunal elements will suffer from. Under bad conditions micro- and mesofauna loose their habitat, air or water filled pores, nearly completely, or the pore continuity is interrupted. The members of the macrofauna which are able to produce their own burrow = macropore system, my be smashed during the compaction process, or they need much more energy to do their work. Having in mind that the soil fauna plays an important role in the soil ecosystem, this ability can be diminished strongly and may cause effects e.g. for the remineralization process.

During the last years the problem of soil compaction has become evident (Ehlers, 1975, Fenner, 1995, Oades, 1993) and different projects in Germany and elsewhere started to estimate the way and amount which is harmful to the soil fauna. On the other hand research focused on the contribution of the fauna to the regeneration of compacted soil. This kind of research needs a cooperation with soil scientists, farmers, engineers of agricultural implements etc. We had the possibility to join two cooperative projects. Within these projects we were able to work on different taxa of soil animals, including micro-, meso-, and macrofauna, and their relation to soil compaction for nearly 10 years. Results were published about Collembola and Acari (Heisler, 1993, 1994 a,b,c, Kracht, Schrader, 1997, Schrader, Lingnau, 1997, Sommer et al., 1996), Enchytraeidae (Langmaack et al., 1996, Lübben, 1993, Röhrig et al., 1998, Schrader et al., 1997), and Lumbricidae (Joschko, 1988, Langmaack et al., 1996, Langmaack et al., 1998, Larink et al., 1998, Söchtig, 1992). Papers dealing with different taxa are Larink et al. (1994, 1995) and Larink et al. (1997). Additional papers are mentioned in the tables and below.

In many projects and papers earthworms are in the center of interest. According to Lavelle (1994) they are described as bioengineers. They change soil structure in different way: forming macropores by building their burrows and producing casts, which are aggregates with special properties (Hindell et al., 1994, Hindell et al., 1997, Marinissen, Dexter, 1990, Shipitalo, Protz, 1988, 1989). Both attributes are important for the regeneration of compaction (Larink et al., 1998, Schrader et al., 1995).

Methods

This paper deals with the different methods we used in our research. To measure the influence of soil compaction on soil animals and the reaction of soil animals on the soil a lot of methods are necessary. They can be divided into the following groups which can be used in field and laboratory experiments:

1. physical and chemical methods to measure soil properties (tab. 1)
2. methods to evaluate biological properties
    2a. methods to determine the abundances and distribution of different soil animal taxa (tab. 2)
    2b. methods concerning the importance and properties of earthworm cast. They are partly the same as under 1 (tab. 3)
    2c. methods to describe the special features of earthworm burrows, including those for a visualization (tab. 4)
    2d. methods to indicate biological interactions, e.g. with microorganisms, ecosystemic parameters like soil biological activity or morphological changes on the soil surface (tab. 5)

Methods to determine the soil physical properties (tab. 1) will not be mentioned here, because other papers will do this intensively, and for the same reason methods of standard procedures for chemical soil analysis is not given here. The activity of different soil enzymes like dehydrogenase, acidic and alkalic phosphatase, nitrogenase etc. was measured according to Alef (1991) and Schinner et al. (1993).

Table 1: List of parameters, measured in experiments with soil animals, concerning soil properties.

		field exper.	**lab. exper.**	**literature**
soil properties				
	bulk density	+	+	10, 21, 32
	soil moisture	+	+	10, 15,32,
	saturated hydraulic cond.		+	10, 32
	pore volume	+	+	10, 20, 21, 32, 33
	tensile strength	+	+	3
	water stable aggregation	+	+	9, 23
	triaxial pressure	+	+	32
	SEM-micrographs	+		23
	nitrogen	+	+	29
	carbon	+	+	29
	enzyme activity		+	29
	polysaccharids		+	29

By micrographs the SEM gives impressions about the micromorphological structure of soil aggregates in different magnifications. Examples are given by Larink et al. (1998). By special equipment it is possible to produce soil compactions by pressure in all three axes (Günther, 1991). The main aim to use it was to observe changes of earthworm burrows after high pressure under different moisture conditions (Söchtig. 1992).

The next part of experiments concerns biological properties (tab. 2-5). They can be estimated by various reactions of soil animals on soil compaction. A primary step is to determine the number of taxa, individuals, and their distribution in the investigated plots which often show clear effects. But to find out the reasons for these effects the determination of further parameters is necessary. Because of the strong mutual influence especially earthworms are in the center of interest. Their cast aggregates can be handled with the same methods than soil aggregates which are just mentioned. The earthworm burrow system needs partly the same, and partly special biology orientated methods, e.g. to realize their importance for other organisms. But the compaction also changes the whole soil ecosystem. This can be quantified when measuring the biological activity, including the microorganisms.

Table 2: Parameters concerning biological properties: abundances of soil animals and theit spatial and vertical distribution.

		field exper.	lab. exper.	literature
Biological properties				
Abundances of **animal taxa**				
	Nematoda	+		in prep.
	Collembola	+	+	4, 5, 6, 17, 20, 21, 22, 28
	Acari	+		4, 5, 6, 7, 20, 21, 22, 28
	Enchytraeidae	+	+	18, 20, 21, 22, 24, 25, 38
	Lumbricidae	+	+	18, 20, 21. 22, 32, 33
Spatial distribution using **geostatistics**				
	Collembola	+		34
	Enchytraeidae	+		in prep.
Vertical distribution				
	Collembola	+		4, 5, 17, 28
	Acari	+		4, 5, 17, 28
	Enchytraeidae	+		18, 25, 37

To determine the abundance of soil animals taxon specific methods are necessary (tab. 2). They rely on the size of the animals and their biology. A lot of different methods are described e.g. by Dunger and Fiedler(1989). The Nematode extraction follows s'Jacob and van Bezooijen (1987). For the extraction of the microarthropods we use a modified MacFadyen apparatus (MacFadyen, 1962, modification described by Larink, 1997). In a gradient of temperature and decreasing moisture Collembola and Acari follow this gradient actively and fall into a jar containing preservation fluid. The method was used by Heisler (1994 a-c), Kracht and Schrader (1997) etc. Enchytraeidae are also actively extracted, modifying the advices of Graefe (1984). To sample earthworms the electrical method according to Thielemann (1986), or simple hand sorting, or a comination of both was used (Langmaack et al., 1996).

The distribution of soil animals in horizontal and especially vertical direction is (among others) strongly influenced by pore volume and pore continuity. This can be recorded by taking samples along transects or in a net-like design for the horizontal distribution and by dividing soil cores in several (vertical) parts (Heisler, 1993, Langmaack et al., 1996, Röhrig et al., 1998, Schrader, Lingnau, 1997, Sommer et al., 1996). Including further parameters, e.g. soil moisture, carbon content etc. correlations can be drawn using geostatistical methods (Joschko, Pacholski, 1997, Sommer et al., 1996).

Earthworms change the soil environment by producing big amounts of cast, as described already by Darwin (1881). The amount is species specific (Larink et al., 1998), but also influenced by soil texture, the ingested plant debris and of course by bulk density (tab. 3). The combination of these factors is described by Flegel et al. (1998). Joschko (1988), Kelm and Schrader (1995), and Schrader and Zhang (1997). The exact amount of cast can be determined only in the laboratory, using the cuvette techniques (Kelm, Schrader, 1995). But from these data it is possible to estimate the amount in the field per year (Larink et al., 1998, Schrader et al., 1995).

Table 3: Parameters concerning biological properties: earthworm cast.

		field exper.	**lab. exper.**	**literature**
Experiments about **earthworm cast**				
	reaction on soil compact.	+	+	10
	reaction on soil texture		+	10, 15, 29
	reaction on food plants		+	3
Properties of **earthworm cast**				
	bulk density		+	10, 11, 21
	aggregate porosity dry		+	23
	aggregate porosity moist swelling		+	23
	value		+	23
	water stable aggregation		+	3, 21, 23, 29, 30, 38
	tensile strength		+	3, 29, 30, 38
	SEM-micrographs		+	23
	nitrogen		+	3, 29, 38
	carbon		+	3, 29, 38
	polysaccharides		+	38

To measure the burrowing activity of earthworms laboratory experiments were designed (tab. 4), using undisturbed soil cores (monolithes) of different size which were taken in the field. After defaunation using a microwave oven different species were introduced in the laboratory to measure the burrowing activity of erthworms (Langmaack et al., 1998), and also the action of Enchytraeids and Collembola (Schrader et al., 1997). In contrary cylindrical holes in the field were lined with gauze and refilled with soil to different bulk densities, and earthworms could be active under natural conditions (Söchtig, 1992).

The morphological changes in such columns can be observed and quantified (tab. 4) using destructive methods (Wendt, Larink, 1990). More convenient are non-destructive methods using X-ray computed tomography (e.g. Joschko et al., 1991, Langmaack et al., 1998) which can be quantified easily to get values about burrow length, volume, continuity, and it is also possible to look at the whole system from either direction using 3D-animation. The above mentioned simple cuvette technique gives only a 2D-impression, but it is very useful in a lot of experiments (Flegel et al., 1998, Kelm, Schrader 1995, Schrader, Joschko, 1991). In the field it is possible to count the numbers of earthworm burrows on different horizontal planes (Poier, Richter, 1995). By this the differences between top soil and subsoil become obvious (Söchtig, 1992). This author was also able to determine the cast layer of old earthworm burrows in the subsoil to an age of about 20-30 years, using a modified ^{14}C-method (Söchtig, 1992).

Earthworms are able to live in compacted soil. Under this condition they partly change their behaviour. Especially endogeic species deposit there cast under these conditions on the soil surface. The amount of cast is higher, because they are not able to press the soil aside, as they mainly do and the ingestion of soil increases. The question is: how strong is an earthworm ?

Table 4: Parameters concerning biological properties: earthworm burrows.

		field exper.	lab. exper.	Literature
Properties of **earthworm burrows**				
	age	+		32
	length		+	10, 11, 19, 20, 21, 30, 32
	volume		+	10, 11, 19, 32
	continuity		+	19, 30
	satur. hydraulic cond.		+	10, 11, 14, 30
	unsatur. hydraulic cond.		+	27, 30
	biological interactions		+	37
Visualization of burrow systems				
	X-ray computed tomogr.	+	+	10, 12, 13, 19, 20, 32
	cuvette technique		+	10, 15, 26
	column sectioning		+	35
amount of **earthworm burrows**				
	in topsoil	+		32
	in subsoil	+		32

There are only a few data available from literature (McKenzie, Dexter, 1988 a,b). We therefore developed a new method to measure the radial and axial forces of different ecotypes and species of earthworms (Keudel et al., 1996) (tab. 5).

Because the pore space is reduced in compacted soil, animals are partly more active on the soil surface. This can be measured in the laboratory, because earthworms, and also the mesofauna, changes the surface relief by feeding activity and production of faeces. These changes of the soil relief can be quantified using a laser relief meter, a method without touching the surface (Helming et al., 1993). In small soil columns or also bigger arenas the surface is scanned at the begin and the end of the experiment, the changing relief is quantified and different coefficients characterizing the roughness can be calculated (Heisler et al., 1996, Schrader et al., 1997).

Table 5: Parameters concerning different biological properties: earthworm forces, influence on the soil surface, biological activity and interactions with microorganisms.

		field exper.	lab. exper.	literature
Measuring of **earthworm forces**				
	radial pressure		+	16
	axial pressure		+	16
Changes of the **surface relief**				
	Enchytraeids		+	9, 21, 31
	Collembola		+	9, 21, 31
	Lumbricidae		+	21
Measuring **biologial activity** in soils				
	bait lamina test	+	(+)	1, 7
	minicontainer test	+		2
	litter-bag test	+		6, 20
Soil animals and **microorganisms**				
	microbial biomass	+		8
	microbial activity		+	in prep.

Further biological parameters can be obtained including microorganism activity (tab. 5). It can be determined as chang in microbial biomass (Andersen, Domsch, 1978, Heisler, 1994b, Heisler et al., 1995, Kaiser et al., 1991). Beside this the changes in enzyme activity can be measured.

Functional aspects of the soil ecosystem can be evaluated using the well known litter-bag test, developed by Seastedt (1984) (Heisler, 1994b), and also using a modification , the minicontainer (Eisenbeis, 1994), Both methods measure the decomposition rate of organic matter (Dittmer, Schrader, 1997). Another possibility to estimate the feeding activity of soil oganisms is the bait-lamina-test (Larink, 1994, von Törne, 1990). The method gave good results on differently compacted plots (Bayer, Schrader, 1997).

Conclusions

Besides many methods of soil physics, soil chemistry, and soil morphology research on soil animals in correlation to soil compaction needs a lot of special methods to describe the necessary biological properties. This review gives a survey about the methods we used. Some of them are standard, some were adapted to special questions, and some were newly developed.

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SOIL COMPACTION IN POLAND: ASSESSMENTS AND EFFECTS

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Abstract

In Poland, due to the recent increase in field traffic, soil compaction has become one of the major factors affecting crop production. Methods for measuring the field traffic intensity and stress distribution in topsoil and subsoil are presented. Soil compaction is shown to result in changes in soil properties which control plant growth and some components of the environment. The influence of subsoil compaction and deep loosening on crop response in relation to soil texture and weather is discussed. The beneficial effect of mechanical deep loosening is often transient and economically not justified. Some experimental evidence indicates the favourable effect of the undisturbed subsoil in sandy soils on crop yield in dry seasons.

1. Introduction

Increasing intensity of use of agricultural land with increasing vehicular traffic are major factors causing soil compaction in Poland. The mass of tractors used varies from 3 to 6 Mg and the mass of combine harvesters from 5 to 11 Mg. Commonly used wheel tractors exert ground contact pressure from 120 to 210 kPa, and the ground pressure of combine harvesters and fertilizer distributors exceeds 300 kPa. In highly mechanised farms the soil surface is covered by wheel tracks up to 2.5 times in the case of cereals and 5 times in the case of root crops (Domżał and Hodara, 1990; Walczyk, 1995; Kozicz, 1996). With root crops, almost half of the compaction occurs during harvesting in automn when the soils are usually wet and very susceptible to compaction. Then compaction by heavy trailors with harvested potato tubers or sugar beets penetrates into the subsoil. The depth of stress penetration depends on soil type and water status.

On coarse-textured soils, which occupy more than 50 % of the arable land, the compactive effect can be frequently enhanced by a wet soil in the subsurface layer while the surface layer is workable. In addition, the compactive effect of the vibration forces of agricultural vehicles can be greater in coarse-than fine-textured soils owing to the lower damping capacity of coarse-textured soils.

Compaction may be also caused by natural factors such as rainfall impact, soaking and internal water suction. The presence of silica, oxides or salts of iron and aluminum may increase the soil hardness. Hard layers in the subsoil are mostly ploughpans (approximately at 25 cm) and fine-textured B-horizons which can seriously restrict drainage and root penetration..

This paper deals with the methods available for assessment of topsoil and subsoil compaction and experimental evidence on the compaction effects on plant growth factors, crop production and some components of the environment in Poland.

2. Methods for soil compaction assessment

Walczyk (1995) gives account of how the number and distribution of vehicular traffic over the field, proportions of the compacted area, overall area of wheel tracks, traffic intensity, as wel as exerted ground contact pressure can be quantified in various tillage technologies. The ground contact pressures were calculated with consideration of the loading tractor wheels by attached machines. A computer database of the above parameters for tillage technologies of 8 agricultural crops was created. The data indicate the possible changes in the technologies toward reducing soil compaction and improving efficiency of agricultural machinery.

The method to measure vertical and elastic soil deformations under the wheel is described by Okhitin et al.(1991). In the method the sensors consisting of two parallel plates which are inserted into the soil profile. The method allows sensor positionning without violation of soil structure and remote measurement of soil layer deformation at depth from 0.1 to 1.2 m with an accuracy of 0.1 mm per 100 mm layer.

Tarkiewicz et al.(1997) described how distribution and changes of the stresses and strains can be measured simultaneously. They used a system consisting of piezoresistive pressure transducers, CCD camera, laser, optical fibres and a computer (Fig. 1). During wheeling, the data of positioning of the minisensors in the plough and subsoil layers (by recording lighting point movement) and stress changes are collected.

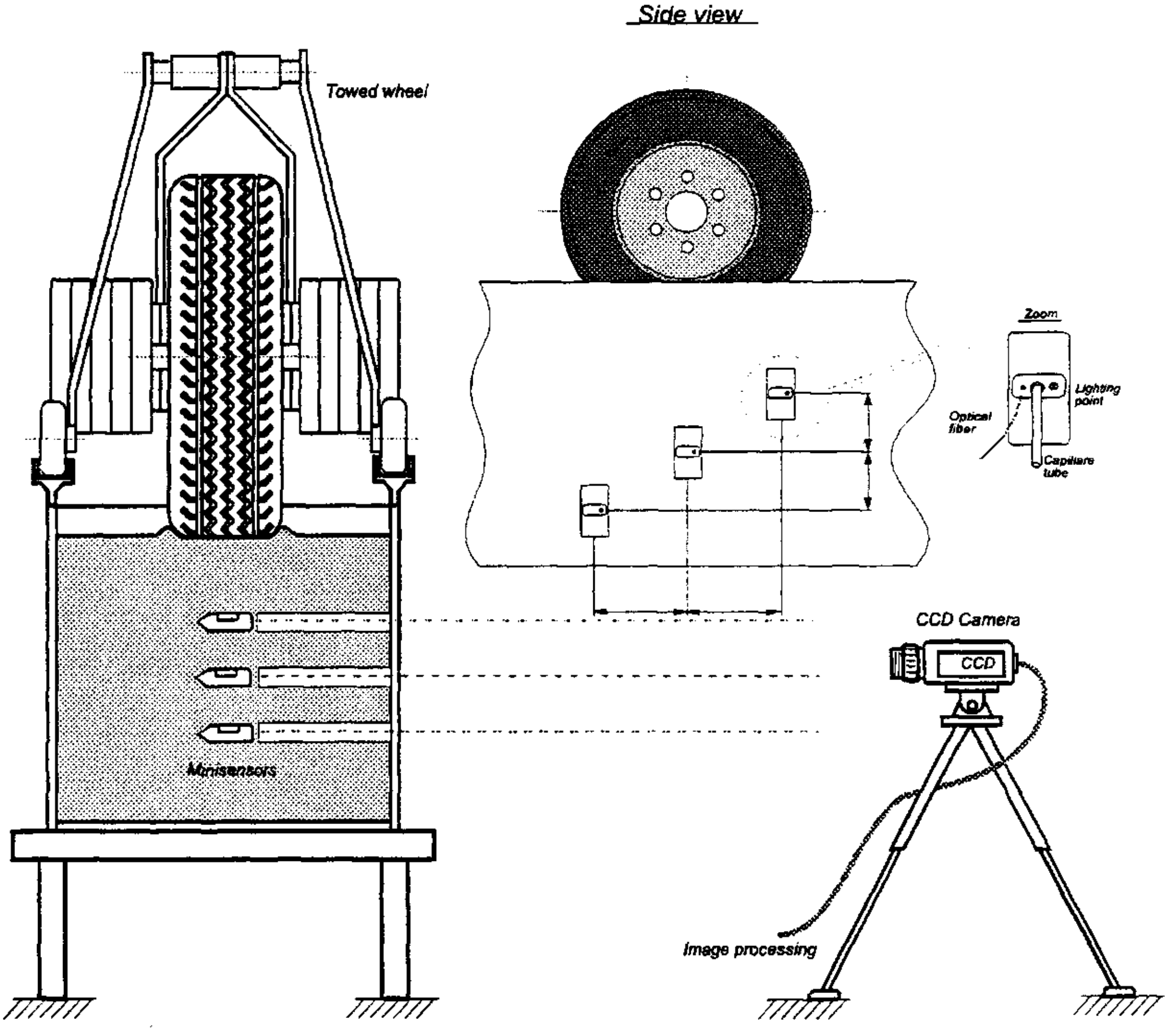

Fig. 1. Measuring system of stresses and strains under the wheel (After Tarkiewicz et al., 1997).

To measure components of the stress tensor and soil deformation at the same time, Pytka (1997) proposed the use of a triaxial head and the similar optical system as in the above method were used. From the course of the stress tensor components obtained, the course of mean stress (MNS) is determined. It was hipothetically assummed that deformation magnitude of the medium is dependent on the MNS. The final deformation is calculated as the difference between the rut depth and soil displacement that was determined using the optical system.

The above methods are useful for measurements of stress and strain distribution in soil profile depending on the number of wheel passes, forward speed, axle load, type of tyres, inflation pressure and vibration of agricultural vehicles.

3. Experiments and measured properties

Most experiments aimed to study the effects of compaction induced by vehicular traffic and deep loosening on soil physical properties and crop response (Table 1). Small-grained cereals and root crops were main crops used in the experiments. Usually duration of the field experiments varied from 2 to 5 years. Soil response was most frequently characterized by bulk density and penetration resistance and crop response - by crop yield.

Table 1. Number of experiments in 1970-1997 with measured properties.

Soil and crop properties	Experiments on	
	Compaction	Deep loosening
Bulk density	21	12
Penetration resistance	12	6
Saturated hydr. cond.	3	1
Unsaturated hydr. cond.	2	-
Water retention	5	3
Air permeability	3	1
Air diffusivity	4	1
Temperature	3	-
Crop yield	11	10
LAI	2	-
Stomatal resistance	2	-
Root depth	4	3
Root density	3	3
Nutrient uptake	3	1
Root/shoot ratio	2	2

4. Response of soil properties to compaction

The effect of vehicular traffic on soil compaction and resulting soil properties is greatly influenced by soil water status. This effect is illustrated by increasing degree of compactness of silty loam with increasing matric water potential at wheeling (Fig. 2). The degree of compactness is defined as the dry bulk density of a soil in percent of a reference bulk density obtained by a standarized uniaxial compression test at a stress of 200 kPa (Håkansson, 1990).

Macro- and micromorphological studies revealed that soil compaction result in destruction of aggregated fragment structure leading to reduction of voids in size and changed shape and spatial distribution (Domżał et al., 1991; Słowińska-Jurkiewicz and Domżał, 1991; Lipiec et al., 1998). The changes influence numerous soil properties, including strength and aeration factors which are usually identified as the most decisive plant growth factors in overcompacted soil. It was shown that the range of matric water potentials in which the critical penetration resistance (3 MPa) and the critical air-filled porosity (10 %v/v) for root growth becomes narrower as the degree of compactness increases (Lipiec et al., 1991). Similar response was observed when ODR (oxygen diffusion rate) was used to characterize soil aeration (Stępniewski, 1980; Czyż and Tomaszewska, 1993).

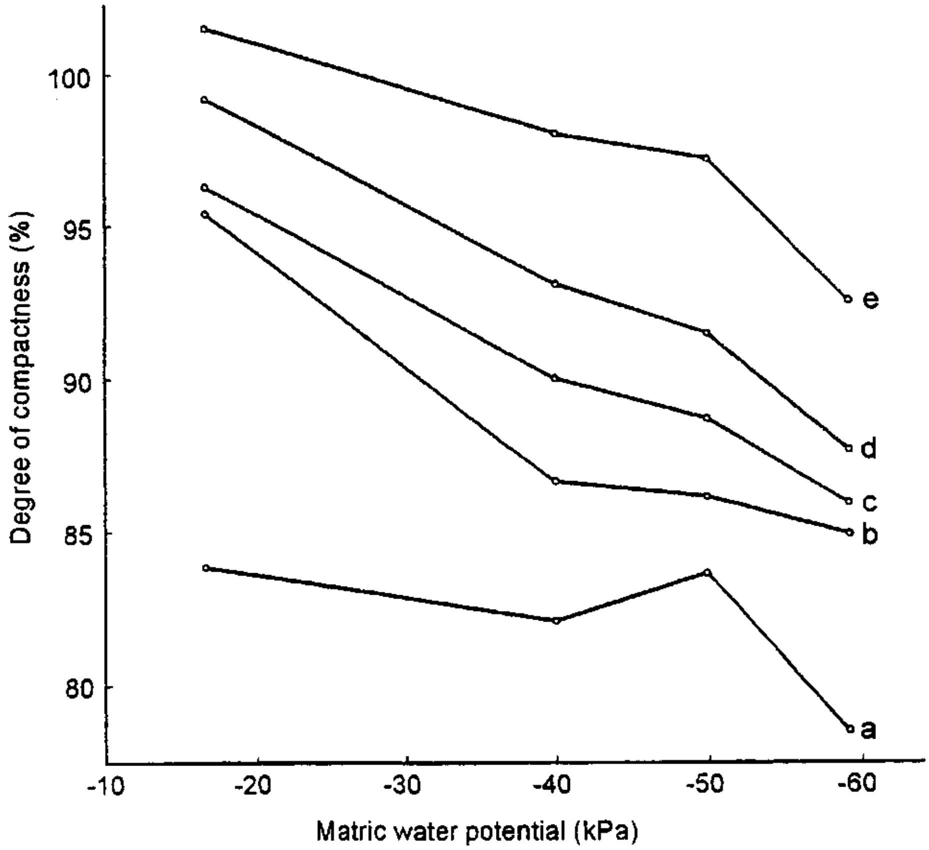

Fig. 2. The degree of compactness in the plough layer of silty loam related to the matric water potential at wheeling (a) unwheeled; (b) one pass of 2.7 Mg tractor, rear axle load 17.0 kN, inflation pressure 60 kPa; (c) one pass of 4.8 Mg tractor, rear axle load 31.8 kN; (d) three passes as in c; (e) eight passes as in c (After Lipiec et al., 1991).

The critical bulk density and critical soil strength for root growth and their relation with other soil factors differ in plough layer and subsoil. Laboratory experiments (Pabin eta al. (1998) showed that for soil materials from the plough layer with 11% of fraction <60 μm content, the root-restricting bulk density for pea seedlings varied from 1.55 Mg m^{-3} at 30% field water capacity (FWC) to 1.77 Mg m^{-3} at 60% of FWC (Fig. 3a). When percentage of the fraction increased to 49% the critical values decreased at a similar rate at all water contents. In the subsoil (Fig. 3c) in which the effect of organic carbon did not occur, the relation between critical bulk density and percentage of fraction <60 μm was much more pronounced than in plough layers. This is shown by a similar reduction in the critical bulk density at lower content of fraction <60 μm that is from 14 to 29%. The same direction of the dependence was found for critical soil strength in the subsoil (Fig. 3d). In the case of soil strength, however, the relation was negative in the subsoil (Fig. 3d) and positive in the plough layer (Fig. 3b). The positive relationship was associated with the favourable effect of organic carbon content on root growth. Comparison of Figs. 3b and 3d suggests that vhe potential risk of inhibiting root growth in plough layer occurs at a lower soil strength in soils with a lower percentage of fraction <60 μm and in the sub-soil in soils with a greater percentage of the fraction.

Kozicz (1996) reported that penetration resistance of the subsoil was more than twice greater than that in plough layer which was compacted at harvesting and ten times greater than in plough layer prepared for sowing. In another study (Lipiec and Usowicz, 1997) geostatistical analysis showed that the semivariance of penetration resistance as expressed by nugget and sill values was greater in plough than subsoil layer. In the layer 0.9-1.1 m i.e. below the depth of compactive stress, the dry bulk density was linearly correlated with a ratio of 0.5-0.1 mm and <0.002 mm particles (r = 0.901) (Wojtasik, 1996). The correlation with the content of single fractions was weaker.

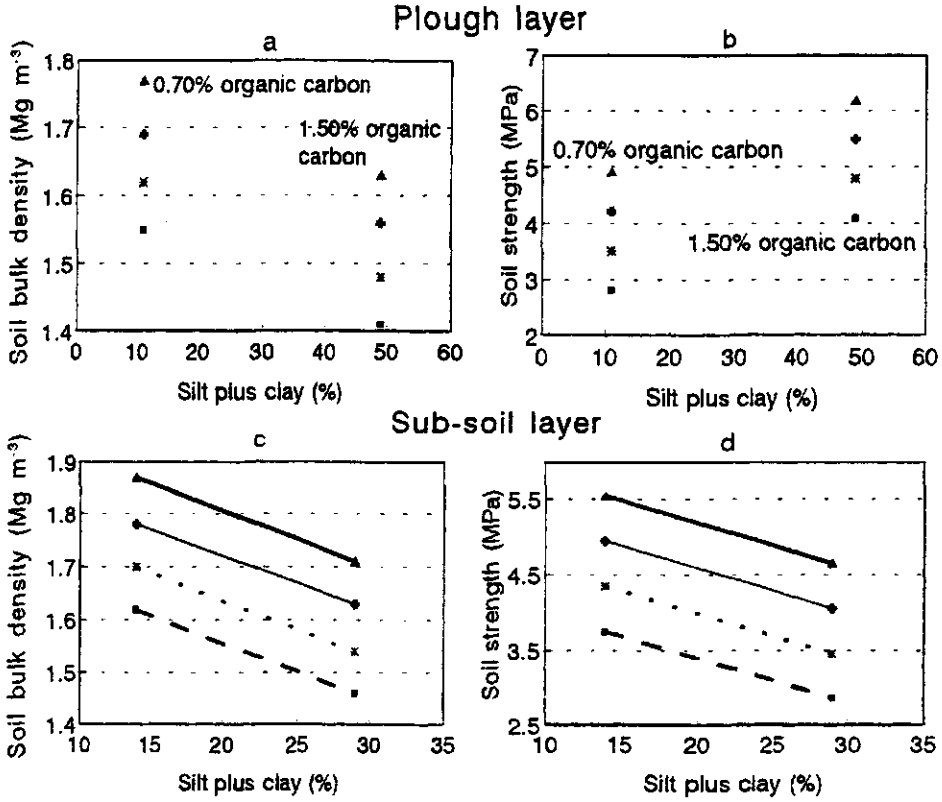

Fig. 3. Critical soil bulk density and strength for root growth in relation to silt plus clay content, and water status: ■ - 30; * - 40; + - 50; ▲ - 60% of field capacity (After Pabin et al., 1998)

In the experiment with infiltration of methylene blue solution (Lipiec et al., 1998) increasing soil compactness induced by vehicular traffic reduced both total volume of macropores (>30 μm) and the volume of stained pores (= macropores that actively contributed to the water flow). The latter was relatively more affected by soil compaction than the former. A greater reduction in stained area and number of stained pores with increasing traffic intensity occurred in the plough layer than in the subsoil. The differences in pore structure patterns caused by soil compaction were reflected in the values of two-dimensional fractal dimension which decreased with increasing soil compactness. The authors observed similar trend of fractal dimension values with depth (to 44 cm) for water conducting pores and roots which indicates the occurrence of the relationship between distribution patterns of pores and roots. Irrespective of the level of soil compaction the stained area in the subsoil was mainly due to tubular earthworm channels. Structure of the vertical channels and their functions can be an effective measure of subsoil 'quality' as they are resistant to vertical compression.

Increasing soil compaction level resulted in lower water content at high matric potentials range (pF 0-2.0) and somewhat greater at pF 3.4-4.2 (Walczak 1977, Domżał, 1983; Miatkowski and Cieśliński, 1996) and lower hydraulic conductivity (Dechnik et al., 1982; Dawidowski and Koolen, 1987).

The effect of compaction was also reflected in lower rate of warming and cooling, the daily temperature fluctuations and the values of the noon temperature in the topsoil (0-8 cm) (Lipiec et al., 1991). In deeper soil, however, a higher temperature was noted in compacted soil. To calculate heat capacity, thermal conductivity and thermal diffusivity using soil bulk density, particle density, organic matter content and mineral composition, the statistical-physical model has been proposed by Usowicz (1993). This model was useful to show that the values of the thermal properties were greater in compacted than uncompacted soil (Usowicz et al., 1995). This effect was more pronounced in wetter soil.

5. Crop response to compaction

5.1. Roots, crop emergence and establishment

A common response of root system to increasing bulk density is a decreased root length (Cieśliński et al., 1994) and shallower rooting depth (Gliński and Lipiec, 1990; Lipiec et al., 1991). The roots of spring barley in severely compacted soil were characterized by a higher degree of flattening, tortuous growth, distorted epidermal cells and radially enlarged cortex cells (Lipiec et al, 1991). The root response to soil compaction depends to a high degree on the pore size distribution, especially of pores having a diameter greater than that of the roots, and on pore continuity (Gliński and Lipiec, 1990; Lipiec et al., 1998).

Pabin and Sienkiewicz (1984) reported that the negative effect of soil compaction on the emergence of sugar beet (*Beta vulgaris* L.) in moist soil increased with increasing sowing depth from 2 to 4 cm. The emergence of oats (*Avena sativa* L.) was relatively less affected by soil compaction than the number of ears and the yield (Droese et al, 1983). The plant population of spring barley (*Hordeum vulgare* L.) on silty loam at bulk densities of 1.35 and 1.58 Mg m^{-3} was lower than the sowing density by 17.6 and 20.8%, respectively (Lipiec et al., 1991).

5.2. Crop yield

In most experiments the final crop yield was the main indicator of crop response to soil compaction (Lipiec and Simota, 1994). The yield response to soil compaction of small-grained cereals such as barley, wheat, rye and oats in a wide range of bulk densities was frequently parabolic (Droese et al., 1982; Śmierzchalski et al., 1984; Pabin and Włodek, 1986; Lipiec et al., 1991). In other experiments with a narrower range of traffic intensities, the yield response was positive, negative or no response was observed (Sienkiewicz et al., 1988; Kęsik, 1990; 1991; Czyż and Tomaszewska, 1993). The negative yield response of carrot (*Daucus carota* L.) to compaction was accompanied by increasing proportion of small roots (shorter than 100 mm and smaller than 25 mm in diameter) and forked roots, as well as dry matter content, increased (Kęsik, 1990; 1991). The marketable yield of potatoes (tubers >35 mm) compared to gross yield, was reduced by 37-81%, depending on the compaction level (rolling before planting) (Starczewski et al., 1984).

The study of Pabin (1995) performed under the same site conditions showed that the small-grained cereals were less sensitive to soil compaction than the legume field peas (*Pisum sativum* L.) and sugar beet. Significant reduction in sugar beet root yields occurred when bulk density of heavy medium sand in the 0-60-cm layer increased to >1.70 Mg m^{-3}, with a simultaneous increase in 0-30-cm layer to >1.64 Mg m^{-3} (Pabin et al., 1991).

The yield decrease in overcompacted soil is frequently attributed to excessive mechanical impedance (Pabin and Sienkiewicz, 1984: Pabin and Włodek, 1986; Lipiec et al., 1991; Pabin,

1995) or insufficient aeration (Czyż and Tomaszewska, 1993; Sołtysik, 1997) depending on weather conditions and crop type.

5.3. *Effect of weather conditions and soil type*

The main climatic factor which can modify the crop response to vehicular traffic is rainfall through changes in soil water content. This effect depends on soil type.

Compaction of dry sandy soil after sowing of spring barley and spring wheat improved upward movement of water and resulted in greater yield by 2 and 18%, respectively (Dzienia and Sosnowski, 1989). However, interactive effect of decreasing sowing-shooting rainfalls and increasing degree of compactness of plough layer led to significant yield reduction on silty loam (Fig. 4) and shallower rooting depth (Kossowski et al., 1991). Similar responses were observed for winter oil seed rape (Śmierzchalski et al., 1988). The negative effect in dry periods with spring barley was more pronounced on loamy sand than on silty loam (Lipiec et al., 1991).

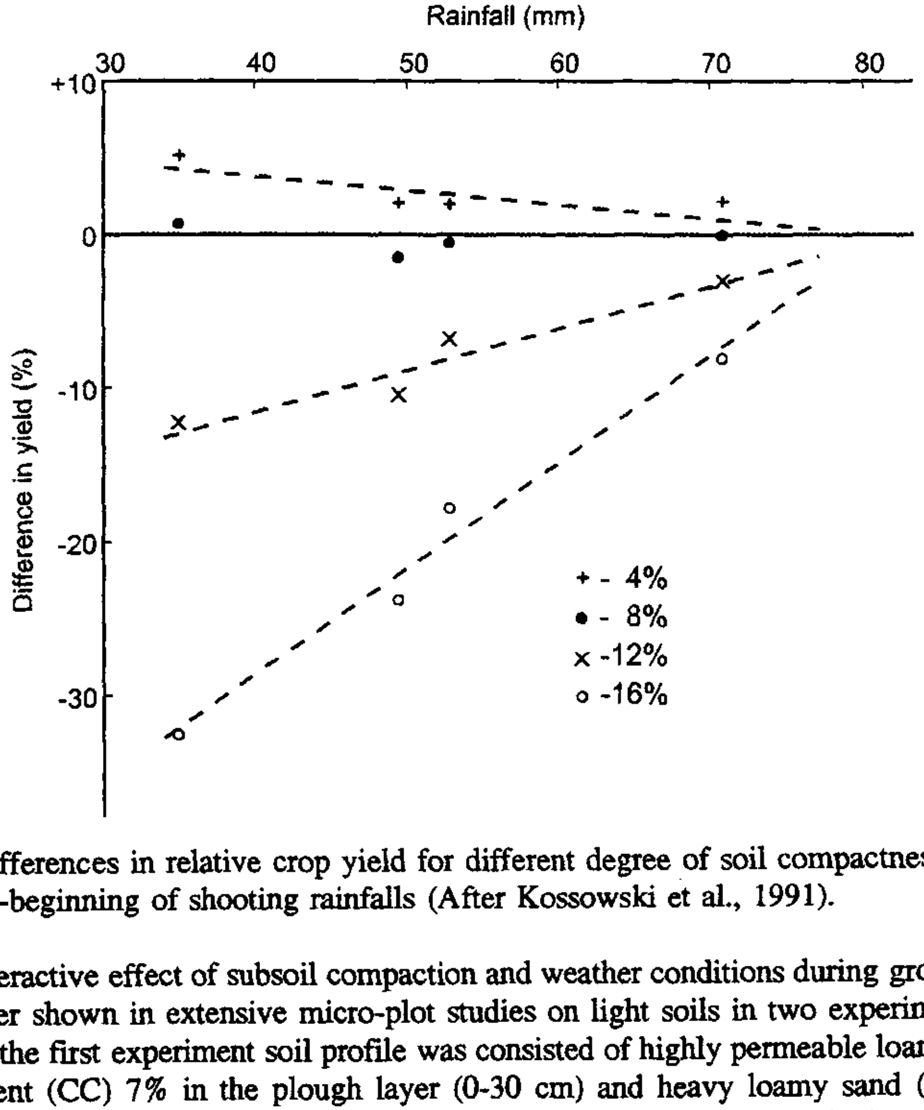

Fig. 4. Differences in relative crop yield for different degree of soil compactness in relation to sowing-beginning of shooting rainfalls (After Kossowski et al., 1991).

The interactive effect of subsoil compaction and weather conditions during growing season was further shown in extensive micro-plot studies on light soils in two experiments (Pabin, 1995). In the first experiment soil profile was consisted of highly permeable loamy sand with clay content (CC) 7% in the plough layer (0-30 cm) and heavy loamy sand (CC 16%) of various bulk density in the subsoil (30-60 cm). In the second experiment the loose loamy sand (CC 19%) in the plough layer was underlined by variously compacted light loam (CC 26 %) in the subsoil. In 1988 and 1990 with dry periods in May and July (most enhanced growth) crop yields decreased with increasing bulk density in the subsoil in both experiments (Fig. 5). The response can be due to shallow root growth.

However, in 1989 and 1991 with favourable rainfall distribution the crop response was opposite (Fig. 6). It has been ascribed to reduced percolation of water through the more compacted subsoil and thereby improving water supply with plants. The beneficial effect of stronger subsoil in sandy soil has been confirmed in another experiment (Pabin, 1995) where yield of sugar beets was positively correlated with soil water content in the plough layer (0-30 cm) which in turn was positively correlated with bulk density of the subsoil (30-60 cm). In this case subsoiling had negative effect on crop yield.

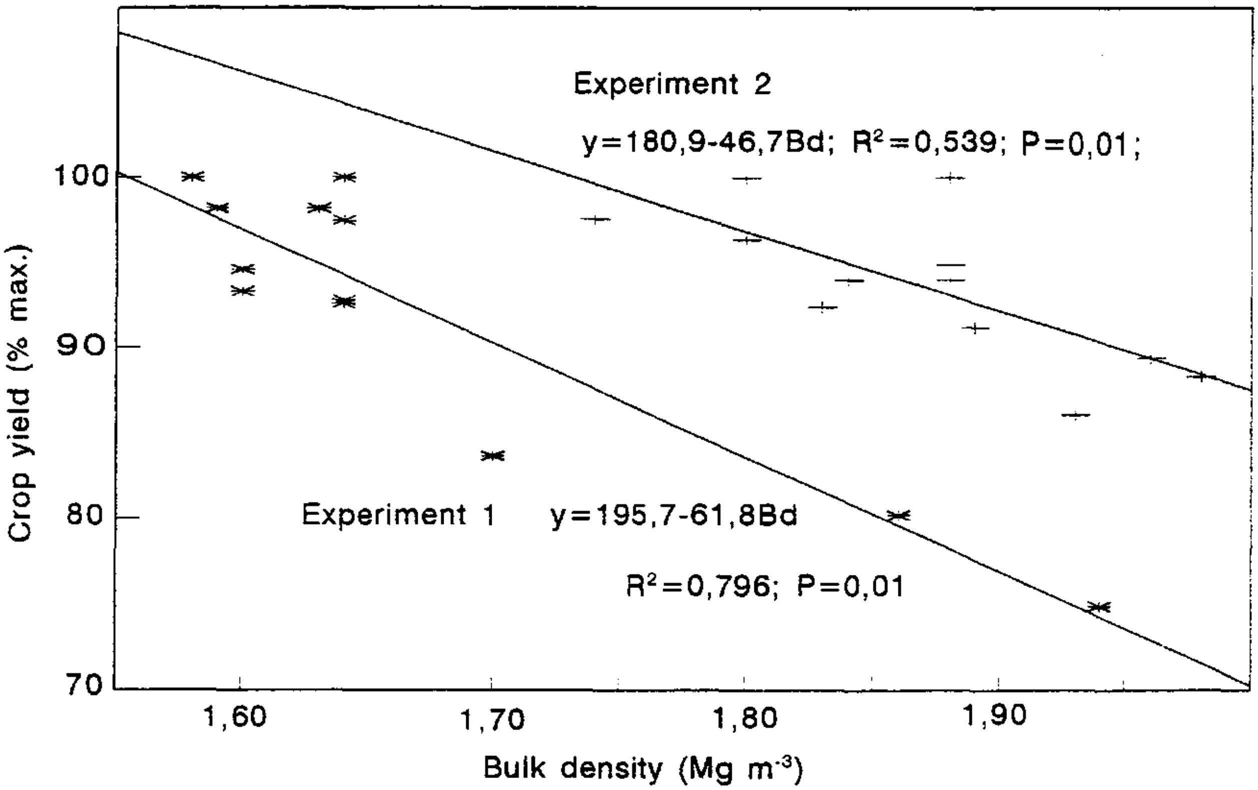

Fig. 5. Crop yield in relation to soil bulk density in the subsoil (30-60 cm) in dry growing season (After Pabin, 1995).

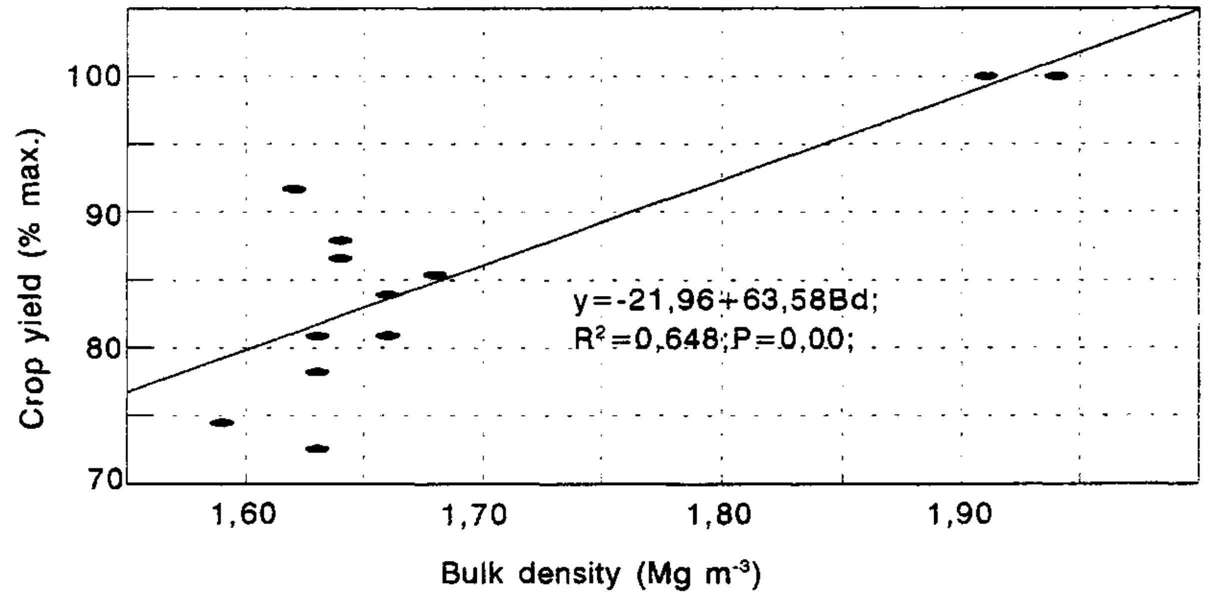

Fig. 6. Crop yield in relation to soil bulk density in the layer 30-60 cm in growing season with favourable rainfall distribution (after Pabin, 1995).

An important plant growth determinant of crop yield in compacted soil can be stomatal behavior. As Fig. 7 shows, the differences in stomatal resistance of spring wheat between the compaction treatments were much greater in droughty periods, mostly due to its increase in the most compacted soil. This increase in stomatal resistance was mostly associated with shallow root system and reduced water uptake. As a consequence the grain yield in the most compacted treatment was reduced by 22 %. A substantial increase in stomatal resistance of plants grown in most compacted soil also occurred at high soil wetness and associated low air-filled porosity in laboratory experiment (Lipiec et al., 1996).

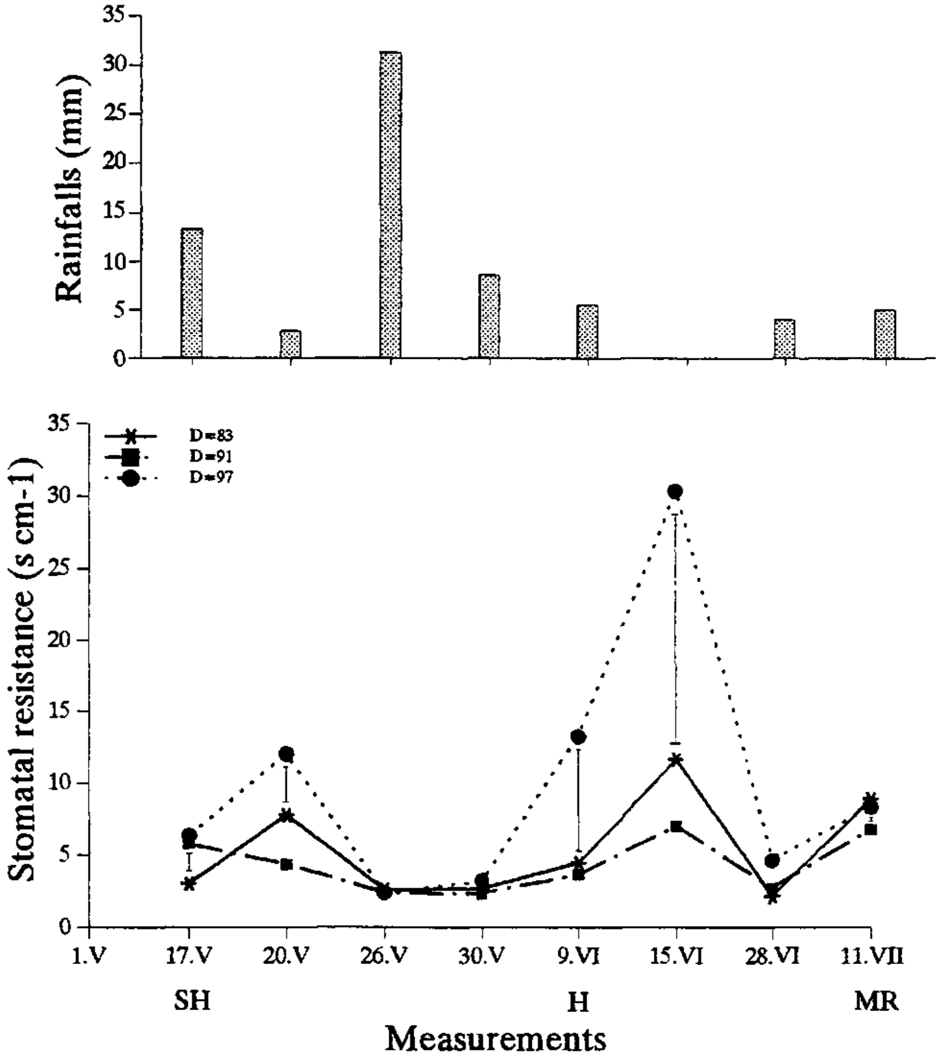

Fig. 7. Stomatal resistance of spring wheat grown on silty loam (Lublin, Poland) in 1994. The bars represent $LSD_{0.05}$. D=degree of compactness; SH=shooting; H=heading; MR=milk ripeness. The sums of rainfalls for periods between the measurements are shown (After Lipiec, unpublished).

5.4. *Nutrient uptake*

In most field and laboratory experiments nutrient uptake was reduced by soil compaction ((Słowik and Soczek, 1971; Stępniewski and Przywara, 1992; Lipiec and Stępniewski, 1995). Field experiments showed that when the degree of compactness exceeded 89 %, considerable reduction of the N, P and K concentration and total uptake of spring barley occurred (Lipiec and Stępniewski, 1995). The reductions were greater for straw than for grain. Laboratory studies with a wide range of soil ODR, obtained by manipulating soil water tension and bulk density, revealed that nutrient uptake of rye (*Secale cereale* L.) was reduced at ODR values below 30 $\mu g\ m^{-2}\ s^{-1}$ (Stępniewski and Przywara, 1992).

Structural discontinuity between tilled layer and untilled and stronger subsoil results in restricted deeper root growth and lower total uptake of water and nutrients (Słowik and Soczek, 1971; Lipiec and Stępniewski, 1995) although the younger roots grown in the subsoil are more effective than roots near the soil surface (Gliński and Lipiec, 1990; Lipiec et al. 1993). As a consequence, the potential for nutrient leaching in compacted soil increases. The negative effects of soil compaction on the components of the environment due to nutrient leaching, surface runoff and gaseous losses to the atmosphere are reviewed by Lipiec and Stępniewski (1995). The authors indicated that soil compaction affects nutrient transformations and uptake mostly through changes in soil hydraulic, aeration, and diffusive properties, as well as by its effect on root growth and configuration.

6. Effect of deep loosening

The effect of deep loosening on soil and crop response depends on soil type and weather conditions.

On coarse-textured soils where compact subsoil decreased downward water movement and increased water retention in the plough layer, the subsoiling had negative effect on crop yield although roots penetrated deeper (Pabin, 1995; Szymankiewicz and Deryło, 1995). The subsoiling then may not be required on the soils. In other experiments the effect of subsoiling was positive (Kęsik, 1980; Nowicki, 1988). Nowicki et al. (1988) reported that the positive effect of deep ploughing (45-50 cm) combined with the insertion of farmyard manure below the plough layer on crop yield was better than deep ploughing alone. Compared with traditional ploughing the increases in crop yield were 28 and 13%, respectively. Pabin (1995) indicates that the positive effect of subsoiling occurs when the subsoil supply plants with extra water and nutrients which are inadequate in the surface soil. This takes place, especially, in very dry seasons. However when water deficit is moderate, the subsoiling may have a negative effect. In some cases the positive effect was ascribed to disruption of the original positioning of non-elastic sand grains fixed with calcium carbonate and ferrous hydroxide, which restricts root penetration (Kęsik, 1980). On sandy loam underlined by light loam the lowest yield of four crops has been obtained on shallow (8-10 cm) tilled plots and considerably greater on plots with ploughing (P) to 25-30 cm and with ploughing plus subsoiling (PS) (Fotyma et al., 1997). Crop yield on PS was only slightly greater than on P.

On fine-textured soils in drier growing periods, the deep loosening has a positive effect on crop growth (Cieśliński et al., 1988). In these locations, deep ploughing (0.45-0.5 m) led to the restoration of water retention and greater root system and its more uniform distribution in soil profile (Cieśliński et al, 1994; Cieśliński and Miatkowski, 1995) and associated greater water use (Cieśliński et al., 1988). This resulted in increased crop yield by 2-16% (Kuś et al., 1986; Łacek, 1988). The increases were greater with deep ploughing (0.5 m) than subsoiling (0.7 m deep and 0.7 m apart) (Cieśliński et al., 1988). The positive effect persisted through 3-5 years (Cieśliński et al., 1988). On badly drained soils, deep ploughing or loosening resulted in deeper root penetration and greater branching (Sołtysik, 1997) and increased availability of soil oxygen to roots, as measured by ODR (Miatkowski and Cieśliński, 1997).

The experiments conducted at the same location showed that the changes in soil properties due to subsoiling were more persistent on loess soil and rendzina than on sandy soil (Kęsik, 1980). It can be related to the low content of finer soil materials and/or organic matter in the sandy soil to stabilize the pore system.

Kuś et al. (1986) reported that the positive effect of subsoiling of loamy soils was more pronounced at lower fertilisation rate and when the subsoiling was combined with fertilisation of the subsoil. There was no positive effect, however, on the fertile chernozem. This implies that the positive effect of subsoiling can be related with better plant supply with nutrients.

The review of experiments on subsoiling effects made between 1948 and 1966 indicates that only in 25% of cases crop responses were positive (Świętochowski et al., 1970). No response or negative effects were obtained in 50 and 25% of cases, respectively . In more recent studies the effects were similar (Pabin, 1995). Because of the high cost of profile modification, its economic response is doubtful (Kuś et al., 1986). But in many cases the economic implications have not been evaluated.

The inconsistency in crop responses to deep loosening and lack of definite reasons for this implies that greater attention shoud be paid to define under which conditions the stronger and usually wetter subsoil will have a negative or favourable effect on crop production and environment. Data so obtained will increase the potential for modelling crop responses under different site conditions.

7. Conclusions

The stress-strain relations in the plough layer and in the subsoil as affected by vehicular traffic can be quantified with the methods presented. Experimental data characterizing soil and crop responses to soil compaction in various site conditions are available. The wide variations of the responses are related to soil type and weather conditions. Crop yield from compacted soil tended to be less reduced in wet seasons and in seasons with favorable rainfall distribution than in dry seasons. The effectiveness of the deep loosening depends on how it improves water economy and nutrient uptake and drainage on heavy clay soils.

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MEASUREMENT OF PHYSICAL PROPERTIES TO DETERMINE SOIL COMPACTION IN SOUTHERN SPAIN

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Abstract

This paper presents some results of measurement of soil physical properties in tillage experiments carried out in the province of Seville (south-west Spain). Measurements were carried out in two sites, one is a sandy clay loam (Haploxeralf) in which the treatments applied were mouldboard ploughing, disc harrowing and no-tillage, the other is a sandy clay loam (Xerofluvent) in which traditional tillage and conservation tillage were applied. On both sites, measurements of penetration resistance, bulk density, and hydraulic conductivity were carried out. Hydraulic conductivity was determined in situ, in the range near saturation, using a tension disc infiltrometer. Results obtained in these experiments showed that for a site differences in penetration resistance, bulk density and hydraulic conductivity at a site are related with the tillage method applied, and reveal different soil consolidation with depth, due mainly to different patterns of soil compaction.

Introduction

In the literature there are many works referring to the effect of different tillage methods on the soil properties and crop development, including different response to soil compaction (e.g. Voorhees et al., 1978; Moreno et al., 1986; Pelegrín et al., 1990) and the influence of compaction on soil physical properties (Moreno et al., 1997).

It is well known that all relationships between soil tillage and soil physical properties depend on soil types and climatic conditions. This, together with the increase of process modelling of water balance in tillage experiments, has imposed the need for accurate measurements of soil physical properties.

The accurate measurement of soil physical properties, such as penetration resistance, bulk density and infiltration rate, can help in determining differences in soil compaction under different tillage methods for a specific soil type and climatic conditions.

This paper presents some examples of results of physical properties in tillage experiments in south-west Spain and their use to determine the degree of soil compaction. The examples shown in this paper are taken from previous and current works carried out by the authors.

Materials and methods

Experiments were conducted in two soils located in the province of Seville (south-west Spain), under different tillage methods.

One of the soil (site 1) is a sandy clay loam (Haploxeralf) situated within the experimental area of the University School of Agricultural Technical Engineering (EUITA), 3 km east of the city of Seville. Plots of 28 x 3 m, with 0.5 m side borders (total width 4m), were used in the experiments. The following tillage treatments were applied: mouldboard ploughing (depth: 25-30 cm), disc harrowing (depth: 12-15 cm) and no-tillage, with three replications per treatment in random blocks. These treatments have been applied since 1984, with a cereal-sunflower crop rotation established in each treatment (Pelegrín et al., 1990).

The other soil (site 2) is a sandy clay loam (Xerofluvent) situated within the experimental farm of the Instituto de Recursos Naturales y Agrobiología de Sevilla (IRNAS-CSIC), located

13 km south-west of the city of Seville. Two tillage treatments were established since 1992: traditional tillage used in the area for rainfed agriculture, and conservation tillage. Tillage treatments were applied in plots of 22 m x 14 m, using three replications per treatment distributed in random blocks. A wheat-sunflower crop rotation was established in each treatment. A detailed description of the experiments is given in Moreno et al. (1997).

The resistance to penetration was determined using a falling cone penetrometer of 1.5 cm^2 conical section and an angle of 30° (Hoyas, 1994) to a depth of 40 cm with ten replicates per treatment, deducing a medium curve for each application period.

Bulk density was determined from the ratio mass/volume of soil cores taken with stainless-steel cylinders of 8 cm diameter and 4 cm height. Samples were taken in four or six replicates per treatment.

The tension-disc infiltrometer was used to determine in situ the hydraulic conductivity and the sorptivity in the range near saturation (Perroux and White, 1988; Smettem and Clothier, 1989). Experiments in 1994 and 1995 were carried out with disc infiltrometers of 125 mm and 40 mm radius. Infiltration tests were carried out on the undisturbed soil surface of treatments. The pressure heads (ψ_0) chosen were -100, -30, and 0 mm. Triplicate flux measurements were made with each disc for the different heads in each treatment. The hydraulic conductivity, $K_0 = K(\psi_0)$, and sorptivity, $S_0 = S(\psi_0)$, were obtained using the multidisc approach as described by Smettem and Clothier (1989). More details about these experiments can be found in Moreno et al. (1997).

Results and discussion

Site 1

Fig. 1 shows results of penetration resistance at site 1 under different tillage treatments during the wheat crop season. These results show that immediately after tillage (December 1986), mouldboard ploughing and disc harrowing present similar values above a depth of 0.15 m, while in the no-tillage treatment values are a little higher as a consequence of a more compact structure. These results are in agreement with bulk densities of the soil from each treatment at that date (Table 1). At greater depths, variation is more noticeable, most probably owing to a plough pan of different compaction and water content, as a consequence of the different tillage depth in each treatment. On the selected dates of February and March of 1987, penetration resistance values showed clearer differences between treatments. Penetration resistance was much higher in the no-tillage treatment than in mouldboard ploughing and disc harrowing treatments for the soil layer 0-20 cm in depth during March 1987.

Table 1. Bulk density (D_b) and water content (θ) in the top layer (0-20 cm)

Treatment	D_b ($g\ cm^{-3}$)	θ ($cm^3\ cm^{-3}$)
Mouldboard plough	1.25a	0.136
Disc harrow	1.34a	0.158
No-tillage	1.51b	0.172

Values of D_b followed by the same letter are not significantly different ($P < 0.05$)

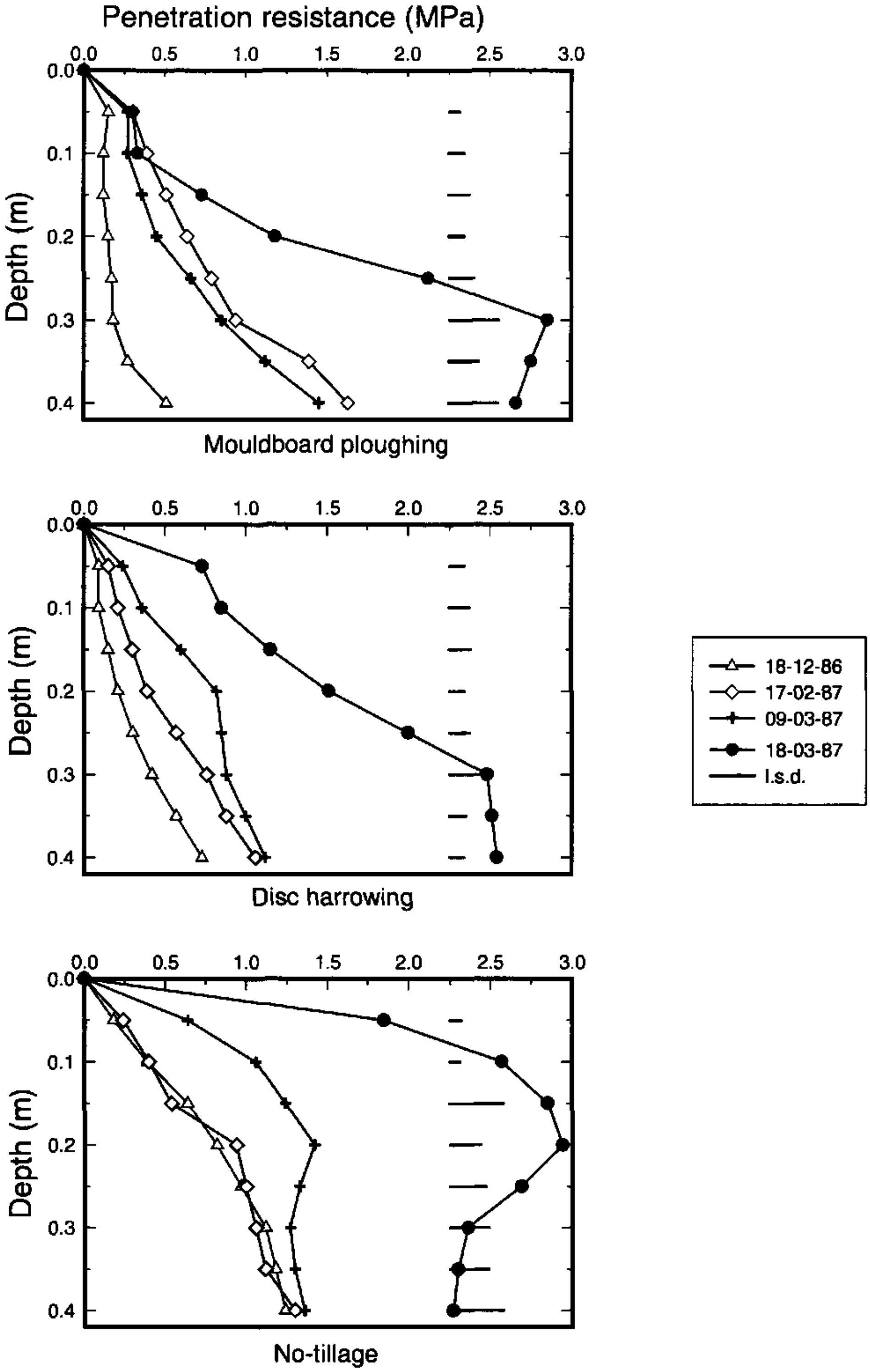

Fig. 1 Penetration resistance in the three tillage treatments on selected dates during the wheat crop season.

To determine the spatial distribution of the penetration resistance, measurements were carried out in the three treatments on 20-04-87, on a rectangular grid of 0.6 m by 2 m in which each measurement was 0.2 m apart. The short side of the rectangle was in the direction of the tillage works, and the other perpendicular to this (Pelegrín et al., 1996). The results of this experiment are shown in Fig. 2. These results show differences between treatments that can be related with differences in the soil water content due to different water extraction by the crop in each treatment (Pelegrín et al., 1996). The mouldboard ploughing treatment shows higher homogeneity in the penetration resistance values than in the disc harrowing and no-tillage treatments for the soil layers below 0.2 m. These results are very useful to establish the compaction zones and their spatial distribution in a soil under different tillage treatments.

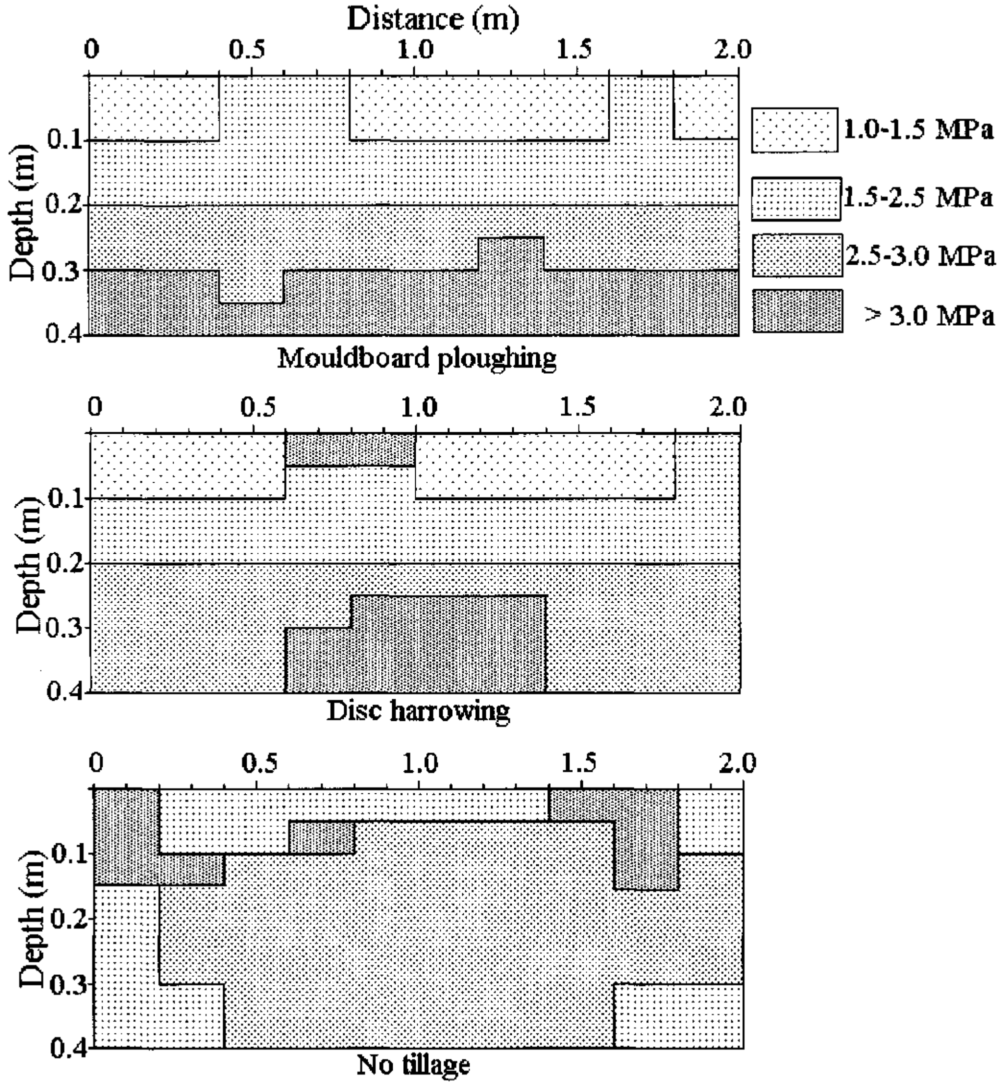

Fig. 2. Spatial distribution of penetration resistance in the three treatments (20-4-87).

Site 2

Results presented here are examples from the comparison of traditional tillage (TT) and conservation tillage (CT) in southern Spain carried out by Moreno et al. (1997). Fig. 3 shows the penetration resistance in both tillage treatments with sunflower crop during 1995. At planting date, penetration resistance values in the CT treatment were significantly higher that in the TT treatment for the depths between 0.1 and 0.25 m. At this time the water content was practically the same in both treatments for these depths (0.208 cm^3 cm^{-3} in TT and 0.221 cm^3 cm^{-3} in CT). From these results we can deduce that in CT treatment the soil layer at a depth between 0.1 and 0.25 m is more compact than in TT treatment. Penetration resistance values in CT treatment higher than in TT treatment (about 2 MPa) could be a limiting factor for root growth. Although the soil is not a vertisol, we observed some small fissures, with water content lower than 0.23 cm^3 cm^{-3}, due to shrinking processes; in the clay fraction the smectite content is about 20-30%. These fissures alow root growth, as has been shown by others. These differences in penetration resistance values between treatments agree with the differences in bulk density (Table 2). At flowering date, penetration resistance values were also higher in the CT than in the TT treatment, but not significantly different.

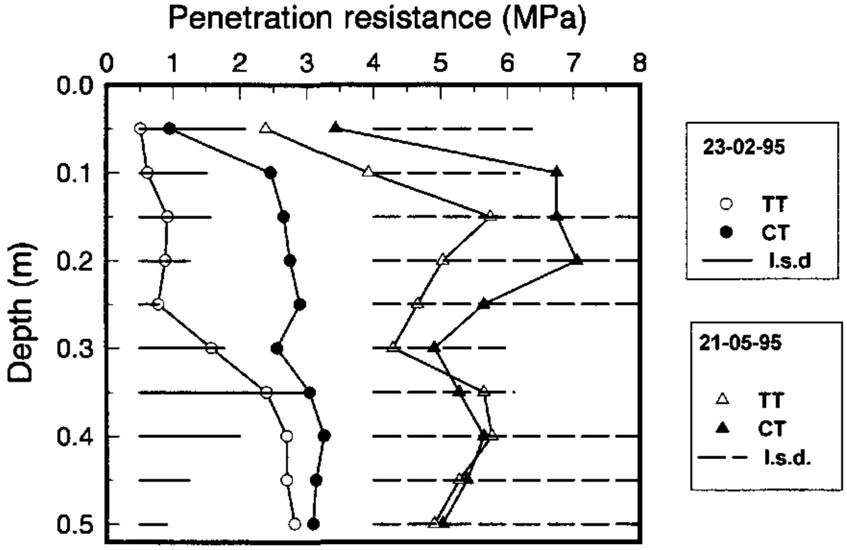

Fig. 3. Penetration resistance on selected dates during the sunflower crop season in 1995. TT, traditional tillage; CT conservation tillage.

Table 2. Bulk density (D_b) and water content (θ) for both treatments (TT, traditional tillage; CT, conservation tillage) at planting of sunflower (23-2-95)

Depth (cm)	Treatments			
	TT		CT	
	D_b (g cm^{-3})	(cm^3 cm^{-3})	D_b (g cm^{-3})	(cm^3 cm^{-3})
0 - 10	1.26a	0.162^*	1.39b	0.195
10 - 20	1.40a	0.208^*	1.62b	0.221^*

Values of D_b in each line followed by the same letter are not significantly different ($P<0.05$).
Values of θ in each line followed by * are not significantly different ($P<0.05$)

Hydraulic conductivity and sorptivity deduced from measurements with the tension disc infiltrometer in the two tillage treatments are shown in Table 3. These results correspond to measurements carried out at the beginning of the sunflower crop (Moreno et al., 1997). The hydraulic conductivity at $\psi_0 = 0$ was significantly higher in CT than in TT. This could be related with the existence of preferential paths created by an increase of the earthworm population in the CT treatment that was visually observed during a soil sampling at this time. These results clearly show better hydraulic conductivity in the soil of CT treatment than in that of TT, although the latter shows lower bulk density (Table 2) and lower penetration resistance (Fig. 3) than in CT. These measurements can be carried out to characterise the hydraulic properties of soil layers at different depths with different degree of compaction, as has been reported by Villaú (1997) and Moreno et al., (1998).

Table 3. Hydraulic conductivity (K) and sorptivity (S) of the soil surface measured at the beginning of the sunflower crop (March 1995) in the TT (traditional tillage) and CT (conservation tillage) treatments

	Treatments			
	TT		CT	
ψ (mm)	K (mm h^{-1})	S (mm $h^{-0.5}$)	K (mm h^{-1})	S (mm $h^{-0.5}$)
0	66.6a	49.2^*	124.6b	39.0^*
- 30	48.2a	40.2^*	16.6a	30.0^*
- 100	4.3a	22.2^*	3.6a	10.8

Values of K in each line followed by the same letter are not significantly different ($P<0.05$).
Values of S in each line followed by * are not significantly different ($P<0.05$).

Conclusions

From the results presented in this paper we can deduce that the combined measurements of penetration resistance, bulk density, and hydraulic conductivity in the range near saturation can provide detailed information on compaction processes in the surface layer and deeper layers of soils under different tillage methods.

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FACTORS INFLUENCING SOIL AND SUBSOIL COMPACTION AND IMPACT OF COMPACTION ON YIELD OF DIFFERENT PLANTS

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Abstract

ITCF has been studying the problem of compaction of soil and subsoil. The institute has measured some factors like water content of soil and subsoil, axle load, inflation pressure of tyres, all of which affect soil and subsoil compaction. Low water content in the first few centimetres (20% of field capacity) of the arable layer prevents subsoil compaction even if the water content of the subsoil is medium (70% of field capacity).

ITCF has also studied the impact of compaction on the yield of several plants, observing that the depth of the seed bed limits the effects of compaction. In seed beds 10 cm deep, impact of compaction is less than that in beds only 5 cm deep. In compacted soil and for a shallow depth of seed bed, nutrients and water assimilation, fixation activity by nodulation was reduced.

In forage maize, compaction has a disastrous impact on yield. Indeed, yield for a compacted and not ploughed soil is half that of soil that has been ploughed. In wheat, however, yield is unaffected by compaction because the filling of grains is better in compacted than in uncompacted soil, although the number of grains is smaller.

Introduction

Ten years ago, compaction was a major issue in French agriculture. Subsequently productivity-oriented research pushed the question out from under the limelight. However, a few years ago the problem of compaction reappeared as an important issue. ITCF has been studying the possibilities of reducing compaction through better choice of tyre pressures and by decreasing operations in the field. ITCF is working on the simplification of soil tillage (direct drilling without ploughing when it is possible to reduce the plough pan).

ITCF has obtained some results on the negative impact of compaction on the growth and yield of some plants, such as spring peas, forage maize and wheat, and it is keen to do more research on this topic.

First we examine the factors which influence soil and subsoil compaction. We conclude that some soil and subsoil textures are able to overcome the negative impact of compaction. Second, we study the impact of compaction on spring peas, forage maize, wheat, sunflower and sorghum.

Part 1. Analysis of factors influencing compaction of soil and subsoil

Methods

Some experiments over three years (1984,1985, 1986) were carried out by J.-P. Gillet to identify factors which influence soil and subsoil compaction. Some factors were studied in an eight-month-old rye-grass crop:

- soil moisture content (as percentage of field capacity, FC)
- inflation pressure: 80, 250 and 500 kPa

- axle load: 3 t and 7 t

The experiments were carried out at ITCF's experimental station "La Jaillière", near Angers. The characteristics of the soil were:
- proportion clay: 15%
- proportion loam: 55%
- proportion sand: 30%
- proportion humus: 2%

The subsoil had a high proportion of clay.

Gillet chose structural porosity as an indicator of compaction. Structural porosity was measured with a high resolution gamma-ray probe.

Results

Water content has a direct influence on soil and subsoil compaction (Gillet, ITCF, 1985). The structural porosity of an arable layer and its subsoil decreases with increasing water content after exposure to axle loads of seven tonnes (Table 1).

Table 1. Influence of water content as percentage of field capacity (FC) on compaction of the topsoil and subsoil (ITCF, 1985). Wheel load 3.5t; type inflation pressure 500 kPa

Layer	Water content	Structural porosity (%)	
		before wheel load	After wheel load
0-0.25 m	High (103% of FC)	**13**	2
	Medium (91% of FC)	**14**	4
	Low (78% of FC)	**16**	12
0.25-0.40 m	High (91% of FC)	7	0
	Medium (92% of FC)	**8**	5
	Low (88% of FC)	**10**	10

If farmers take care to ensure the correct water content of their soils for soil cultivation, they are less concerned about the inflation pressure of the tyres of vehicles carrying out the operations. Yet incorrect inflation pressure contributes to soil compaction. The structural porosity of the arable layer decreases with higher inflation pressure (Table 2).

Table 2. Influence of inflation pressure on soil compaction (ITCF, 1985). Wheel load 1.5 t

	Structural		Porosity (%)	
	Tyre inflation pressure			
Water content	**Before Operations**	80 kPa	250 kPa	500 kPa
High (103% of FC)	**13**	11	8	7
Medium (91% of FC)	**14**	12	8	8
Low (78% of FC)	**16**	16	13	12

Farmers should be particularly careful about inflation pressure of tyres because of the great weight of their machines and poor climatic conditions (as is often the case in France for the harvesting of sugar beet).

Now tyre manufacturers are proposing the use of wide tyres (up to one metre), low inflation pressures, to reduce pressure on the soil and, consequently, compaction. (In practice the pressure average exerted on soil is equal to the inflation pressure of the tyre). For example, the Pirelli TM 800 (width = 800 millimetres) is able of working at pressures as low as 40 kPa, i.e. less pressure than that exerted by an average man, which is approximately 80 kPa. But the best performances have been obtained with wide rubber tracks which are only fitted to some high-powered tractors (> 200 HP). The pressure they exert on soil is 39-40 kPa. More and more wide tyres are being fitted to other wheeled equipment, such as trailers.

Axle load does have an impact on soil (Table 3) (Gillet, ITCF, 1986), especially when water content is higher than 78% of field capacity. An axle load of 7 has a disastrous impact on structural porosity when water content is high, and nowadays equipment with axle loads of 7 are widespread in agriculture.

Table 3. Impact of axle load on structural porosity of soil

	Structural		**Porosity (%)**
Water content	**Before wheel load**	**1.5 t after a wheel load 250 kPa inflation pressure 250 kPa**	**3.5 t after a wheel load of 250 kPa inflation pressure**
High (103% of FC)	**13**	8	2
Middle (91% of FC)	**14**	8	8
Low (78% of FC)	**16**	13	13

Non visible, the subsoil compaction is effective when the axle load is high and the water content of soil greater than field capacity (Table 4). Subsoil compaction is less perceptible in the arable layer than ruts and yet the effect is dramatic. A soil and subsoil profile is necessary to observe the compaction underneath the arable layer.

Table 4. Impact of axle load on structural porosity of subsoil (ITCF, 1985)

Water content		**Structural porosity of subsoil**		
0-0.25 m	0.25-0.40 m	**Before wheel load**	After a wheel load: of 1.5 t; inflation pressure 250 kPa	Load: 3.5 t; inflation pressure 250 kPa
103%	91% FC	**7**	5	0
91%	92% FC	**8**	8	4
78%	88% FC	**10**	10	10

We think that a low water content of arable layer limits subsoil compaction (Table 4). As a matter of fact, at a low water content of the 0-0.25 m layer, the subsoil structural porosity does not decrease. Guerif (INRA) has confirmed that. He has shown that a low water content of the first few centimetres of soil reduces compaction of the layer (0.05-0.30 m) (Table 5). Indeed, at a water content corresponding to 20% of field capacity, for the first five centimetres and an inflation pressure of 50 kPa, the structural porosity decreases by 17%, while it decreases by 58.3% at a water content of 82%. So, a thin surface layer of dry soil (1-2 cm) was sufficient to restrict the sinkage to the half its value under wet conditions (Guerif, Gillet).

Table 5. Influence of the first few centimetres of the soil on the sublayer
(Guerif, INRA, Avignon, 1986)

Water content		**Structural**		**Porosity (%)**	
		Type inflation pressure			
0-0.005 m	0.005-0.30 m	**Before wheel load**	50 kPa	125 kPa	250 kPa
82% FC	100% FC	**24**	10	6	5
20% FC	100% FC	**29**	24	17	11

To conclude, we know that some soils are able to recover from negative effects of compaction. Indeed, a soil with high clay content is able to reduce the effects. Climatic variation (dry and wet season, frost and thaw) cracks clay soils and improves their structure. That's why, in most cases, using subsoiler is not necessary in clay soils.

Part 2. Impact of compaction on yield of spring pea, forage maize, wheat, and sunflower and sorghem

2.1 Spring pea (Gillet et al., 1988, 1989, 1990)

In France, spring pea is sown when soil moisture content is high, so risk of soil compaction is an important consideration.

Material and methods

Experiments were carried out over three years (1988, 1989, 1990) at the ITCF's experimental station of ITCF near Angers.The variety used was SOLARA. The aim of the study was to compare three different treatments of compaction in combination with depth of seed bed (defined by Manichon, INAPG):

- O10: seed bed of 10 cm on an uncompacted soil
- C10: seed bed of 10 cm on a compacted soil
- C 5 : seed bed of 5 cm on a compacted soil

Results and discussion

Compaction has a negative effect on root development. Indeed, it limits rooting depth and speed of rooting is lower than in uncompacted soil. That is why in compacted soil sowing depth is very important. A sowing depth of 10 centimetres limits negative effects to a greater extent than a sowing depth of 5 cm in the same compacted soil (Table 6).

In uncompacted soil (O10) and compacted soil (C5, C10), the number of nodules is practically the same, but the distribution in the profile is different. Without compaction, depth of nodulation is 18.7 cm and the dry matter content is 77 mg/plant. In a layer compacted at 5-6 cm, nodulation stops at 7.7 cm and the dry matter content is 61 mg/plant.

Table 6. Characteristics of air-nitrogen fixation potential of spring pea (30 plants observed per treatment) in an uncompacted soil (O10) and in a compacted soil (C5, C10)

	O10	**C10**	**C5**
Depth of seed bed	10-12	10-11	5-6
Maximum number of nodules/plant	124	105	122
Maximum dry matter of nodules (mg)/plant	77.2	68.9	61
% of nodules in seedbed	84.7	99.3	75.2
Maximum depth of nodulation	18.7	11.4	7.7

Rooting is better in O10 which is proved by a greater depth of nodulation. In compacted soil, plants have difficulties assimilitating nitrogen. In the same field, a comparason of non fixating plants was made (Table 7). In both cases (irrigation and no irrigation), the quantities of nitrogen in the aboveground parts were reduced by 50% in compacted soils. These differences are due to low mineralisation in compacted soils and especially to poor assimilation of water, nitrogen, phosphorus and potassium by roots. Indeed, the rooting depth of these plants is reduced.

Table 7. Nitrogen quantity assimilated by non fixating plants at the beginning of flowering of spring pea

	Non-irrigated			Irrigated		
	O10	C10	C5	O10	C10	C5
Dry matter (g/m^2)	165	80.5	70.7	143.4	58.8	51.4
% N	2.45	2	1.9	2.58	2.28	2.39
N kg/ha	40	16	13	37	13	12

Gillet also observed that compaction accelerates the transition through growth stages. Each stage is shorter than in uncompacted soil.

For a non-irrigated crop, yields in O10 and C10 are practically the same (Table 8). But with irrigation, the yield of O10 is better (+92%) than C10 (+75%) and C5 (+30%). This results from the good rooting growth in O10. Protein content is better in O10 than in C10 and C5; its content depends on the number of nodules.

Table 8. The spring pea harvest

	O10		C10		C5	
	non-irrigated	irrigated	Non-irrigated	irrigated	non-irrigated	Irrigated
Yield (0% H 0)	4.11	7.91	3.97	6.96	2.92	3.81
Protein rate (%)	23	24.2	21.9	22.6	19.6	20.6
Grains/m^2	1682	2768	1581	2506	1118	1246
Weight thousand grains	246	285	251	278	262	306
Total dry matter (t/ha)	9.6	13.7	8.4	13.8	6.2	6.3
Total N (kg N/ha)	204	320	175	317	117	119

In fact, in uncompacted soil, the potential is higher but the expression of the potential depends on climate. Or, during the `filling of grain' stage, water supply was poor and temperatures were too high (>28°C). This would explain the lack of difference between uncompacted and compacted soil (Gillet, ITCF, 1990).

2.2 Forage maize crop (Simonneau, 1986)

Methods

An experiment over three years (1985, 1988, 1989) was carried out for three levels of compaction at ITCF's experimental station near Angers:
- state O: seed bed on an uncompacted arable layer
- state B: seed bed on a compacted and ploughed arable layer
- state C: seed bed on a compacted and unploughed arable layer

The soil characteristics were:
- proportion clay: 12%
- proportion loam: 57.7%
- proportion sand: 28.3%

Results and discussion

The compaction of the arable layer decreases rooting development speed but does not modify rooting depth. The yield is, however, different (Table 9).

Table 9. Impact of compaction on yield of forage maize (yield dry matter(t/ha)

	Degree of compaction		
Years	O	B	C
1985	13.9	12.0	9.5
1988	10.8	8.8	8.3
1989	8.8	5.8	4.4

Compaction had a negative impact on forage maize yield. Impact is disastrous on compacted, unploughed soil (state C). Indeed, compaction had an effect on aboveground development because of limited rooting development. Then, the number of grains/m² is lower than in uncompacted soil.

2.3 Wheat crop (D. Robert, ITCF, 1991)

Material and methods

Experiments were carried out at ITCF's experimental station at Boigneville, near Paris. Soil characteristics were:

- proportion clay: 25%
- proportion loam: 65%

The subsoil is calcareous.

Robert compared growth and yield of a wheat crop under two levels of compaction:

- state O: seed bed on an uncompacted arable layer
- state C: seed bed on a compacted and unploughed arable layer

Results

In the compacted layer of state C, rooting speed is lower than in state O. Under the compacted layer, the rooting speed is the same in state C as in state O (Figure 1).

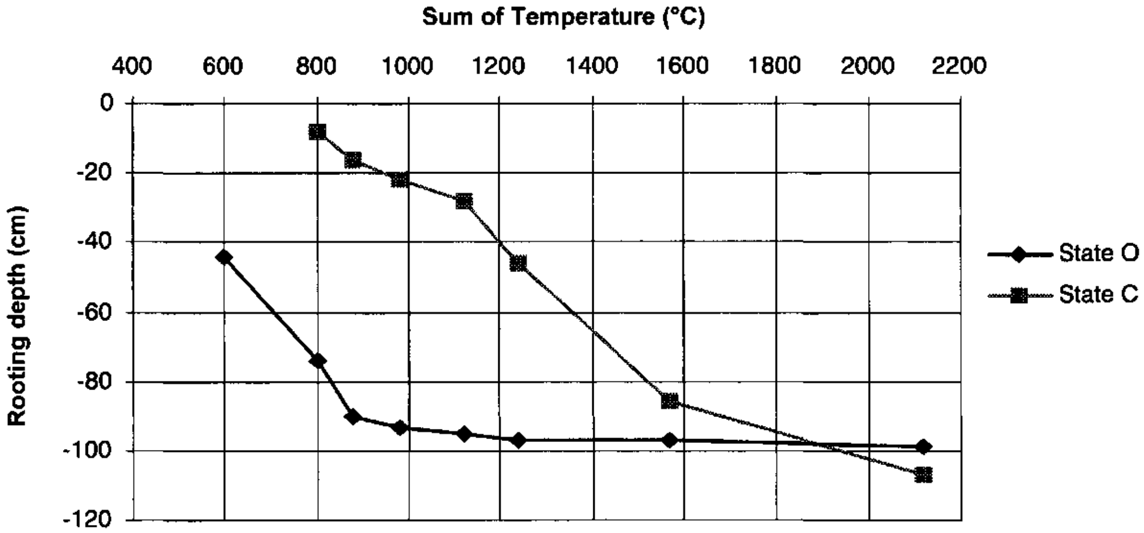

Figure 1: the rooting speed of wheat in a compacted (state C)and no-compacted soil (state O)

Compaction has a negative impact on the amount of dry matter content of the abovegrond parts but the amount of dry matter content in ears is not affected (Figure 2

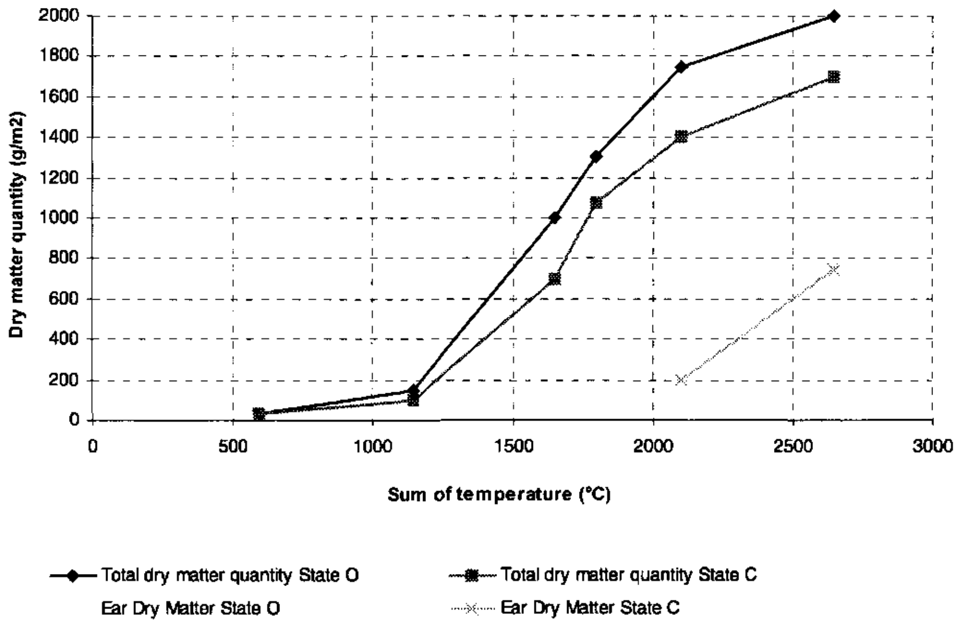

Figure 2: impact of compaction on the dry matter quantity of aerial parts and ears

In fact, compaction had a negative effect on the number of ears/m² and the number of grains/m², but a positive impact on filling of grain. Consequently, yields are not affected by compaction.

2.4 Sunflower, Sorghum (ITCF, Baziege)

Plants	Year	Yield (t/ha)	
		uncompacted (state O)	Compacted (state B)
Sunflower	1985	4.08	3.04
Sorghum	1986	9.13	7.94
Sorghum	1987	9.24	9.39

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SOIL COMPACTION EXPERIMENTS OF THE INSTITUTE FOR LAND AND WATER MANAGEMENT RESEARCH, PETZENKIRCHEN

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Abstract

The paper describes the work of the Institute for Land and Water Management Research (IKT) on soil compaction problems. After giving a general outline, some experiments are described in detail. A list of the methods used is given.

1. Introduction

The IKT in Petzenkirchen, Austria, was established about 50 years ago. One of its main tasks was the improvement of waterlogged soils, many of which were too wet for intensive agricultural use because of "natural compaction" of the silty soil profiles. Up to the seventies, regulations for economical drainage methods were worked out for these "Pseudogley" soils. Later work focussed on the mechanical loosening of compacted soils. More recently the effects of wheeled traffic on soil structure, water regime and plant growth have been studied.

Nowadays, IKT deals mainly with quantitative and qualitative problems of the soil water and groundwater regimes on local and regional scales using simulation models, which were developed and tested at the institute (Feichtinger, 1995; Stenitzer, 1988). One necessary input parameter for these models is information on soil resistance to penetration by roots. Furthermore, hydraulic soil parameters (pF-curve, saturated and unsaturated hydraulic conductivity) are supposed to depend strongly upon bulk density. Therefore, model outputs are greatly influenced by soil compaction. Until now, bulk density was assumed to be constant during the simulated period. Further research will be directed to formulating an appropriate model by which the dynamic nature of the bulk density in the upper layers of a cultivated field may be simulated more realistically.

2. Case studies

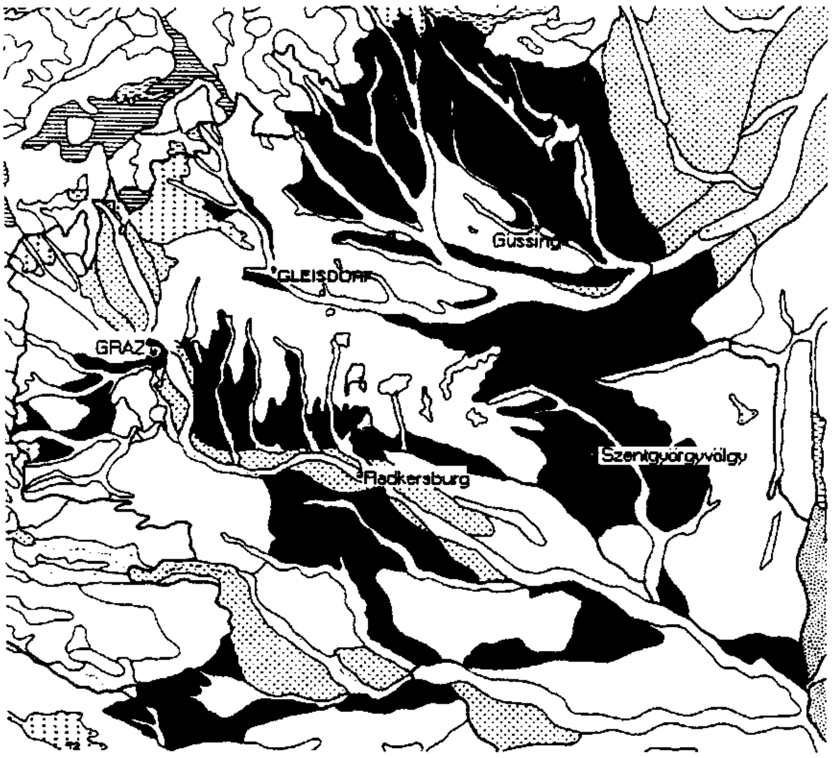
2.1 Drainage of waterlogged Pseudogley Soils

As mentioned above, early work at our institute concentrated on the improvement of waterlogged soils with dense subsoils (stagno gleyic combisols). Summarising the findings of Feichtinger Sen. (1978) it can be stated that after 30 years of systematic drainage those soils did not change their soil structure to any extent of hydrologic relevance. Such development of the soil structure can be initiated by mechanical loosening, although the duration of the loosening effects strongly depend on soil type.

2.2 Impact of subsoil loosening of a silty loam soil upon the soil-water balance of winter wheat and maize

For six years (1984-1989), the impact of deep loosening of a heavy silty loam soil in Western Hungary was studied by comparing the soil-water balance and the yields of mechanical loosening and untreated experimental plots (Murer, 1993). This soil type covers a rather huge area in southeastern Austria, as well as in Western Hungary (Fig. 1, Fig. 2). It is of aeolian origin, but differs from loess-soils because it contains no carbonates.

Figure1. Experimental location



■ Pseudogleye

Figure 2. Area of Pseudogley soils (stagno gleyic cambisol) in southeastern Austria and Western Hungary

Field measurements from soil moisture sensors and penetrometers, various soil physical parameters, root dry matter and crop yields were analysed. Although significant differences for yield, root dry matter and penetration resistance existed between the treatments, no such differences could be detected for the soil physical parameters (bulk density, pore size distribution and saturated conductivity). Monitoring soil-water status by gypsum blocks during dry periods showed that on the loosened plots the crop was able to use more soil-water. The experiments showed that judging the effects of loosening methods by only using undisturbed soil samples would be misleading!

2.3 Testing of a tractor-drawn horizontal soil penetrometer

The aim of this experiment was to find a rational method for evaluating areal soil conditions relevant to tillage operations. The measuring device consisted of a horizontal penetrometer cone (Fig.3) connected to a pressure sensor. Two cones were mounted on two vertical "holders" of a special tractor-drawn trailer (Fig.4). The holders enabled the equipment to be fixed to the desired soil depth.

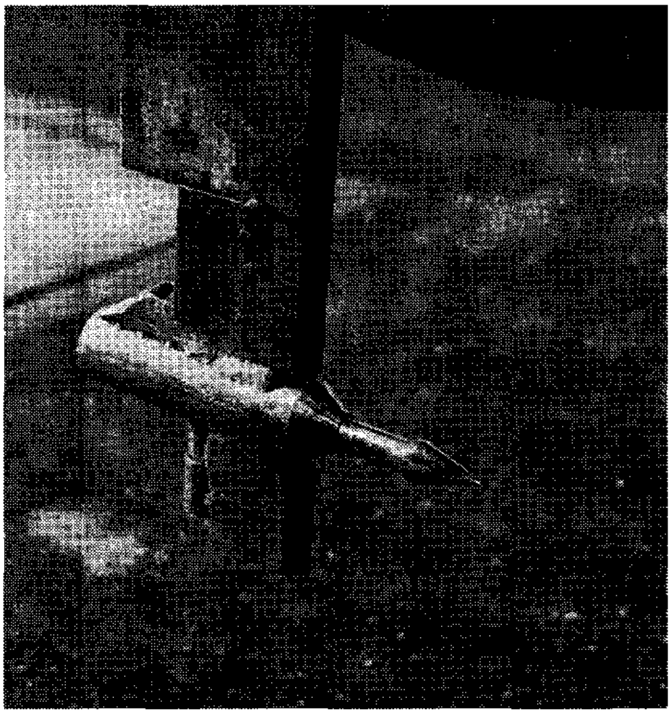


Figure 3. Horizontal cone penetrometer

The cone index is recorded with an electronic data processor at intervals of 0.1 s. Tests were carried out at velocities between 22-57 cm/s (0.8-2 km/h).

The tests were not satisfying: measurements only could be taken when the soil-water content was above or near field capacity and only for soil depths of a few centimetres. Under dry soil conditions and at deeper soil depths the device could not be drawn by normal tractors. Another problem concerned the friction between the soil matrix and the pressure sensor. After short time the instrument began to heat up, causing bias in the signals of the pressure transducer.

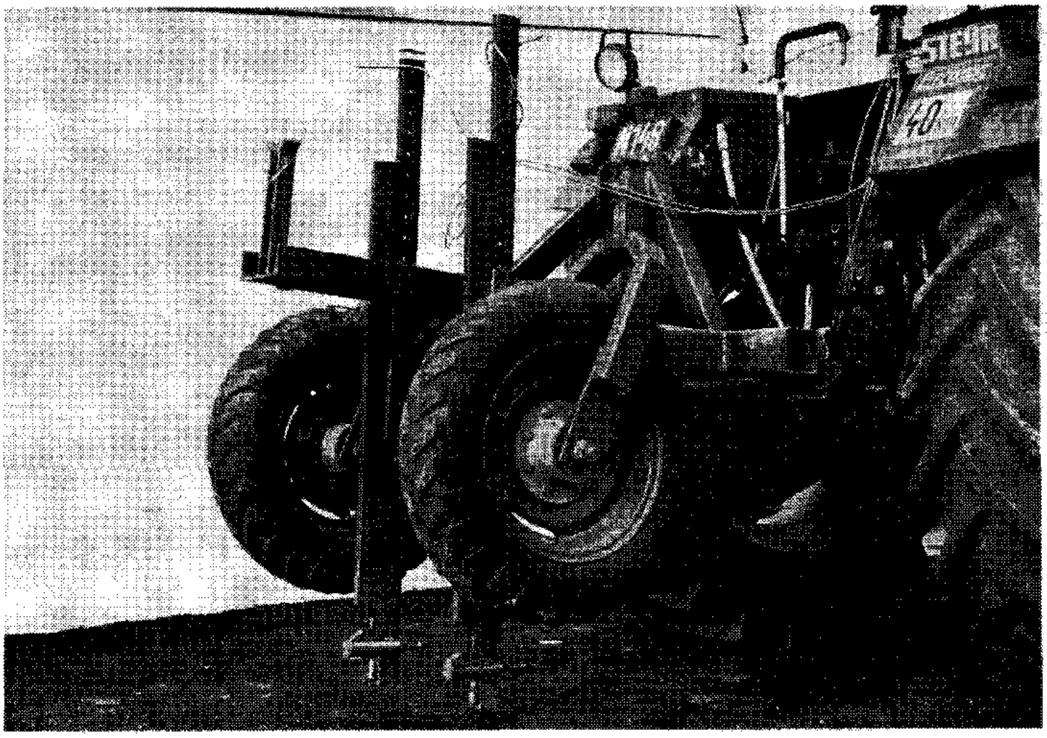


Figure 4. Special tractor trailer with vertical holders and penetrometers

2.4 Influence of wheeled traffic upon soil structure, water regime and plant growth (Murer, 1993)

Introduction

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 at an elevation of 260 m in the semi-humid sub-alpine zone of Austria. Mean air temperature there is 8.6 °C and the mean annual rainfall 708 mm.

Table 1. Soil characteristics of the experimental field near Wieselburg, Austria

Depth (cm)	Particle size distribution clay (%)	silt (%)	sand (%)	Organic matter content (%)	Lime content (%)	pH ($CaCl_2$)
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	---	7.4

Compaction effects were expressed by comparing the soil physical properties (dry bulk density, pore size distribution, saturated hydraulic conductivity, penetration resistance, soil water suction) and plant growth (grain weight) of a compacted and an uncompacted plot.

Material and Methods

In spring 1988, when soil was at field capacity, the test plot was uniformly compacted by a tractor-drawn trailer (Fig. 5), which had a tire load of 33 kN and tire pressure of 0.5 MPa. The type of the tire was Trelleborg 400- 15.5 (tire width 400 mm and rim diameter 394 mm).

In spring 1990, when the soil water content was at field capacity, the test plot was again compacted by tractor, but this time with a tire pressure of only 0.2 MPa and a tire load of 32.5 kN. The type of the tire was Semperit 18.4-38 (tire width 429 mm and rim diameter 965 mm).

Figure 5. Soil compaction by tractor driven trailer

Results

In 1988, all measured soil physical parameters of the compacted plot were significantly different from the untreated plot (Fig. 6) down to ploughing depth, causing a drop in maize yield of 31 % in the maize crop (Table 2).

Differences in soil physical properties still could be found in the following year, 1989 (Fig. 7), while wheat yield fell only 5 % (Table 2).

Table 2. Measured yield data for the three years of the study

treatment	1988 maize		1989 winter wheat		1990 summer barley	
	kg/ha	%	kg/ha	%	kg/ha	%
uncompacted	9422	100	4304	100	3878	100
compacted	6498	69	4066	95	3666	95

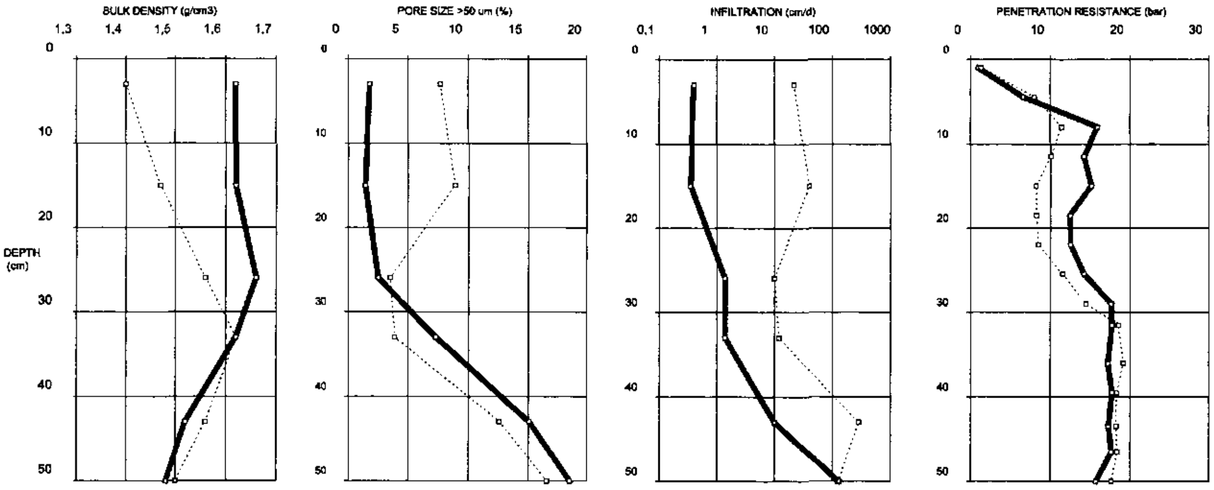


Figure 6. Soil physical properties after soil compaction 1988 (.... untreated plot, — compacted plot)

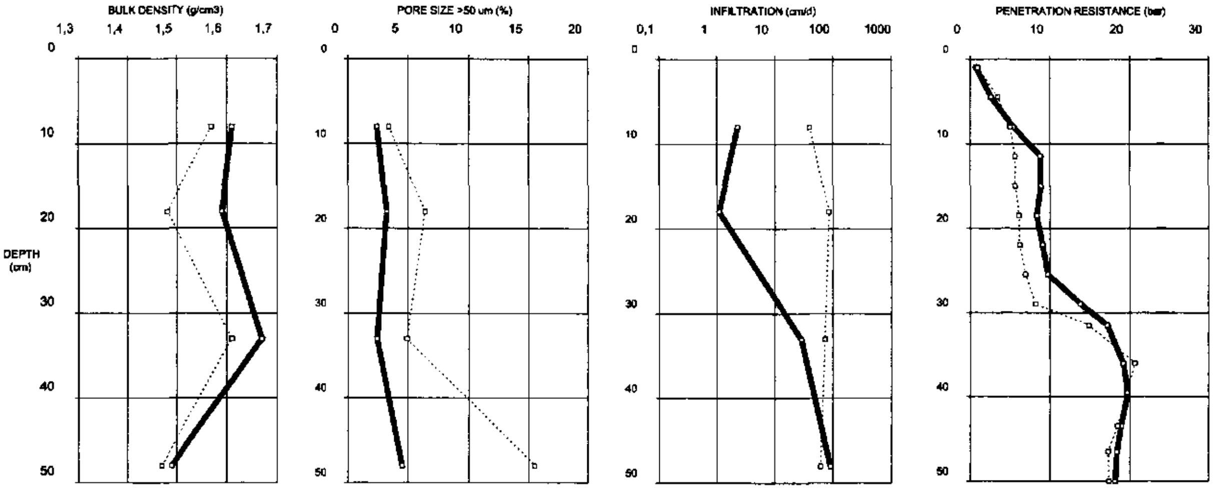


Figure 7. Soil physical properties 1989 (... untreated plot, — plot compacted 1988)

In 1990, the effect of compaction with lower tire pressure upon bulk density and pore size distribution was limited to only about 25 cm depth (Fig. 8) and yield depression of the summer barley crop was restricted to only about 5 % (Table 2).

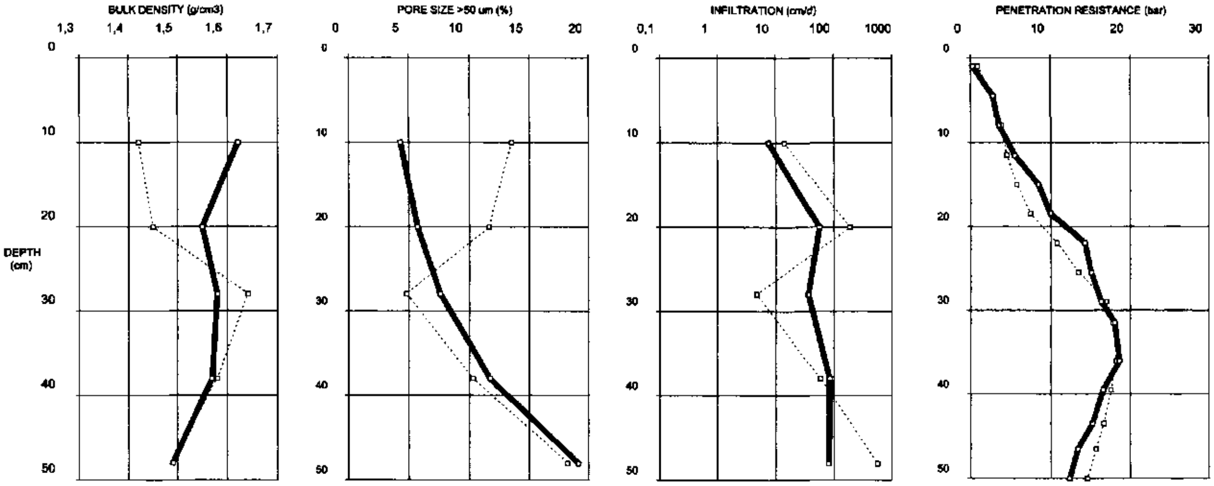


Figure 8. Soil physical properties after second soil compaction 1990 (... untreated plot, — compacted plot)

The experiments clearly demonstrated the adverse effect of compaction of this loamy silt-soil upon crop yield by reduction of the pore volume and by permanent plastic deformation of the soil structure.

3. Definition of the soil physics parameter

3.1 Laboratory methods

3.1.1 Water retention measurement (pF)
Method: Pressure chamber; sample size 200 cm^3
Range of measurements: 1-1500 kPa suction
Supplier: Soilmoisture Equipment Co., Santa Barbara, CA 93105
Unit: kPa

3.1.2 Density
Particle density (ρs)
Particle density is the density of the material
Method: Pycnometer method
Unit: g/cm^3

Dry bulk density (ρd)
Dry bulk density is the ratio of the mass of dry solids to the bulk volume of the soil. Mass is determined after drying to constant weight at 105 °C and volume is that of the sample as taken in the field. There was a minimum of three repetitions per soil layer; normally there are five repetitions.
Method: undisturbed samples; size 200 cm^3
Unit: g/cm^3

3.1.3 Particle size analysis
Textural triangle for soil textural analysis using the AG Bodenkunde, 1994 classification scheme.
Method: (< 2 mm particle size)
- organic matter removal with hydrogen peroxide (H_2O_2)

- Sieving:	dry sieving	> 2 mm
	wet sieving	≤ 2 mm
- Sedimentation:	pipet method	≤ 0.063 mm

3.1.4 Soil water content
Water content mass
The mass of water evaporating from the soil when it is dried to a constant mass at 105 °C, divided by the dry mass of the soil.
Unit: %-mass

Water content volume
Volume of water evaporating from the soil when it is dried to constant mass at 105 °C, divided by the original bulk volume of the soil.
Unit: % Volume

3.1.5 Saturated hydraulic conductivity

Method: constant head, undisturbed samples; size 200 cm^3
Unit: mm/d

3.1.6 Unsaturated hydraulic conductivity

Unsaturated hydraulic conductivity curves as a function of water content and pressure head.
Method: Experimental set-up uses microtensiometer and time-domain reflectometry microprobes in 1000 cm^3 undisturbed cylinders (Plagge et al., 1989).

Unit:	hydraulic conductivity	mm/d
	water content	cm^3/cm^3
	soil moisture tension	hPa

3.2 Field Methods

3.2.1 Penetrability (cone index)

Method: cone penetrometer ASAE Standard (1985)
cone diameter 12.83 mm, cone angle 30°, velocity 3 cm/s
Unit: bar

3.2.2 Soil water content

Method: Time-domain reflectomety
Unit: % Volume

3.2.3 Moisture Sensors

Gypsum block types:

"Beckman CEL WFD soil moisture blocks"	range: 40 - 1500 hPa
"Watermark granular matrix sensors"	range: 5 - 200 hPa

4. Literature

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MEASURING OF SHEAR PROPERTIES ON LARGE SOIL SAMPLES

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Abstract

A loading device for testing of large soil samples brought into the laboratory from the field is described. The measuring method is based on obtaining large cylindrical samples of undisturbed soil. Sample size is 0.30 m in diameter and 0.30 m height. The samples are placed in the loading apparatus where normal stress is applied to the top by means of a circular plate. Part of this plate consists of a shear ring which may be rotated through app. 170 deg while the normal load is maintained. During the measuring process the sinkage of the loading plate, the sinkage of the shear ring during rotation, and the development of the shear stress are recorded. Some measurements were performed on samples of clay soil obtained from experimental plots. Half of the samples had received annual mouldboard ploughing and the other half was unploughed. The results showed no significant difference between the two treatments concerning cohesion and angle of internal shearing resistance. Likewise, no significant difference was found regarding the shear deformation modulus. Concerning the latter parameter it was, in addition, found to be independent of the normal stress.

Introduction

Measurement of the soil's mechanical properties is an ever important problem. Various devices are used depending on the particular property about which information is needed. The information may be used for solely soil characterising purposes as in Olsen (1986) or it may be used for simulation of a process. Examples of the latter is modelling the soil surface's resistance to erosion (Zimbone et al., 1996), prediction of the force required to move a tine through the soil (Reece and Hettiaratchi, 1989) and prediction of the drawbar pull force from a tractor's driving wheels (Wong, 1984).

Some measuring methods as, e.g., penetration measurements provide results that consists of an unresolvable mixture of strength parameters. Others, as measurements of the soil's shear strength, has the benefit of expressing the results in terms of well-defined physical parameters, i.e., cohesion and angle of internal shearing resistance

Shear measuring devices may be classified according to their use in the laboratory or in the field. Usually the laboratory equipment operates on soil samples of limited size which may give rise to problems due to the inhomogeneities in the form of stones and cracks that are often present in the soil. The advantage of laboratory equipment is that, usually, the measuring conditions may be very well controlled.

For the devices to be used in the field there exist, of course, no limitations due to sample sizes. However, limitations concerning the soil volume under test may arise from the amount of available power, the limited weight of the equipment, or similar factors. Though, usually the amount of soil involved in the measurements will exceed the amount for a corresponding laboratory test whereby the influence of inhomogeneities may be reduced as compared to a laboratory test. The problem of field measurements is very often that the measuring conditions may not very easily be controlled. Quite often one has to be content with recordings of the actual conditions concerning, e.g., soil moisture.

In an attempt to - at least to a certain degree - combine the benefits of field- and laboratory measurements a new device was constructed and tested. Basically, the apparatus is a laboratory ring shear device that operates on relatively large soil samples.

Objective

Prior to the construction of the device, some desires and goals were set up concerning various details of the system.

The sample

The overall basic requirement of the soil sample when loaded in the laboratory is that it behaves mechanically just as if it were in undisturbed condition in the field and exposed to an identical loading. This is hardly possible to achieve totally but it should be the goal to come as close as possible to this condition.

The first condition to be fulfilled in order to approach this goal is that the soil sample should be disturbed as little as possible by the sampling procedure, i.e., when physically obtained from the field. Generally, this calls for large samples and a cautious sampling procedure. The machine used to obtain the samples comes very close to these requirements as described by Persson and Bergström (1991). The cylindrical soil sample is continually lined by a strong plastic tube during the drilling process and thus safely enclosed when finally obtained. The maximum working depth for the sampling machine is 1 m and the sample diameter is 0.30 m. The height of the sample may be anything between approximately 0.3 m up to 1 m depending on the height of the sample tube mounted in the sampling machine. Likewise, intermediate soil samples may be obtained from, e.g., 0.5 to 0.8 m depth by cutting out the appropriate height from a full-height sample.

The apparatus

The primary task of the loading apparatus is to set up a certain stress field in the soil sample. Ideally, the soil sample should be acted upon in the same way as if it had never been taken. This is hardly fully possible but it may serve as a goal that should be approached as closely as possible.

The stress field is accomplished by applying a combination of normal- and shear stress to the soil sample's surface. The shear stress should be set up for only a part of the sample's surface in order to avoid complex stress fields at the outer cylindrical boundary of the sample. It is considered essential that normal stress should be applied on all surfaces that surround the shearing surface, as reported by Janosi and Karafiath (1981). Furthermore, normal stress should, of course, be maintained at the desired level on both shearing and non-shearing interfaces.

Before mechanical loading of the soil sample it should be possible to establish a certain water tension in the sample. This tension should be maintained throughout the mechanical loading during the shear test.

During the loading process the apparatus should allow measurement of both the mechanical loading intensity and the soil's response. For the loading intensity, the magnitude of the stress levels may be measured indirectly by individually recording the forces on the faces setting up the normal stress and the face for the shear stress on the soil surface. Additionally, the shear magnitude, i.e., the length of the movement of the shearing face, should be measured.

The reaction of the soil should primarily be measured in terms of sinkage of the stress faces. Here it should be observed that the shear face may have a sinkage different from the normal stress faces. Furthermore, the soil's loss of water during the loading process should be measured.

Design

The most feasible design of the loading apparatus was found to be a modified type of shear ring device. The modification, as compared with a more traditional type like the device described in Olsen (1984), concerns the way the surface stresses are set up by the loading head. For the traditional device, the soil surface outside and inside the ring is unloaded concerning normal as well as shear stresses. This means that as the soil below the ring is loaded it will have the possibility to move laterally out of the way below the ring in order to escape the stress field. Therefore, the sinkage of the ring - especially during the shearing process - will be false. It does not correctly reflect the soil's deformation as a function of the applied stress field as described by Janosi and Karafiath (1981).

The loading head

For this reason, the loading head was designed as shown in Fig. 1. The circular plate which transmits the normal stress and fits into the plastic tube containing the soil sample is divided into three parts. The outer ring-shaped part and the central circular part are fixed together by means of a bridge construction and constitute the static part of the normal load system. The intermediate ring-shaped part constitutes the shear ring itself.

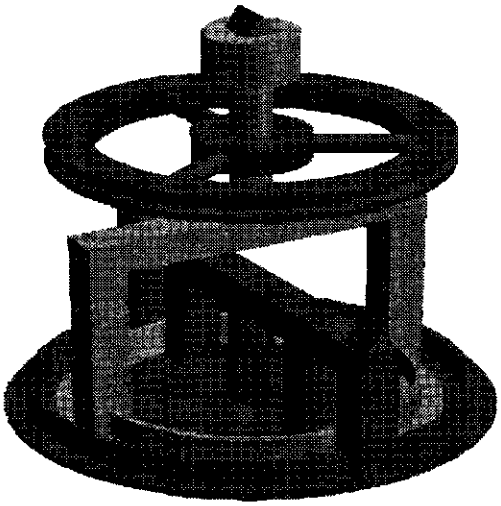

Fig. 1. Schematic picture of the loading head for the apparatus. The normal stress is applied to the soil sample's surface by the lower circular plate. Part of the plate constitutes the shear ring and is shown in a lighter shade of grey.

The normal stress exerted by the shear ring is applied by means of another bridge carrying a short vertical axle with a horizontal roller bearing at its top and a knife edge bearing on the top of the roller bearing. Another vertical force is applied to the top knife edge while still - by virtue of the roller bearing - allowing the shear ring to turn.

The shear stress is set up by applying a torque to the vertical axle by means of a drive pulley as shown in

Fig. 1. Two wires are fixed to the pulley and wound up so that when opposing forces are applied to the wires a torque is set up to the shear ring without introducing side-forces to the loading head. From

Fig. 1 it is noted that - due to the bridges - the shear ring may be rotated through a little less than half a circle. However, the resulting shear length of app. 300 mm was considered sufficient.

In order to transmit the shear stress to the soil, the bottom faces of the loading plates are covered with a sandpaper of grain size P16, i.e., a relatively coarse quality. In order to withstand the moisture from the soil sample a sandpaper with textile base was used and it was glued to the loading head using a water resistant cement.

Normal stress system

The normal stress for both the static and shear ring part of the loading head is set up by means of dead weights. The arrangement is shown in Fig. 2. The required normal forces on the loading head are accomplished by the use of 2 levers resting in points with knife edge bearings. Both levers are loaded by a common dead weight at the left-hand ends. The loading ratio for the individual levers is adjusted according to the area of the shear ring and the static part, respectively. In this way, the static part and the shear ring may - within certain limits - have different sinkages and still the same normal stress will be maintained on both surfaces. Adjustment of the sample's vertical position is accomplished by means of a manually operated hydraulic ram.

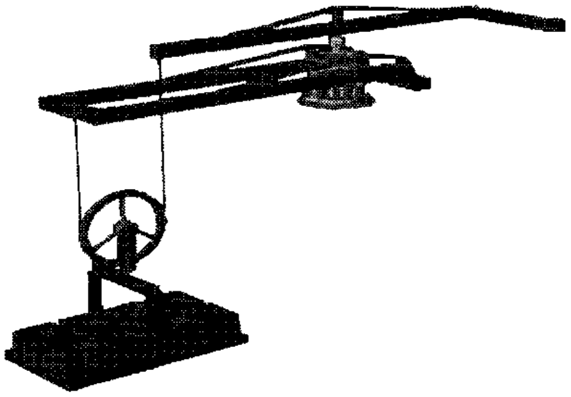

Fig. 2. Loading arrangement for the normal stress. The upper lever controls the normal stress for the shear plate and the lower one for the static part of the loading head. At their right-hand end both levers are suspended in knife edge bearings and thus restricted with respect to translational movements. The loading head is shown below the intermediate bearing points of the levers.

The diameter of the loading face is 0.293 m and thus the area amounts to 0.0674 m^2. The system is designed for a maximum normal stress of 200 kPa. The minimum normal stress is 21 kPa due to the weight of the loading head and lever arms.

Shear stress system

The shear stress on the sample surface is accomplished by means of a wire system and an electric motor assembly as shown in

Fig. 3. At the loading head, the torque is set up by opposing forces in 2 wires in order to avoid a side force on the head.

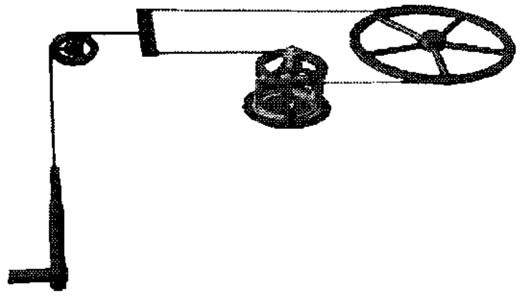

Fig. 3. The shear stress system. The loading head is shown in the middle of the figure. The torque required to set up the shear stress below the shear ring is brought about by means of a wire system and a linear electric motor shown to the left.

The outer diameter of the shear ring is 0.232 m and the inner is 0.174 m which means that the area of the ring is 0.00264 m^2. The rotational movement of the shear ring is restricted by the mechanical construction to app. half a circle, thus maximum shear length measured at the mean radius is 0.29 m. The device is designed for a maximum shear stress of 150 kPa.

Measuring system

During a loading cycle the soil sample's reaction is measured by means of various techniques. The force that accomplishes the normal stress is not measured. Because this force is set up using dead weights it is assumed that it may be calculated with sufficient accuracy.

The bridge that transmits the torque to the shear ring is instrumented with strain gauges. In this way the torque is measured as close as possible to the shear ring and the shear stress is then calculated based on the area of the ring.

The vertical movements of the static and shear parts of the loading head and the rotation of the shear part are measured using a video camera which records various markers on the head. The images are transmitted to a computer which calculates the movements of the markers.

Similarly, the vertical position of the lower edge of the triangular marker shows the sinkage of the shear ring. Finally, the height of the triangular marker immediately below the circular marker shows the actual angle of rotation for the shear ring. This height is indicated in the figure as the vertical distance between the arrows.

The video image is transferred to an image analysis system in a computer and the positions and distance mentioned above is determined by means of a suitable program.

Fig. 4 shows a photo of the entire loading device. A soil sample lined in its plastic tube is mounted and ready for testing. As mentioned earlier, the normal stress is set up by means of dead weights. The basket for the weights is visible in the left-hand side of the picture.

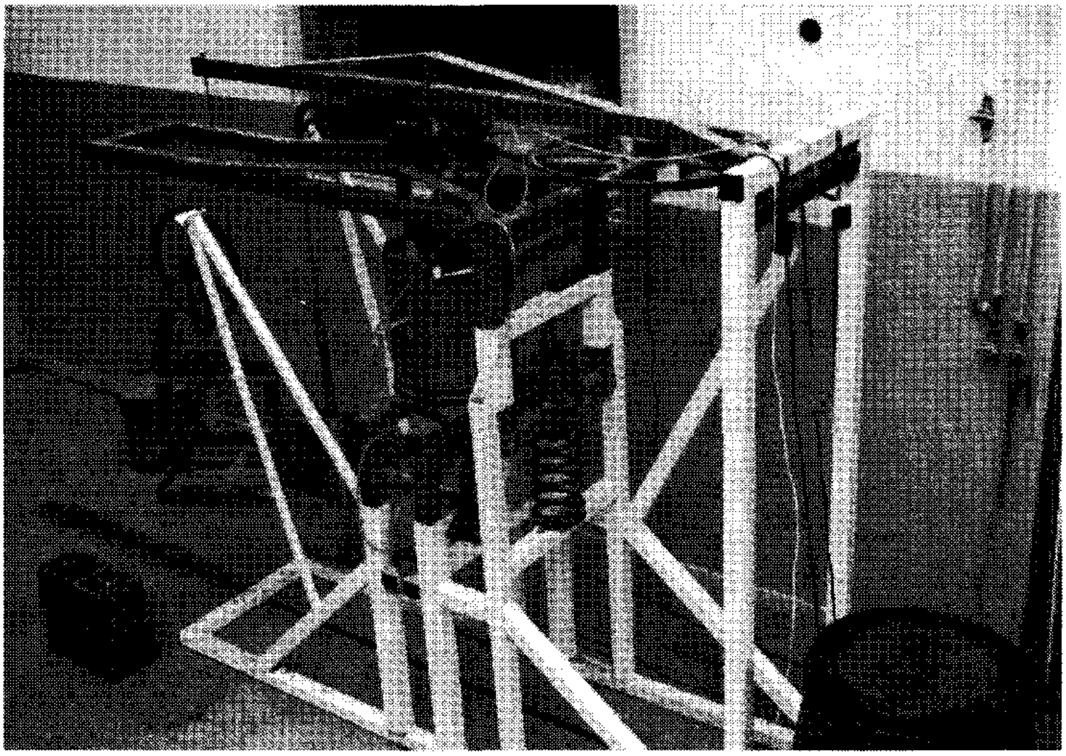

Fig. 4. Photo of the loading device. A soil sample is mounted for loading.

Measurements

In order to obtain some experience with the device and to investigate the difference in mechanical properties for agricultural soil that has been ploughed annually compared to the same soil that has been tilled in the top 0.15 m only large samples were brought into the laboratory and exposed to shear tests.

Soil material

The soil samples for the measurements were obtained from experimental plots. A total of 14 samples were collected. Half of these had received annual mouldboard ploughing in the autumn as is normal agricultural practise in this area. The ploughing depth was 0.25 m.

The other half of the plots had not been mouldboard ploughed for a period of 10 years. Instead, these plots had been tilled in the autumn with a cultivator to a depth of 0.15 m.

The soil type was heavy clay with 8 % sand, 31 % silt, and 61 % clay. During the previous 10 years it had been in a rotation with barley, oats, winter wheat, and rape.

The samples were obtained in undisturbed condition in strong plastic cylinders using a special equipment as described in Persson and Bergström (1991). The cylinders measured 0.4 m in height and 0.3 m in diameter.

Method

In order to obtain an estimate of the coulomb curve for a specific soil a number of shear tests at different normal stresses must be performed each test resulting in one point on the curve. It is obvious that these tests in the ideal case should be carried out on the same soil at the same place. This is, however, not meaningful because once a shear test has been done in a certain location the soil's internal structure at that place has been changed - a considerable number of the bondings between the soil particles have been broken.

Therefore, in the field, the tests should be performed as close to each other as reasonably possible in order to minimise the soil variation from one test to another. Translated to the laboratory environment this means that each sample should be used only once for a shear test at one particular normal stress. In the field, the samples should, of course, have been obtained close to each other.

However, primarily due to the size of the samples a considerable amount of labour and cost was invested in each sample once it was ready for testing. Therefore, it was decided to run successive shear tests on the same sample. This testing scheme made it necessary to determine the depth to which the soil below the shear ring was permanently disturbed as the internal bondings in this part of the soil was destroyed and this soil layer would have to be removed prior to the next test. Determination of this depth was done by carefully drilling a hole 2 mm in diameter and 15 mm deep in the part of the soil surface that would be subject to shearing during the following test. The hole was filled by stacking coloured plastic spheres of 1.8 mm diameter. The position of each sphere with reference to the sampling cylinder was recorded.

After the shear test the spheres were carefully excavated and their new position recorded. In this way it was found that the spheres below 6 mm depth were never displaced even at the highest normal stresses used. Based on this experience from 6 experiments it was decided to remove the top 6 mm of the samples between each shear test. The removal was done using a special knife mounted in a frame that referred to the top edge of the sampling cylinder so that it could be adjusted to the exact depth for the following shear test. The knife was operated very carefully so that the soil below the knife edge was left undisturbed. Because the removed volume of soil was well known it was dried and its moisture content and dry bulk density determined.

In this way, successive shear tests for the same Coulomb curve were performed on soil layers of increasing depth as each layer was located 6 mm below the preceding. This is certainly not ideal since the soil mechanical properties changes with depth. However, it was assessed that the soil properties did not change considerably over the depth interval of interest. This depth interval comprised approximately 50 to 60 mm as, typically, 8 to 10 shear tests were done for estimating the Coulomb curve. This limitation of the number of tests was due to, partly, the necessity of limiting the depth interval between the first and the last shear test and, partly, the construction of the shear head limited the intrusion of the shear- and normal stress surfaces into the sample cylinder to approximately 80 mm. The reason that only 8 to 10 tests could be done was that, in addition to the removed soil, the surface would sink due to the normal stress.

This way of performing the tests also included that the normal stress for the individual tests had to be steadily increased so that the first test was done at the lowest normal stress and the last one at the highest. This is also not a very ideal way but, again, necessary due to the limited number of samples available. In the field situation the normal stress for a certain shear test should be selected randomly within the capacity range of the equipment. For the actual tests this was, however, not possible. Consider a test performed at a high normal stress and the following one at a lower normal stress. This would cause the soil to be overconsolidated for the latter test.

Due to constructional limitations of the device the shear velocity was relatively low. Thus, at the mean radius of the shear ring it amounted to 32 mms^{-1}.

First time a sample was mounted in the apparatus it was subjected to a normal stress of 21 kPa which was the lowest normal stress that could be set up. This stress was maintained until water had ceased to leave the sample, normally about 24 hours.

Between each test the sample was moved out of the loading device and onto an auxiliary frame for penetration tests and removal of the upper disturbed soil layer. For this operation it proved very convenient that the water collecting arrangement was fastened to the sample cylinder so that the hydraulic head was maintained.

While setting up the normal stress prior to a shear test the amount of water leaving the soil was collected and measured. Likewise, during a shear test an eventual change in soil water content was recorded.

The soil cores were obtained from the field by means of the equipment described in Persson and Bergström (1991). After being brought home they were covered with plastic sacks and stored in an unheated barn. In this way they would dry out to some degree but extensive anaerobic processes in the soil was prevented. The drying was considered less important since the water content would be adjusted at testing time.

Because the aim was to compare the influence of the two treatments the upper 0.15 m of the soil was removed for all samples in order to expose the soil below the tilling depth for the unploughed plots and measure at the same depth for the ploughed plots. Thereafter, the remaining soil was moved within the cylinder so that the new surface was flush with the upper edge of the cylinder. The bottom of the soil core was covered with geotextile after which the empty space below the soil core was filled with stone flour, i.e., crushed and ground granite sieved through an 80 mesh sieve.

Below the stone flour a one millimetre thick water permeable sheet of sintered, very small, plastic spheres was inserted. The sheet rested on a 20 by 20 mm mesh of plastic wire with 2 mm diameter and the mesh, in its turn, rested on the firm bottom lid for the sampling cylinder. The bottom was equipped with 4 holes through which the water could escape in 4 hoses interconnected into one that had its other end submerged in a container so that no air could enter through the bottom of the sample. The bottom lid was mechanically fixed to the sampling cylinder with 4 screws and the connection between the lid and the cylinder was covered with a 50 mm wide plastic tape wound around the sampling cylinder. In order to secure an airtight connection, the upper and lower edge of the plastic tape were covered with heat-melting glue. Fig. 5 shows a schematic picture of a sample, to the left a view of a prepared sample ready for testing and to the right a vertical cross section of the sample.

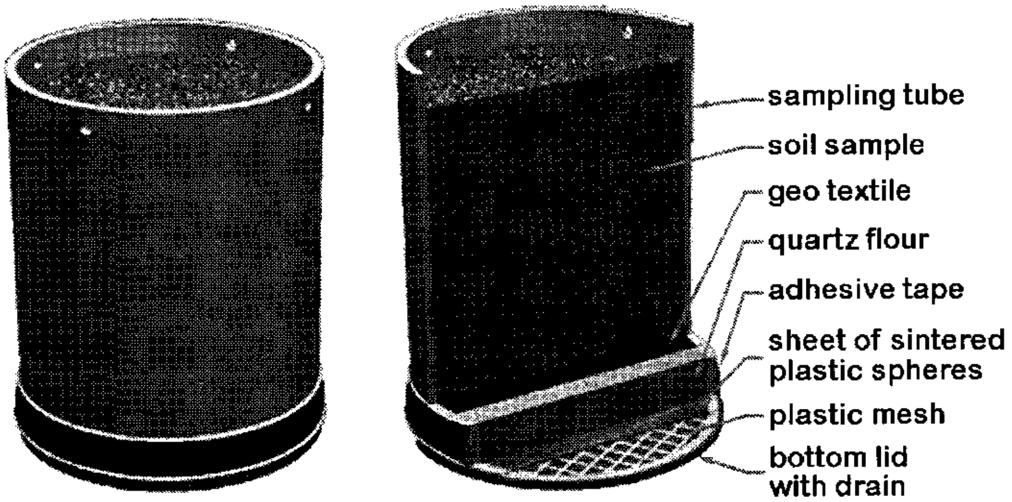

Fig. 5. Schematic picture of a soil sample ready for testing. To the left an outside view of the sample. To the right a cross section through the sample which shows the positions of the various components. See text for further details.

The various components of the sample had the following functions. The geotextile simply served to separate the soil from the stone flour. The role of the flour was to fill up the space below the soil and extend the soil's pore system to the bottom of the sampling cylinder thus securing that a reasonable water tension might be set up in the sample. The sheet of sintered plastic spheres prevented the flour from following the drainage water out of the sample and eventually block the external plastic hoses. The coarse mesh at the bottom secured that the water could move freely to the holes in the bottom lid. The self-adhesive tape was fitted in order to allow minor movements between the sample cylinder and the bottom without loosing the air-tightness when the sample was loaded mechanically.

After being prepared the sample was placed in a container and slowly soaked with water. The water was let into the sample from the bottom as the water level in the container was slowly raised. The level was raised 20 mm per day and after the soil surface was flooded the sample was left for a 14 days period. Then the water level was lowered, also at a rate of 20 mm per day.

When the water level reached the sample bottom a cup was connected to the draining plastic tube and attached to the sample cylinder. The sample was lifted off the water container and placed in the loading apparatus. Before setting up the pre-load of 21 kPa the cup was lowered at the same rate as earlier until it reached the level of 0.6 m below the soil surface. Thereafter, this level with respect to the soil surface was maintained during the shear tests so that these were performed at a water tension of 6 kPa.

The following shear tests were then performed at normal stress levels of 46, 71, 96, and 121 kPa. Two to three repetitions were done for each level as allowed by the limited sinking of the shear head due to the device's construction.

Results

The shear deformation modulus (*K*) reflects the distance that the soil must be sheared before the maximum resistance to shear is developed. Thus, when the soil is sheared under a certain normal stress, the shearing resistance increases more or less linearly up to the maximum value for that particular soil. This maximum value is denoted the shear strength of the soil. During the process the soil material yields to a limited extent as shown in Fig. 6. Here the result from a real test is shown together with an idealised curve where *K* is shown as the x-value for the breakpoint. Thus, the *K*-parameter reflects the plasticity of the soil and it influences the maximum thrust that a driving wheel may deliver according to Wong (1978).

The data material was examined for dependence of *K* on the soil treatment and the result is shown in Fig. 7. An analysis of variance was performed for each group of constant normal stress in order to reveal whether there was any difference between the ploughed and unploughed soil. In no case did the analysis show any significant difference on a 95 percent level.

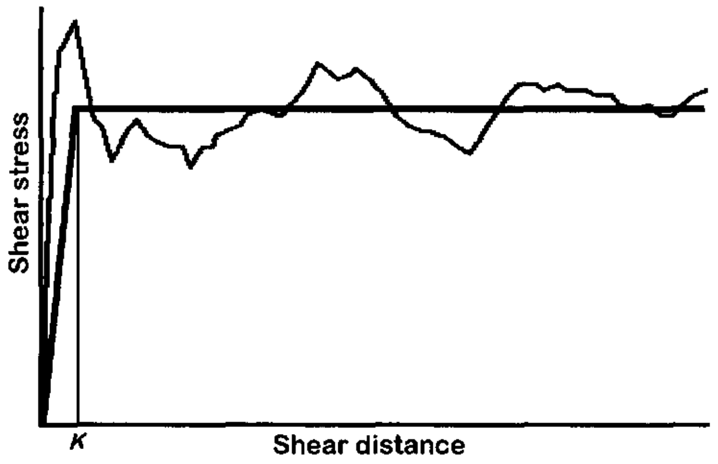

Fig. 6. Example of a shear stress vs. shear distance curve shown together with an idealised curve demonstrating the definition of the *K* -parameter.

In order to find out whether there was dependency between *K* and normal stress data from the ploughed and unploughed soils were joined. This combination of data from the two treatments was justified by the result from the analysis of variance described above. The analysis for dependency was done by calculating a linear regression between *K* and normal stress. The slope of the regression line did not differ from zero when a 95 per cent significance level was used. Thus, it was concluded that no dependency exists between *K* and normal stress.

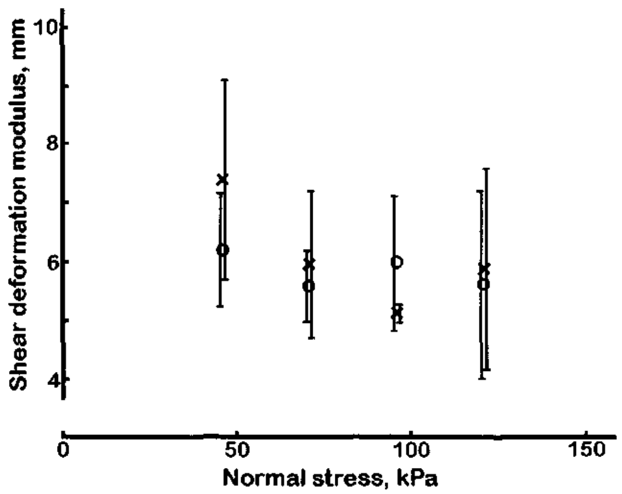

Fig. 7. The diagram shows the relation between *K* and normal stress. The label "x" denotes the ploughed soil and "o" the unploughed. The error-bars have a length of 2 times the standard deviation and are centred on the mean values. For better legibility the error-bars for the unploughed soil are slightly offset to the left.

For each sample a Coulomb curve was calculated based on the normal stresses and readings of the maximum shear stress for each level of normal stress.

Fig. 8 shows an example of such a Coulomb diagram where the curve is fitted by means of a least squares regression. The cohesion is found as the offset on the y-axis and the angle of internal shearing resistance as the slope of the curve.

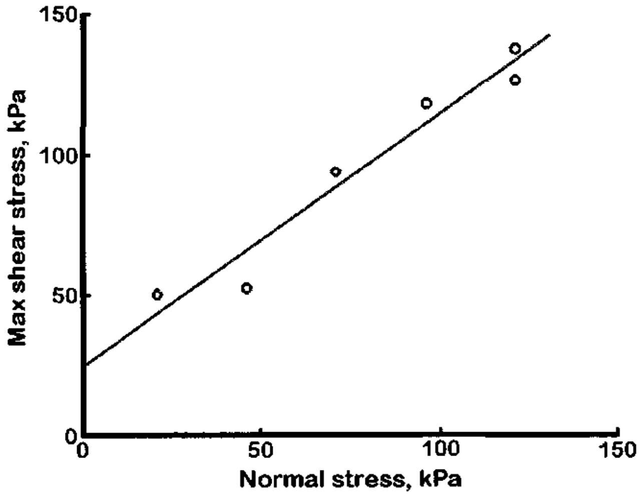

Fig. 8. Example of Coulomb diagram. The estimated parameter values of cohesion and angle of internal shearing resistance for this measurement is 25 kPa and 52 deg. respectively.

An analysis of variance was calculated in order to investigate whether there was any difference between the cohesion and angle of internal shearing resistance for the two treatments. The probability of getting the resulting F-statistic was calculated to 75 and 92 per cent respectively. Thus, no significant difference concerning the cohesion and angle of internal shearing resistance for the two treatments was found.

Discussion

In order to simulate normal agricultural conditions to a higher degree it would have been desirable to perform the measurements at a somewhat higher water tension than 6 kPa. In a few initial trials it was tested whether a tension of 7 kPa could be maintained. However, it proved nearly impossible to handle the samples at this water tension and, therefore, 6 kPa was selected as standard.

There has earlier been some ambiguity as to whether the *K*-parameter was dependent of the normal stress. Thus Olsen (1981) found a slightly increasing tendency of the *K*-parameter as a function of normal stress. However, the device that was used for these measurements was of a conventional type with no provisions for setting up a normal stress on the soil surface outside and inside the shear ring. Hence, the observed dependency of *K* on normal stress could be caused by soil escaping from below the ring in radial direction during the initial increase of shear stress. Due to this escaping the ring may sink and engage new soil material in the shear process which will be extended before stable conditions are met and the maximum shearing resistance occurs.

The explanation above seems plausible in the light of the present results where no relation between *K* and normal stress could be detected. Furthermore, the shape of the shear-deformation curves like the example shown in

Fig. 6 differ for the new device compared to previous constructions. The residual stress, i.e., the part of the curve for the deformation exceeding *K*, is generally more constant when measured with the new shear head. The major difference between earlier devices and the actual one concerning the shear head is that, due to the provision of a normal stress both inside and outside the shear annulus, the soil cannot escape in lateral direction during the test. In addition, this is confirmed by the fact that no sinkage of the shear head - not the static normal stress part nor the shear ring - could be measured during the shearing action.

Compared to earlier experiments in which the shear deformation modulus was recorded the values of *K* for the actual tests are considerably smaller. Thus, Olsen (1981) found values of *K* about 30 to 50 mm whereas these values for the current measurements fall in the range from app. 4 to 8 mm, i.e., nearly 10 times smaller. These results corresponds well to the experiences reported by Janosi and Karafiath (1981) who also recorded considerably smaller *K*-values than those obtained when using a conventional shear ring device.

Based on the above explanation of the large *K*-values one may think that the newly measured smaller values are more correct than the old ones. This may, however, be a somewhat wrong conclusion. If one is concerned with calculation of the drawbar pull that may be developed by a certain wheel the correct *K*-values to use in these calculations will probably be very different from those measured by use of the actual device. This is due to the circumstance that, also for the case of a wheel, the soil surface surrounding the contact area lacks a normal stress. Thus, the soil will also have some possibility to escape in lateral direction in this situation.

Rather, one may conclude that the results from measurements of the shear deformation modulus will depend on the method and - probably - on the dimension of the shearing device that is used.

As noted earlier, no significant difference was found concerning the cohesion and angle of internal shearing resistance for the two treatments. This may seem a little surprising since the unploughed soil samples were generally in a somewhat denser state compared to the annually ploughed. It may, however, be prescribed to the moderate water tension which caused the soil to be in a quite wet state. Therefore, both soils had a reduced strength compared to dryer conditions which will be prevailing when agricultural operations are performed. The softer state of the experimental soil may have obscured a larger difference in the Coulomb parameters which would have occurred under dryer conditions.

It is noteworthy that the angle of internal shearing resistance often exceeded 45 deg. This means that the shear stress required to produce failure is higher than the normal stress for that test. This is seldom found with a conventional shear ring apparatus and it is believed, that the frequent occurrence in the actual experiments is due to the special normal loading of the soil surface.

Conclusions

Based on the results and experiences for the experiments described above the following conclusions may be drawn.

1. Only the very top layer of less than 10 mm depth was permanently affected by the shear process.

2. At a water tension of 6 kPa the cohesion and angle of internal shearing resistance was found to be unaffected of annual mouldboard ploughing compared to no ploughing.
3. No relation was found between the shear deformation modulus and normal stress.
4. The shear deformation modulus was unaffected by annual mouldboard ploughing compared to no ploughing.
5. Due to the maintenance of a static normal stress around the shear annulus no shear sinkage occurred.

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SUBSOIL COMPACTION IN SCOTLAND

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Abstract

SAC and its predecessors have conducted research into soil compaction in Scotland since the 1960's. Although subsoil compaction has not been identified and addressed as a separate problem, several research projects have produced relevant data. We developed suitable methods and techniques for compaction work. Among the measurements we have made are bulk density, shear strength, cone resistance, macroporosity, relative diffusivity, air permeability, water infiltration rate and image analysis. In addition to crop yields, we have measured the emissions of nitrous oxide from the soil and nitrate leaching. The climate of Scotland is moist, so soil compaction is likely. The average sizes of new tractors are increasing consistently, and there are no indications that this trend will change, so the problem is likely to increase in the future. Many Scottish subsoils are naturally compact, so additional machine-induced damage is unlikely on these soils. On compactible soils, regeneration of subsoil structure by natural process is negligible. Gamma-ray transmission is a useful method for measuring bulk density of subsoils because it is relatively non-destructive; it is faster than competing methods; and depth resolution is good with suitable equipment. However, soil variability is a major problem in assessing the intensity, extent and impact of subsoil compaction or loosening. Large numbers of samples are needed to detect typical subsoil compaction effects. The cone penetrometer can be useful but sometimes results are inconclusive and anomalous. On imperfectly drained soils, subsoil denitrification is a substantial sink for nitrogen and subsoil compaction is likely to increase the denitrification rate.

Introduction

SAC is the main centre for research into soil compaction in Scotland and the upland parts of the UK. This research has its origins in the 1960's in the former National Institute of Agricultural Engineering, Scottish Station, and the East of Scotland College of Agriculture (Soane, 1970). These organisations have since changed their names and amalgamated with others to form the present SAC. The original concern was that permanent damage to the soil was likely to result from the increasing mass of agricultural machines and number of field traffic operations. At that time there was a move towards continuous arable cropping and away from grass leys and also increasing intensity of use of marginal land. Both of these trends would intensify any compaction problem. The main emphasis was on topsoil compaction and the effects of compaction on crop productivity (Soane, 1975). During the 1980's, there was a change in emphasis away from maximising crop yields to protecting the environment.

Much of the work has been concerned with the measurement of soil structural quality and these aspects were reviewed by Ball *et al.*, (1997). Methods and techniques were designed to give results with enough accuracy, precision and spatial resolution to discriminate between experimental treatments. We developed instruments and sampling techniques to detect the often thin layers of compact soil that can be important for root penetration and fluid movement. Among the variables we have measured in compaction work are bulk density, shear strength, cone resistance, macroporosity, relative diffusivity, air permeability and water infiltration rate. We have also analysed images of pores from resin-impregnated blocks of soil. Among the environmental impacts we have measured are the emissions of nitrous oxide from the soil and nitrate leaching. We have also developed innovative methods for measuring the mechanical properties of soils in the laboratory. Among these methods are the constant cell volume triaxial apparatus (Hettiaratchi *et al.*, 1992) and a simple shear box that allows us to measure the effects of deformation on structural parameters (O'Sullivan *et al.*, 1997).

Subsoil compaction has not been a central theme to any of the research projects but we have studied it in a number of ways. We have carried out experiments on compaction under wheels that have provided some insights into the causes and likely intensity of subsoil compaction. We have also conducted field experiments on subsoil loosening. Some of our work on the nitrogen cycle is potentially relevant to the environmental impacts of subsoil compaction. There has been no work, to our knowledge, that examined the crop productivity implications of subsoil compaction by heavy vehicles in Scotland or in the wetter, upland parts of the UK generally.

The objectives of this paper are three-fold. First, to describe what is known about the nature and extent of subsoil compaction in Scotland; second, to outline some of our experiences in measuring compaction in subsoils; and third, to describe some of our work on soil nitrogen that is relevant to the environmental impacts of subsoil compaction.

Incidence of subsoil compaction in Scotland

Scottish climate

The climate of Scotland is classified as warm temperate maritime or very maritime (Martyn, 1992). Within the agricultural areas, the median maximum soil water deficit is less than 75 mm, except for some small areas on the east coast. Excess winter rain increases from about 195 mm in the south eastern coastal plain up to about 545 mm in upland areas. Typically, the soils depart from field capacity in early March and return to field capacity in mid October (Francis, 1981). Average January temperatures vary from 0.9° C in the north eastern uplands to 3.5° C at Ayr on the south west coast.

The subsoils tend to remain wet throughout the year (Duncan, 1979). This is illustrated by results from one of our field experiments (O'Sullivan, 1985). We found that, below about 600 mm depth, water content remained fairly constant with time, while matric suction was generally less than 10 kPa and rarely exceeded 30 kPa. Such wet conditions make soil both weak and compactible and, consequently, increase the likelihood of compaction and structural damage by wheel traffic.

Extent of the problem

There is very little information about the extent or severity of subsoil compaction in Scotland because the subject has not been studied explicitly. However, there are some pieces of information that indicate how seriously farmers perceive the problem.

In the mid 1980s, Soane and Kershaw (1987) carried out a survey of Scottish farmers to discover the extent of compaction problems generally and the measures that were being adopted to control compaction. This survey did not ask specifically about subsoil compaction but 25% reported that they encountered a compaction problem in most or all years. The severity of the problem increased with farm size and was greater on arable than on stock or dairy farms. The most damaging operation was thought to be harvesting potatoes and root crops, followed by slurry and dung spreading, silage making and harvesting of grain crops. The most frequently employed precaution or remedy was cultivation, such as deeper ploughing or subsoiling. The choice of deep cultivation as a remedy is an indication that many farmers believed that compaction was affecting the subsoil.

There is also anecdotal evidence that subsoil compaction is seen as a problem. For example, SAC agricultural advisers report that that many farmers have trouble with cultivation pans.

Scottish subsoils

There are a number of local soil factors that are likely to affect the incidence and severity of subsoil compaction in Scotland. Some characteristics of the subsoils make machine-induced compaction less of a problem than one would expect from the climate. On the other hand, there are also some characteristics that could increase the severity of the problem and reduce the extent of natural recovery.

In the farming areas of north east Scotland, most soils have naturally occurring indurated layers that are hard and compact (Glentworth and Muir, 1963). These horizons are thought to result from freezing and thawing of puddled soils in permafrost conditions, possibly with some later translocation of clay. Since they are already highly compact, with dry bulk densities commonly up to 2.0 Mg m^{-3}, further compaction by human activity is unlikely. Although these indurated layers are a barrier to root growth and can impede drainage, mechanical loosening tends to be unsuccessful. The yield benefits of subsoiling are small compared to the costs of the operation, while any positive effect tends to be short lived. The particle size distribution tends to make the subsoils naturally compactible and poorly structured, so they re-compact very easily. Subsoil loosening also causes damage to the topsoil and disrupts other farming operations.

Indurated layers are uncommon in central and southern Scotland. However, many of the soils under arable cultivation in this region are developed on lodgement till, or basal till, which is material that was deposited under glaciers. This material was subjected to high loads at and after deposition and, as a result, many of these subsoils are naturally compact. Similar compact subsoils occur in other parts of northern Europe and North America (Håkansson and Reeder, 1994). Dry bulk densities of 1.6 to 1.7 Mg m^{-3} are common at 400-500 mm depth in such soils in Scotland (Smith and Dickson, 1990). As with the indurated layers in the north east, further compaction of these soils by human activity is unlikely. In this case also, subsoiling is generally ineffective because the soils rarely dry out enough for brittle failure to occur and they re-compact easily after loosening (O'Sullivan, 1992).

Apart from these two cases of naturally compact subsoils, the wet state of many Scottish arable subsoils makes them susceptible to compaction. Furthermore, recovery from subsoil compaction by natural processes is likely to be minimal for a number of reasons. There are not many heavy clay subsoils in Scotland. The main clay minerals are kaolinite and illite (Ragg and Futty, 1967), which do not shrink very much on drying, compared to montmorillonite. In addition, as we have already mentioned, the subsoils do not dry out very much. Consequently, shrinkage and swelling are unlikely to contribute much to recovery from compaction. Frost does not penetrate into the subsoil in the arable areas of Scotland, so freezing and thawing do not contribute to subsoil loosening either. An additional factor is that, as a consequence of the wet subsoil conditions, there is very little root growth below 400 mm depth and almost no root or faunal activity below 600 mm depth (Willatt, 1986; Ball and O'Sullivan, 1987). This reduces the possibilities of amelioration of compaction by biological activity (Håkansson and Reeder, 1994).

Future trends

Problems of subsoil compaction are likely to increase in the future. The average size of tractors sold in the UK has increased by about 1.7 kW per year over the last ten years. This increase has been consistent despite fluctuations in the total numbers sold (Fig. 1) and there are no indications that this trend is likely to change. The most remarkable change has been in the medium size range, where the proportion of 75-100 kW tractors has increased at the expense of the 50-75 kW machines, as shown in Fig. 1. The proportion of very large tractors (>100 kW) has also increased. The size of the average tractor sold in 1997 was about 80 kW, excluding small tractors of less than 30 kW. The mass of tractors and, thus, their potential for causing subsoil compaction tends to increase in proportion to power. Farmers will buy bigger machines to match the big tractors, so this trend towards increasingly large machinery will increase the probability of subsoil compaction.

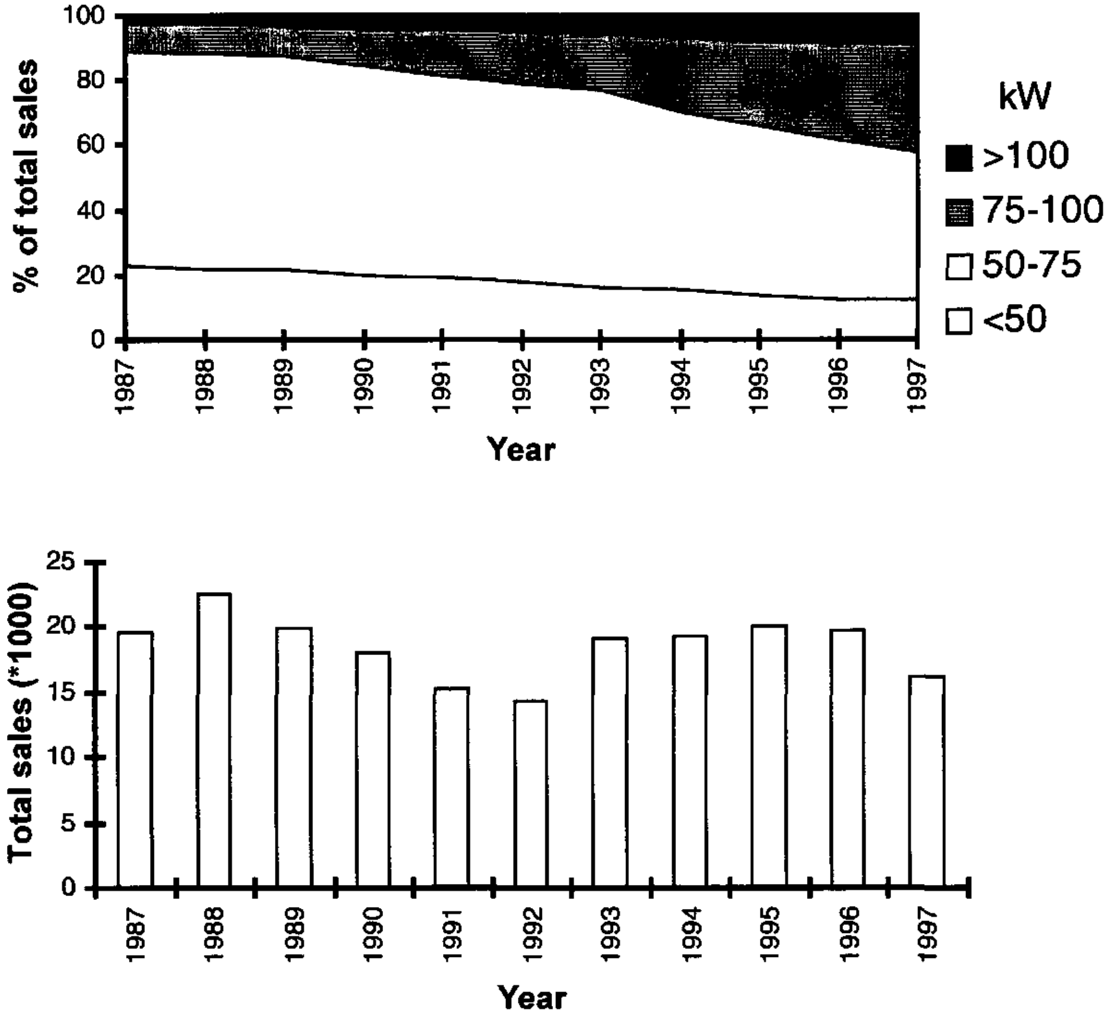

Fig. 1. Tractor sales in the UK, 1987-1997. (Source: Agricultural Engineers Association)

Measurement of subsoil compaction

There are many variables that could be measured to estimate the extent, intensity or impact of subsoil compaction. A complete description of the soil would include measurements of soil strength and fluid transport characteristics, structural stability and resilience. The most direct and, in some ways, the simplest measurement is dry bulk density or some other expression of packing state. However, subsoil density is difficult to measure, it is variable and, though an essential part of soil description, it is insufficient to characterise completely the state of the soil.

Variability is a particular problem if we want to describe the amount of deformation that took place during a particular event. Density cannot be measured easily at the same location in the soil before and after deformation, although there are radiation methods that can be used in the laboratory. Therefore, it is usually best to measure deformation directly. However, if we want to predict how a soil is likely to behave after deformation, we need to know its bulk density and so we have to address the problems of variability and precision.

Bulk density errors and sampling effort

Gamma-ray transmission is probably the most effective way to measure subsoil bulk density. Equipment of this type was designed and built at a forerunner organisation of SAC in the mid 1960s (Soane, 1967, 1968) and it has been developed and used extensively since then (Campbell and Henshall, 1991). The method is relatively non-destructive and it is faster than competing methods because it avoids the necessity of digging a pit. Depth resolution can be good if an energy discriminating detector is used. The errors in a set of gamma-ray transmission measurements can be divided into measurement errors and uncertainty due to soil variability. The measurement errors include variability due to the random nature of radioactive decay, thermal effects, errors in depth location and source-detector separation. These last two are likely to be greater in subsoil than in topsoil. The standard deviation arising from measurement errors in dense soil is typically of the order of 0.03-0.05 Mg m^{-3}, for a reasonable counting time (J.K. Henshall, personal communication, 1998). This represents the minimum error before considering the effects of soil variability. An overall standard deviation of around 0.1 Mg m^{-3} is typical for a set of field measurements of subsoil bulk density and it tends to be independent of the method of measurement (Campbell and Henshall, 1991).

The precision needed depends on the size of the effect being measured and the likely impact of a given change. Van Den Akker *et al.* (1994) reported density increases of 0.04-0.06 Mg m^{-3} at about 400 mm depth when a tyre carrying 32 kN was run on loose soil. Smith and Dickson (1990) compared the compaction caused by light and heavy vehicles running on deeply loosened soil and found a maximum treatment effect in the subsoil of about 0.1 Mg m^{-3}. Danfors (1994) reported porosity changes of up to 2% in the 300-400 mm depth layer under heavily laden vehicles, which translates into a maximum bulk density change of about 0.05 Mg m^{-3}. A useful rule of thumb for the maximum acceptable bulk density increase is the value likely to reduce the air-filled porosity to less than 5%. In the case of the Smith and Dickson (1990) data, the initial water content in the subsoil was about 21% w/w and the initial dry bulk density was about 1.55 Mg m^{-3}, giving an air-filled porosity of 9%. The dry bulk density change necessary to reduce this to 5% is about 0.07 Mg m^{-3}. All of these changes in dry bulk density are of the same order as a typical value for standard deviation and in many cases even smaller.

The number of samples (N) needed to establish a particular difference (δ) as statistically significant depends on a number of factors. These include the size of δ, the standard deviation of the difference between means (σ_D), the significance level desired (α) and the probability (P) of obtaining a significant result if the true difference is δ. The standard deviation of the difference (σ_D) is $\sqrt{2}\sigma$, where σ is the sample standard deviation. For comparing two treatments, Snedecor and Cochran (1967) gave a formula for estimating N, assuming independent samples:

$$N = 2M\,\sigma_D^2/\delta^2 \qquad (1)$$

where M is a multiplier derived from the standard normal distribution and tabulated by them for values of α and P.

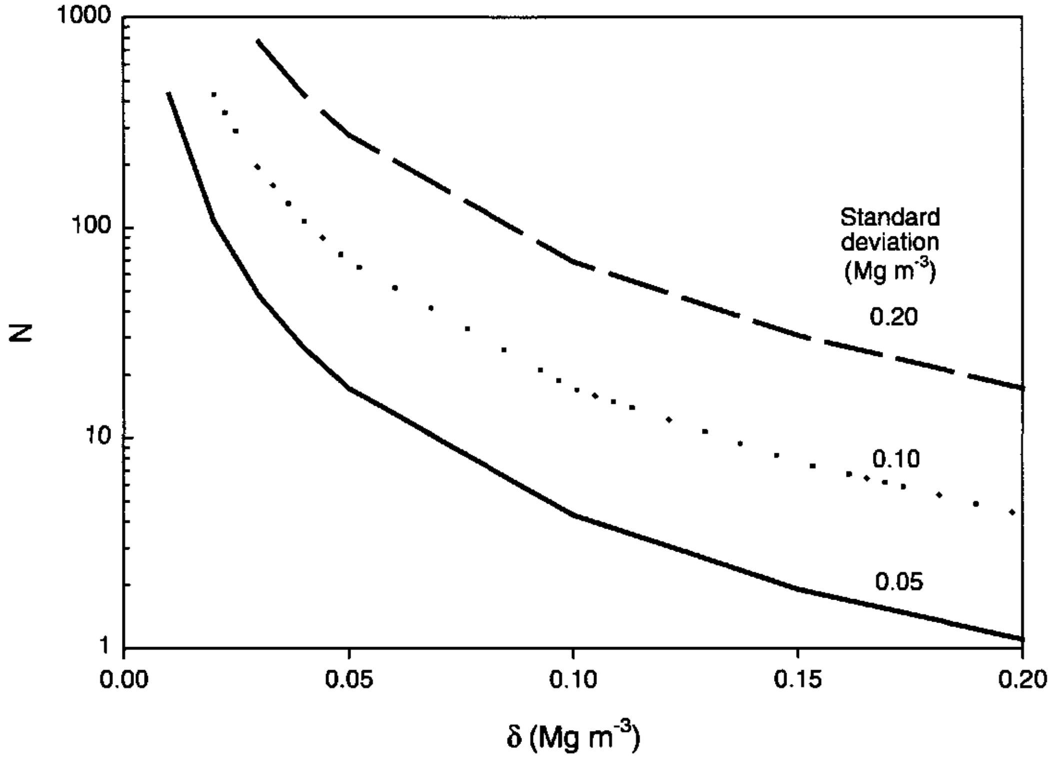

Fig. 2. The number of samples (N) needed to find the stated difference (δ) significant (α=0.05, P=0.90) for three representative values of standard deviation.

Fig. 2 illustrates the effects of δ and σ_D on sample size for a one-tailed test, using the typical values α=0.05 and P=0.90, for which M=8.6. To detect a typical bulk density change of 0.08 Mg m^{-3} with a σ_D=0.14 Mg m^{-3}, 54 samples would be needed. A one-tailed test is appropriate if we want to show whether a particular wheel compacted the subsoil. A two-tailed test needs more samples (M=10.5) but would be appropriate for comparing the compaction caused by different wheels. On the other hand, if more than two treatments are being compared, then N will be less than indicated by Equation 1 because errors can be pooled across treatments. Fewer samples would also be needed if we are willing to accept a lower probability (P) of detecting compaction, for example, if P=0.80 and α=0.05 as before, then M reduces to 6.2. The large numbers of samples required, as indicated by Fig. 2, are often not feasible. This probably explains the failure of many experiments to detect significant subsoil compaction where it might be expected from theory.

Cone resistance

The cone penetrometer has been widely used in subsoil compaction research because it is a quick and easy measurement to make and the results can often be related to bulk density and water content. It is particularly useful for assessing the spatial variability associated with traffic (O'Sullivan, *et al.*, 1987). Håkansson *et al.* (1994) and Schjønning and Rasmussen (1994) showed the persistence of subsoil compaction from penetrometer measurements. Van Den Akker *et al.* (1994) used a penetrometer to assess the extent and location of compaction under individual wheels. Other authors have used the penetrometer to assess the extent, intensity and persistence of subsoil loosening (e.g. O'Sullivan, 1992). However, we have found that the penetrometer does not always give clear answers or conform with other measurements, especially in the subsoil. In a study of tyre load and ground pressure effects on compaction, Smith and Dickson (1990) reported that penetrometer results were inconclusive and contained anomalies, whereas bulk density measurements tended to substantiate theoretical predictions. This is not surprising, given the number, complexity and interactions of the factors that influence cone resistance (Campbell and O'Sullivan, 1991). Among the factors that are particularly important to subsoil measurements are friction on the penetrometer shaft, overburden effects and the presence of stones (Glasbey and O'Sullivan, 1988).

Impacts of subsoil compaction

Subsoil denitrification appears to be a significant pathway for loss of nitrogen from imperfectly drained soils. We have studied the nitrogen cycle in hydrologically isolated, drained field plots and used models such as ANIMO and SOILN to simulate the processes.

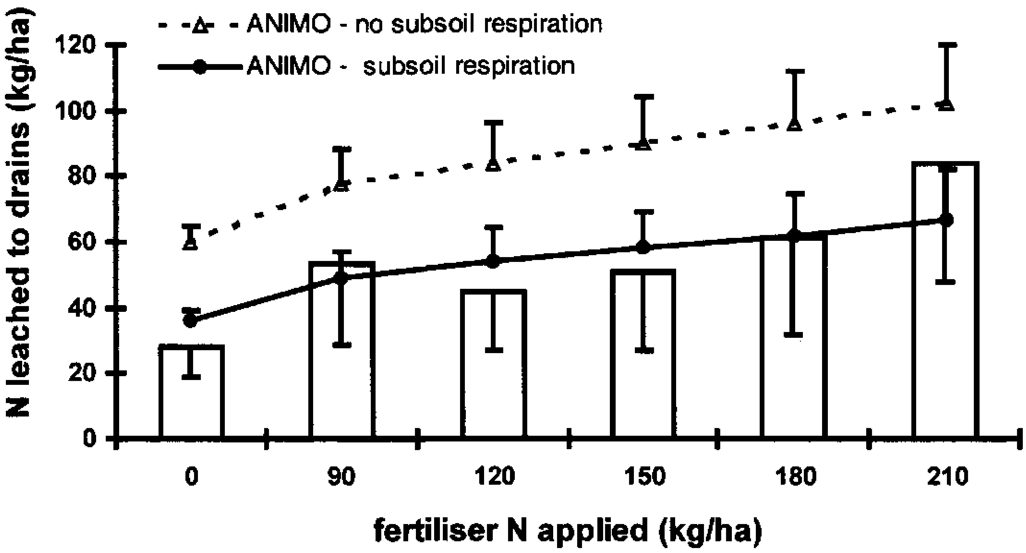

Fig. 3. Nitrate leaching measurements and simulations by the ANIMO model, with and without subsoil respiration. The bars represent the annual mean, 1990-1994. The error bars represent one standard error.

We found that the model simulations tended to over-predict nitrate leaching. However, these models took no account of subsoil respiration and anoxia. When subsoil processes were included (at rates determined by separate experiments), simulations were much improved, as shown in Fig. 3. Recently, we have also produced direct experimental evidence showing the importance of subsoil denitrification as a sink for N in imperfectly drained soils. Subsoil compaction is likely to increase anoxia, so increasing denitrification.

Conclusions

The Scottish climate makes subsoil compaction likely and trends towards the use of heavier agricultural machinery will intensify any problems. However, many Scottish subsoils are already naturally compact. Soil variability will be a problem in assessing the extent, intensity and persistence of subsoil compaction. Denitrification is likely to be a significant sink for nitrogen in compact subsoils.

Acknowledgements

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CHANGES OF PORE SYSTEM FOLLOWING SOIL COMPACTION

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Abstract

Soil compaction is one of the most important factors responsible for environmental degradation. It causes strong modifications to soil structure and reduces soil porosity. Therefore the measurements of such a physical property can help to quantify the effects of compaction. This is now possible because of the increasing use and availability of the technique of image analysis allowing the measurement of soil porosity on thin sections or impregnated soil blocks, prepared from undisturbed soil samples.

Results showed that compaction not only reduces total soil porosity but also modifies the pore system. In fact, the proportion of elongated pores, useful for water movement and root growth is strongly reduced in compacted soil. The modifications to the pore system also changes the type of soil structure: the platy structure is a common feature in compacted soil. Results also showed that the reduction of porosity and of elongated pores following compaction, is strictly related to the increase of penetration resistance and to the decrease of hydraulic conductivity and root growth. Soil regeneration after compaction depends on the type of soil and on the degree of damage to the soil.

Introduction

Soil compaction is caused by a combination of natural forces, which generally act internally, and by man-made 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. This is because trends in agricultural engineering over the last few decades have resulted in machines of a greater size and weight. Therefore, soil compaction has become one of the most significant aspects of environmental degradation and problems of finding tyres, inflation pressures, etc., able to reduce soil compaction are far from being solved. It is therefore fundamental to evaluate the impact of wheel traffic on soil compaction and soil structure degradation.

To evaluate the impact of management practices on the soil environment it is necessary to quantify the modifications to the soil structure. Soil structure is one of the most important properties affecting crop production because it determines the depth that roots can explore, the amount of water that can be stored in the soil and the movement of air, water and soil fauna. Soil quality is strictly related to soil structure and much of the environmental damage in intensive arable lands such as erosion, compaction and desertification originate from soil structure degradation. To quantify soil structural changes following agricultural activities, besides traditional measurements such as aggregate stability and hydraulic conductivity, pore space measurements are being increasingly used. In fact, it is the size, shape and continuity of pores that affect many of the important processes in soils (Ringrose-Voase and Bullock, 1984). Detailed insight into the complexity of the pore system in soils can be obtained by using mercury intrusion porosimetry to quantify pores with equivalent pore diameter < 50 μm (micropores) within the soil aggregates (Fiès, 1992). Image analysis on thin sections prepared from undisturbed soil samples allows pores > 50 μm (macropores) to be quantified, which determine the type of soil structure (Pagliai et al., 1983, 1984). Technological and theoretical advances, regarding both sample preparation and image analysis, have improved the methods for direct quantification of soil pores. These methods allow the quantification of the effects of tillage practices on soil porosity and structure and in turn the definition of optimum tillage needs for sustainable agriculture (McBratney et al., 1992; Mermut et al., 1992; Moran and McBratney, 1992).

Methods

The pore system was characterised by image analysis on thin sections from undisturbed soil samples to measure pores >50 μm (macroporosity) and by mercury intrusion porosimetry to measure pores <50 μm (microporosity).

For the image analysis, at the least six undisturbed samples must be collected in the surface layer (0-10 cm) and at selected depths along the profile and at selected times in the compacted areas and in the adjacent areas (control). Samples are dried by acetone replacement of water (Murphy, 1986), impregnated with a polyester resin and made into 6×7 cm, vertically oriented thin sections (Murphy, 1986). Such sections are analysed by means of image analysis techniques (Pagliai et al., 1984), using a PC-IMAGE software produced by Foster Findlay Associates (London). Total porosity and pore distribution are measured according to their shape and size. The instrument is 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 can be 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 are also examined using a Zeiss "R POL" microscope at 25x magnification to observe soil structure.

For mercury intrusion porosimetry, six undisturbed samples can be collected in the areas adjacent to those sampled for thin section preparation. Aggregates with a volume up to 4 cm^3 are air-dried and degassed prior to analysis using a mercury intrusion porosimeter (Carlo Erba WS Porosimeter 2000) equipped with a Carlo Erba 120 macropore unit. The porosity and pore size distribution are determined within the range 0.007-50 μm.

Other methods for assessing the effect of soil compaction can be the measurement of penetration resistance by standard cone penetrometer and the comparison of results between compacted and uncompacted soil.

The effects of soil compaction can be reflected in water movement which can be assessed by infiltration measurements in the field. Such a measurement is time consuming and complicated. The laboratory measurement of saturated hydraulic conductivity may be useful in evaluating the effect of compaction on water flow. For this it necessary to collect undisturbed cores (5.68 cm diameter and 9.5 cm high) from the compacted and uncompacted areas. The samples are slowly saturated and the saturated hydraulic conductivity can be measured using, for example, the falling-head technique (Klute and Dirksen, 1986).

Soil porosity

Fig. 1 shows the results of an experiment dealing with the modification of soil porosity, expressed as a percentage of area occupied by pores larger than 50 μm per thin section, induced by tractor wheels in a loam soil (Pagliai et al., 1995). Results show that porosity significantly decreased (until three times with respect to the control) in the surface layer (0-10 cm) just after a single pass. Such a decrease still increased after four passes, even though not significantly when compared to the single pass. A new recent experiment on the same type of soil confirmed that the compaction caused a four times decrease in soil porosity between the wheel tracks and a six times decrease under the wheel tracks compared to the adjacent uncompacted soil (Pagliai et al., 1998). The compacting effect of wheel traffic, in this type of soil with a water content at the time of compaction of 0.16 m^3m^{-3}, seemed to be limited to the surface layer: in fact, the porosity in the 10-20 cm layer did not show significant differences between uncompacted areas and those compacted by one and four passes of the tractor.

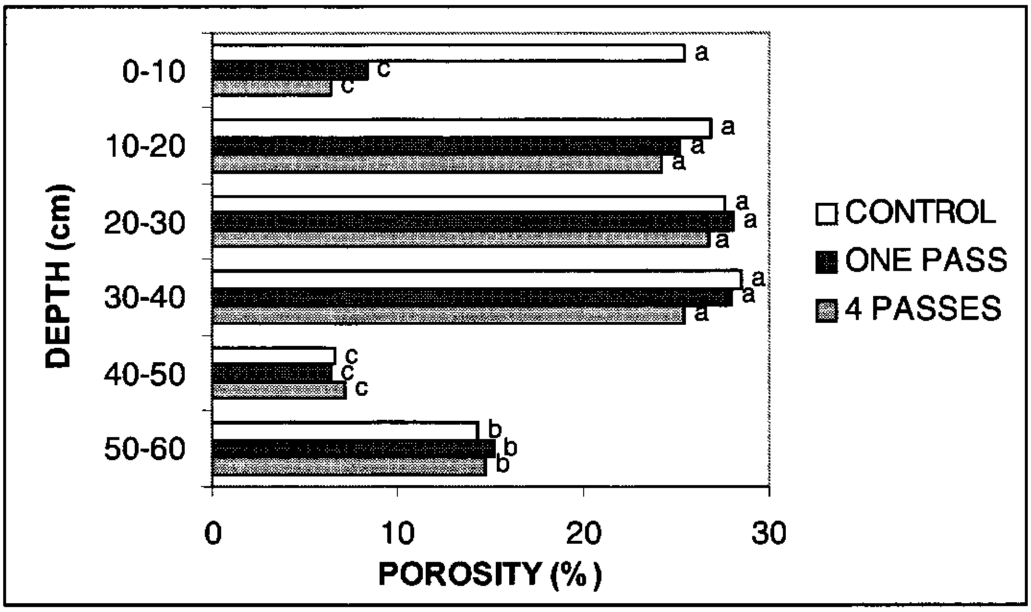

Fig. 1 – Effects of soil compaction, caused by one and four passes of tractors, on soil porosity expressed as a percentage of area occupied by pores larger than 50 μm per thin section. Mean of six replications. Values followed by the same letter are not significantly different at the 0.05 level employing Duncan's Multiple Range Test.

In the 40-50 cm layer the porosity drastically decreased from over 25% of the upper layer to 6-7% due to the formation of a ploughpan at the lower cultivation limit. The investigated soil was, in fact, cultivated to maize and ploughed to a depth of 40 cm. The adoption of alternative tillage systems such as ripper subsoiling may remove or prevent the formation of this compact layer (Pagliai et al., 1998).

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 moderately porous and the compaction is significant because it decreased the porosity below 10%.

For a thorough characterization of soil macropores, the main aspects to be considered are not only the pore shape but also the pore size distribution, especially of elongated continuous pores, because many of these pores directly affect plant growth by easing root penetration and 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 provide the water reservoir for plants and micro-organisms, while transmission pores ranging from 50 to 500 μm (elongated and continuous pores) are important both in soil-water-plant relationships and in maintaining good soil structure conditions. Damage to soil structure can be recognized by decreases in the proportion of transmission pores.

The soil compaction following the wheel traffic of the tractors not only reduced the total porosity but also modified the pore system in soil, i.e., modified the shape and the size distribution of pores. Pore shape and size distribution in the 0-10 cm layer of the areas compacted by the passes of the tractors showed large differences compared with uncompacted areas (Fig. 2). The reduction of porosity following the compaction of one and four passes of the tractors was due to a reduction of all larger pores but mainly the elongated pores which can negatively affect water infiltration. Such pores are the most important, because, as already said, many of these pores directly affect plant growth by easing root penetration and storage and transmission of water and gases.

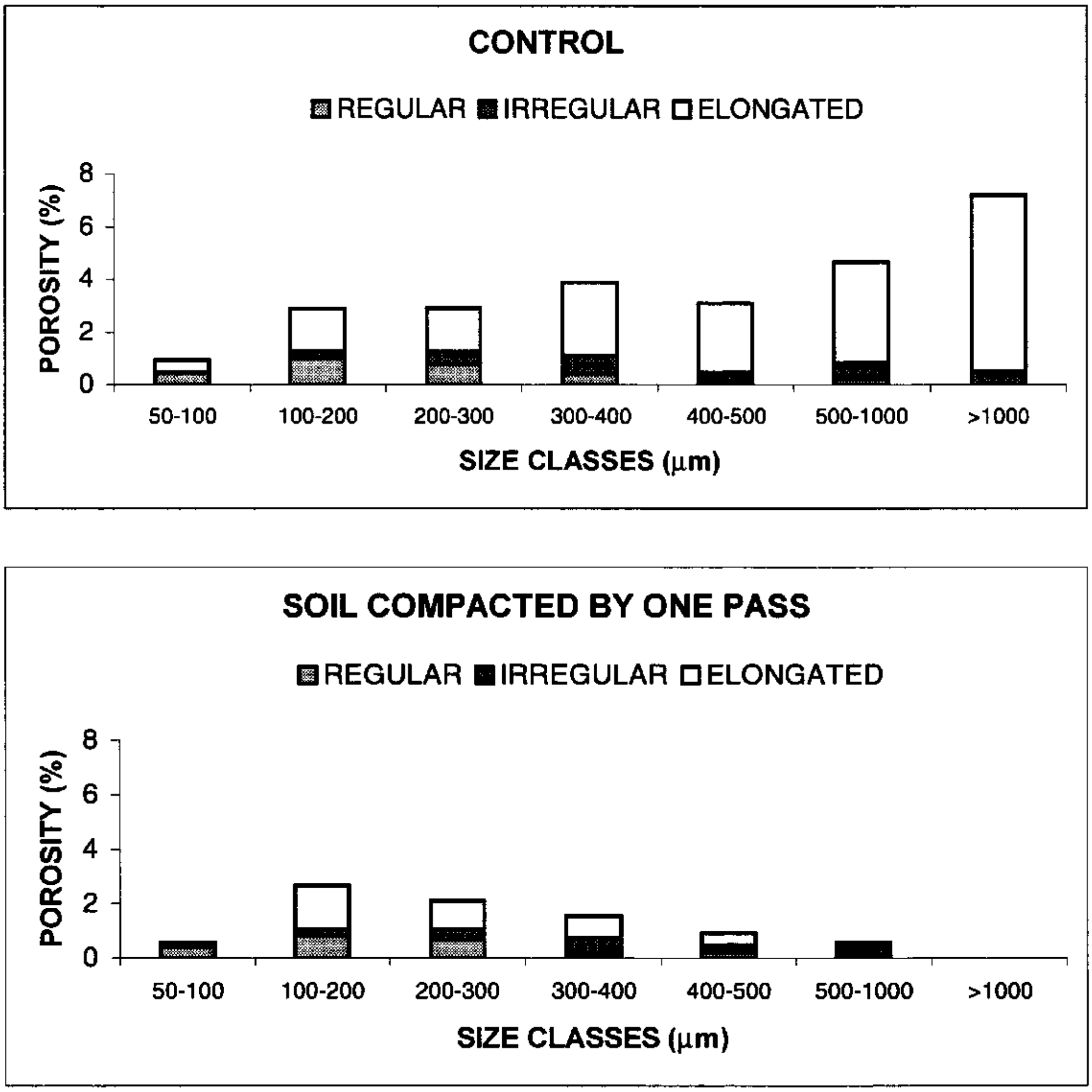

Fig. 2- Pore shape and size distribution, according to the equivalent pore diameter for regular and irregular pores, or the width for elongated pores, in the surface layer (0-10 cm).

Similar results in changes of macroporosity and pore shape and size distribution following compaction were also obtained in a sandy loam soil (Pagliai et al., 1988; 1992) and in a clay soil (Marsili et al., 1998). In these experiments the effect of compaction due to wheel traffic with different types of tyres used at two inflation pressures (Pagliai et al., 1992) and tractors with rubber and metal tracks (Marsili et al., 1998) was also studied. The former experiment showed that the tyres with a narrower section caused a more pronounced compaction effect than those with a wider section, while the different inflation pressures did not seem to cause significant differences on soil compaction effect. The latter experiment 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 uncompacted soil.

Total pore volume measured by the mercury intrusion porosimetry inside the aggregates of the 0-10 cm layer was lower in the compacted areas than in the adjacent control soil. This decrease in compacted soil was mainly due to the reduction of volume of storage pores (0.5-50 μm). However, such a decrease was not so pronounced as was the case of macroporosity.

Soil structure

The variations in porosity, pore shape and size distribution following compaction by wheel traffic were reflected in the type of soil structure. Microscopic examination of thin sections revealed that in the uncompacted areas an angular to subangular blocky structure was homogeneously present down the 0-40 cm layer (Fig. 3), while in compacted areas the structure was massive in the 0-10 cm layer and only in the surface layer (0-5 cm) the thin elongated pores were oriented parallel to the soil surface, thus originating a platy structure typical of compacted soils (Fig. 3). Therefore, the few elongated pores were not vertically continuous and practically useless for water infiltration, thus increasing the water stagnation or the surface runoff and, as a consequence, the risk of soil erosion depending on the soil slope.

The wheel traffic may also cause damage, in terms of soil porosity, in sandy soil. Fig. 4 shows a sandy forestry soil with high interconnected porosity and accumulation of organic matter mixed by biological activity. The wheel traffic of machines reduced the porosity causing a compaction of organic materials and a packing of quartz grain. Such a condition may hamper the root growth (Pagliai et al., 1993). The decrease of porosity, even though in this case the continuity in a vertical direction was not interrupted, may however reduce the water infiltration in case of heavy rains with the increase of risk of surface runoff.

Correlation between soil porosity and penetration resistance

In studies on the effects of compaction caused by different types of tyres on porosity and structure of a sandy loam soil Pagliai et al. (1992) showed a strong correlation in the surface layer (0-10 cm) between soil porosity and penetration resistance.

The same results were obtained in the previously mentioned experiment on a loam soil (Pagliai et al., 1995) where the decrease of porosity in compacted areas was associated with an increase of penetration resistance. Fig. 5 shows a good correlation between porosity, measured by image analysis on soil thin sections, and penetration resistance in the surface layer (0-10 cm) of both compacted (porosity values below 10%) and uncompacted areas. These results confirmed previous findings on the same type of soil which showed a significant increase of penetration resistance after the tractor passes (Bazzoffi and Chisci, 1986).

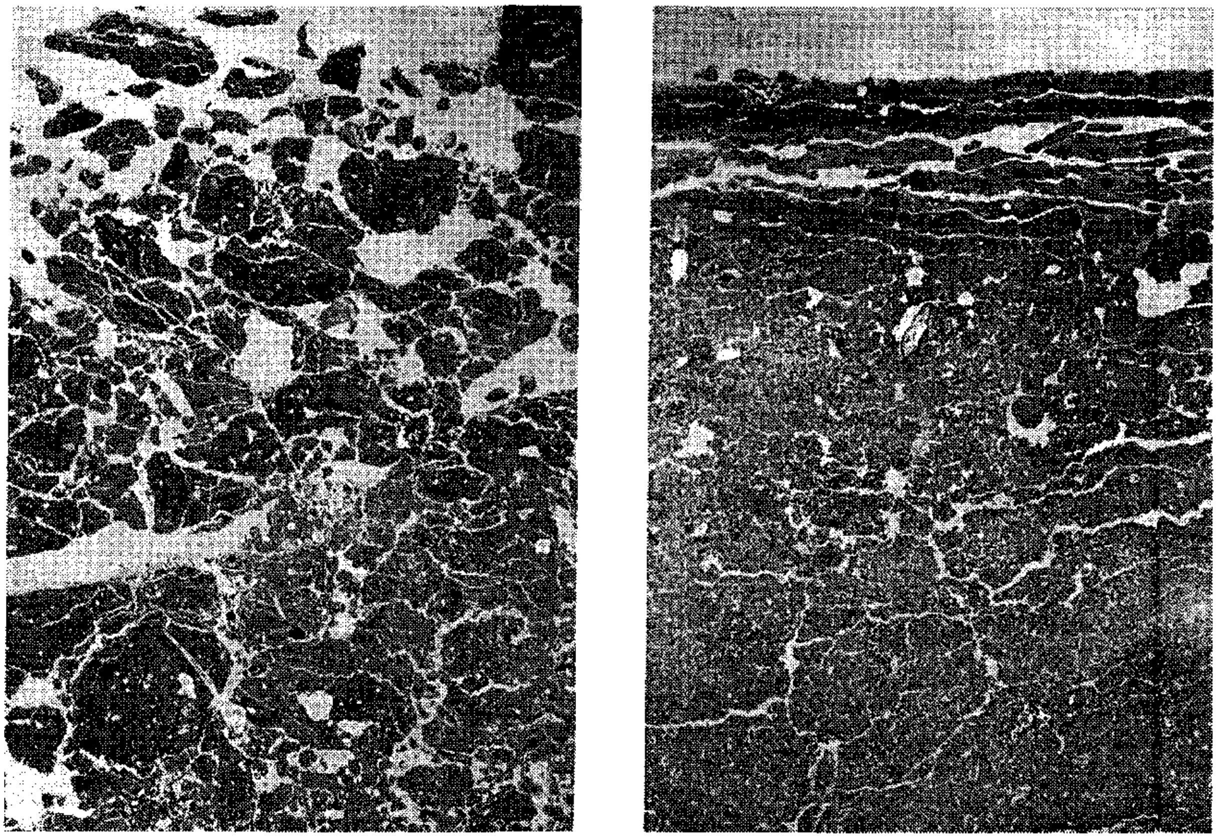

Fig. 3 – Macrophotographs of vertically oriented thin sections from the surface layer (0-5 cm) of the uncompacted (left) and compacted areas (right) of a loam soil. Plain polarized light. Pores appear white. The change of the subangular blocky structure of the uncompacted areas into a massive platy structure of the compacted areas is very evident. Frame length 3 cm.

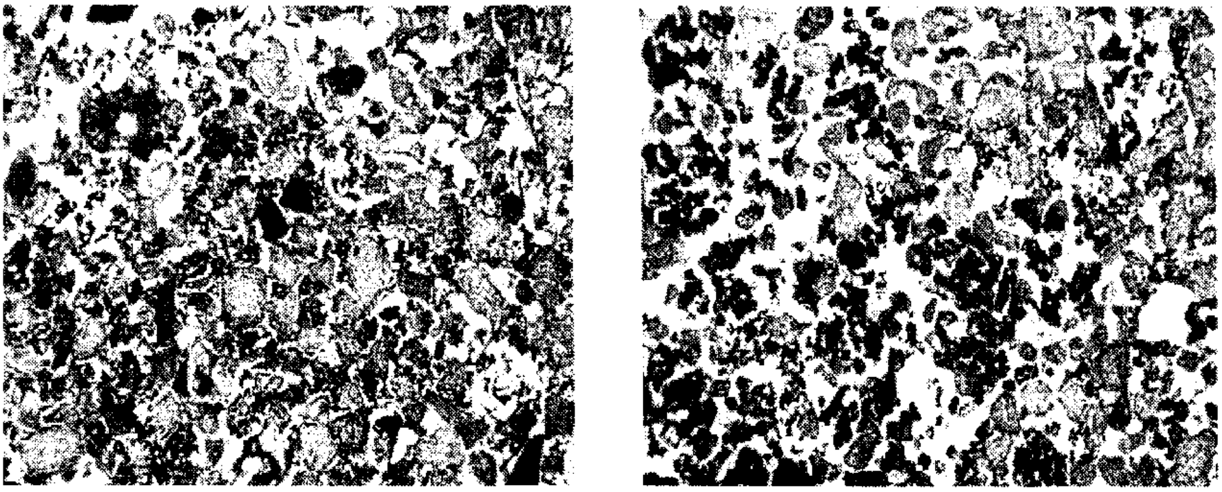

Fig. 4 - Microphotographs of vertically oriented thin sections from the surface layer (0-5 cm) of the compacted (left) and uncompacted areas (right) of a sandy forestry soil. Plain polarized light. Pores appear white, quartz grains grey and organic materials black. The reduction of porosity in compacted areas (left) which may cause difficulty for root growth is evident. Frame length 3 mm.

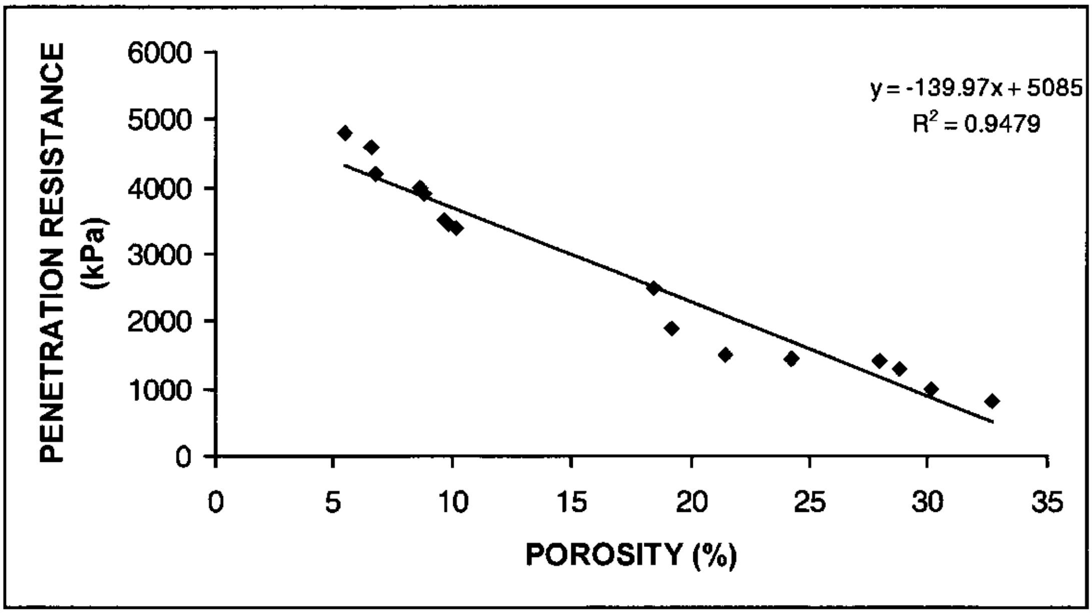

Fig. 5 – Correlation between soil porosity and penetration resistance in the surface layer (0-10 cm) of the compacted and uncompacted areas.

Another experiment on a clay loam soil with a slope of 15%, in which the effect of compost addition and compaction by normal and low-pressure tractor tyres on the physical properties and erosion of soil was investigated, Bazzoffi et al. (1998) showed that the compost addition reduced the penetration resistance in compacted soil after the wheel traffic. Some difference were also foud between conventional and low-pressure tyres. These latter seemed to have a lower compacting effect concerning the penetration resistance but they increased surface runoff and erosion. In fact, compaction due to low pressure tyres, although lower than with normal tyres, involves a larger surface of soil because of the wider tread. Consequently, the wheel-pass tracks are larger when low-pressure tyres are used and the number of isolated aggregates on the soil surface decreases. The passage of tyres also determines the destruction of surface aggregates, with the production of smaller compound particles (Dexter, 1988). When using large low-pressure tyres, a wider track is formed up and down the slope compared with normal tyres; consquently there is a more widespread destruction of larger aggregates of the seed-bed. This action may explain the higher quantity of fine fraction in the sediment when large low-pressure tyres were used. Wider tracks may also be responsible for the increase runoff volumes observed during the experiment; in fact, compression reduces the superficial roughness and laminar flow may involve a wider zone.

Correlation between soil porosity and saturated hydraulic conductivity

Fig. 6 shows a highly significant correlation between hydraulic conductivity and elongated pores in a loam soil compacted by wheel traffic and uncompacted (Pagliai et al. 1995; 1998). This confirmed that hydraulic conductivity is directly correlated with elongated continuous pores and these results stressed that the compaction is one of the most significant aspect not only of soil degradation but also of environmental degradation, since the reduction of water infiltration may increase the risk of soil erosion.

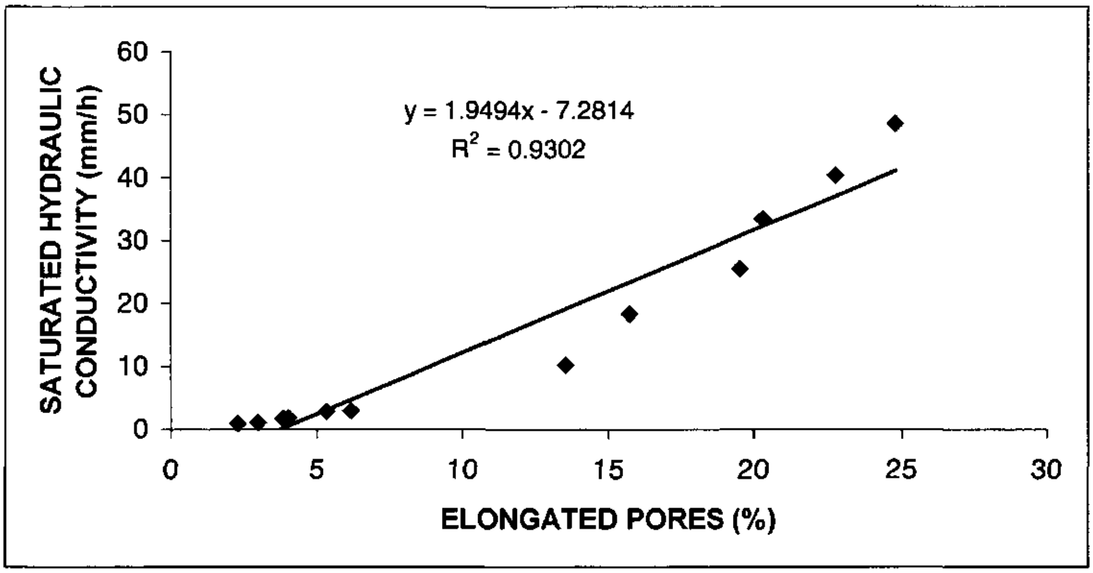

Fig. 6 - Correlation between soil porosity formed by elongated pores and saturated hydraulic conductivity in the surface layer (0-10 cm) of the compacted and uncompacted areas.

Correlation between soil porosity and root growth

The soil structure modifications, the decrease of soil porosity, the increase of penetration resistance following compaction may hamper root growth besides reducing water infiltration. This aspect was studied in a sandy loam grassed soil cultivated to peach orchard (Pezzarossa and Pagliai, 1990). The porosity and root density were measured until a depth of 50 cm in the areas compacted by the continuous wheel traffic for all management practices (pesticide treatments, harvesting, etc.) and in the adjacent inter-row areas. Results are summarized in Fig. 7.

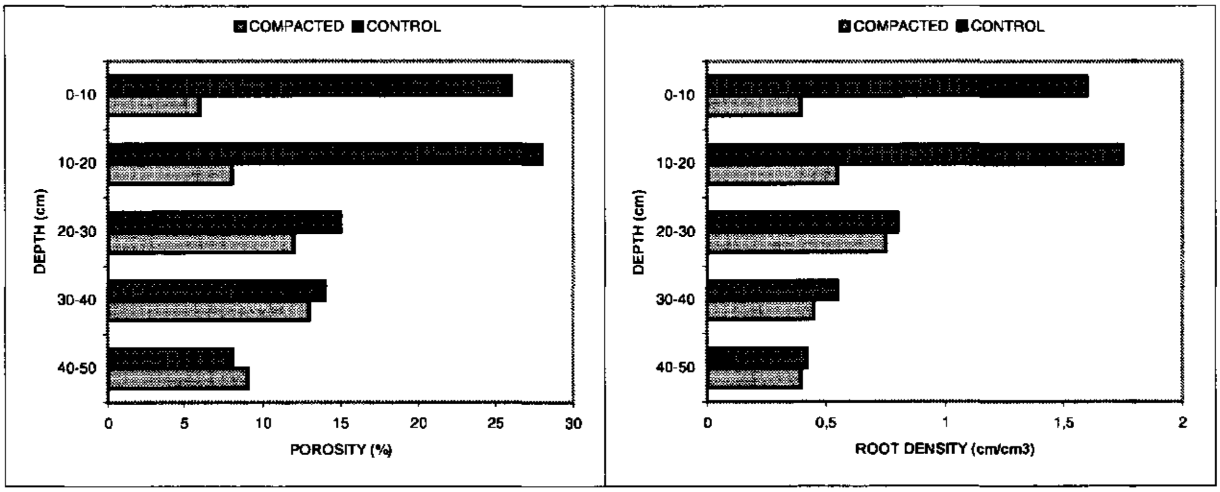

Fig. 7 - Effects of soil compaction, caused by wheel traffic of machines in a peach orchard, on soil porosity expressed as a percentage of area occupied by pores larger than 50 µm per thin section (on the left) and on root density expressed as root length/cm^3 (right).

The large reduction of porosity in the 0-20 cm layer of the compacted areas is evident, while in the 20-30 cm layer porosity increased, even though its value remained lower than in uncompacted areas. The root density, measured by image analysis and expressed by root length per cm^3 of soil (Pezzarossa and Pagliai, 1990), showed the same trend: in the 0-20 cm layer of the compacted areas it showed a value about three times lower than in the same layer of adjacent uncompacted areas. In the 20-30 cm layer, where the effect of compaction was lessened, the root density increased showing approximately the same value as in uncompacted soil. It should be stressed that the peach orchard field was permanently grassed and irrigated, so the continuous wheel traffic on the same track caused a more pronounced compacting effect than in the previous mentioned loam soil cultivated to maize.

Soil structure regeneration

Soil structure regeneration is a characteristic strongly related to the soil type and depends on the alternation of wetting and drying cycles. This aspect was studied in a clay loam soil by Pagliai (1987) where, besides the sampling at the compaction time, sampling at 4, 8 and 12 months after wheel traffic were planned; in the meantime the soil remained undisturbed. Just after the compaction the porosity showed a strong reduction involvimg all morphological type of pores, over all the size of elongated pores was drastically reduced. After 4 months the situation was practically the same and after 8 months from the compaction the porosity increased, even though it remained significantly lower than in uncompacted areas. Only after 12 months the porosity did not show significant differences between uncompacted and compacted soil due to the effect of wetting and drying cycles and the biological activity which allowed the soil to regenerate its structure. Other experiments showed that in some clay soils the soil structure regeneration after compaction may take several years (Bullock et al., 1985). In the sandy loam soil previously mentioned (Pagliai et al., 1988; 1992) the soil structure was good but strictly dependent on the number of wetting and drying cycles.

Conclusions

Experimental results showed that the soil compaction due to wheel traffic and the subsoil compaction (plough pan or plough sole) caused a reduction of soil porosity to values inadequate for water movement and root growth, because such a reduction involved not only elongated pores larger than 500 μm but also those ranging from 50 to 500 μm i.e, the transmission pores. The reduction of soil porosity is always associated with an increase in penetration resistance and with a decrease in hydraulic conductivity.

The damages cause by soil compaction after wheel traffic appear just after one pass and they may increase after multiple passes on the same track. The more the compacting effect is pronounced, the longer is the time necessary for soil structure regeneration. Deep investigations are still necessary into the type of tyres and pressure inflation and probably it would be necessary to reconsider, where possible, besides the size and weight of agricultural machinery, the use of tractors with metal tracks to prevent or decrease soil compaction damage.

In Italy subsoil compaction is strongly under evaluated, especially the compact layer at the lower limit of cultivation (plough sole) largely widespread in the alluvial soils in the plains generally cultivated by monoculture.

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RESEARCH ON SOIL COMPACTION AND PHYSICAL / MECHANICAL PROPERTIES OF AGRICULTURAL SOILS IN NORTHERN GREECE

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Abstract

The most important research, related to soil physical-mechanical properties, compaction and root growth, strength, stress-strain relations, which was performed in the Soil Science Lab, Aristotle University, during the last years is presented. Especially, a detailed description of the methods used is given along with some results related to the physical - mechanical properties and to the occurrence of subsoil compaction of agricultural soils in Northern Greece.

Introduction

Compaction of agricultural soils in Greece is believed to be a serious problem which results in both soil and environment deterioration and in a decrease of both the quantity and the quality of agricultural products. This is the consequence of increased use of larger machinery and increased intensive cropping practices. However, no much work on soil compaction and related properties has been done in Greece so far.

In this paper the most important research which was undertaken on compaction, strength, stress-strain relations, root growth, and related physical and mechanical properties in the Soil Science Lab, Aristotle University, during the last years will be presented.

1. Survey work of soil physical / mechanical properties of soils in areas of great agricultural importance. One of the objectives of this work was to confirm the occurrence of subsoil compaction by comparing the physical/mechanical properties of the Ap and the subsurface horizons (Panayiotopoulos and Papadopoulou, 1993, 1994).
2. Compaction - penetration resistance and their influence on root growth of maize seedlings (Panayiotopoulos, *et al.*, 1994a).
3. A statistical model for predicting soil compaction based on matric suction (Panayiotopoulos *et al.*, 1994b).
4. The effect of matric suction on stress-strain relations and strength of Alfisols (Panayiotopoulos, 1996).

Methods

1. For the soil surveys, particle size distribution, bulk density, porosity, pore size distribution, weighed mean aggregate size, degree of aggregation of particles < 50 μm, water retention, saturated hydraulic conductivity, field air-capacity and penetration resistance were studied.

Undisturbed soil samples were taken by means of stainless steel cylinders (57 mm in diameter and 40 mm in length) from the Ap and the subsurface horizon from 29 sites in Thrace area, Northern Greece. These samples were used for bulk density, water retention and penetration resistance determination. For the saturated hydraulic conductivity determination the undisturbed samples were taken by means of brass cylinders 75 mm in diameter and 105 mm in length.

Bulk density was determined by the core method (Blake and Hartge, 1986) and was calculated by using the volume and the dry mass of the undisturbed samples.

From the cores which were going to be used for water retention and penetration resistance determination, a thin layer (3 - 4 mm thick) of soil was removed by a spatula from the lower base of each sample. The space created was covered with a mixture of plaster of Paris and distilled water in a ratio 6:5 by mass. The layer of plaster of Paris was necessary in order to establish a good hydraulic contact between soil and the ceramic porous plates on which the samples were equilibrated at a series of matric suctions.

For the water retention characteristics the samples were saturated under vacuum (2 - 3 kPa) with 0.005 M $CaSO_4$ solution and allowed to equilibrate at matric suctions of 1, 2, 4, 10 (tension table), 33, 100, 1000 (pressure plate) and 10^5 kPa (air-dryness). The 0.005 M $CaSO_4$ solution was used instead of water in order to avoid clay dispersion. After equilibration at a given matric suction the samples were weighed. After equilibration at the 10^5 kPa matric suction the soil was removed and the cylinder was weighted empty and full with distilled water. Three replicates were used for each soil horizon. Porosity was taken as the water content (on a volume basis) at saturation while pore size distribution was calculated by means of the capillary equation using the water retention data. Field air-capacity was calculated as the fractional volume of air when the soil reached a water content equal to field capacity (matric suction = 10 kPa).

For the penetration resistance determination the samples were saturated as previously described and allowed to equilibrate in matric suction of 1, 10, 100 and 1000 kPa. A modification of a compression test machine (Wykeham Farrance Eng. Ltd) was used. A metal probe with a 2.5 mm shaft diameter and a conical end (60^0 cone angle and 3 mm base diameter) was attached to the shaft of the compression machine which could then move at a constant rate of 1.52 mm sec^{-1}. During penetration, the resistance of the soil as well as the depth of penetration were measured with electronic transducers and recorded automatically. Penetration resistance was calculated as the force exerted by the penetrometer divided by its cross-sectional area, when the conical tip reached a depth of 10 mm. Three penetrations were made on each sample (replicate) and three replicates were used for each soil horizon and matric suction studied.

Before the saturated hydraulic conductivity determination, each sample was put on a perforated perspex base and saturated under vacuum (2 - 3 kPa) with 0.005 M $CaSO_4$ solution. After saturation the hydraulic conductivity was determined by means of a constant head permeameter and a 0.005 M $CaSO_4$ solution was used as test fluid (Klute and Dirksen, 1986). Ten replicates were used for each soil horizon.

Weighed mean aggregate size and degree of aggregation of particles < 50 μm were also determined on partially disturbed bulk soil samples by dry sieving (Kemper and Rosenau, 1986) and by mechanical analysis with and without dispersion (Richards, 1954), respectively (three replicates).

Finally, particle size distribution was determined on disturbed and sieved (< 2 mm) soil samples by the pipette method (Day, 1965) in two replicates.

2. Two soils of different texture and of contrasting structure (an Alfisol and an Entisol) were used. Topsoil samples (0 - 25 cm depth) were collected from two sites, air-dried, sieved through a 2 mm diameter sieve, moistened to field capacity and kept in air-tight plastic boxes. Cylindrical metal pots, 105 mm in length and 75 mm in diameter with one end covered with plaster of Paris, were used for the compaction of soils as well as for the study of root growth of maize seedlings. The plaster of Paris at the one end of the pot was used in order to support the soil as well as to allow hydraulic contact between the soil and the tension table on which the samples were equilibrated. The amount of soil which, after compaction of 0 (control), 50, 100 and 200 kPa, would almost fill the pots was found after preliminary experiments. Half of this amount was poured into each pot under continuous mechanical vibration and compacted

by static uniaxial loading for 1 minute by means of a compression test machine (Wykeham Farrance Eng. Ltd, Slough, UK). The second half of the sample was then added and compacted in the same way. The range of compactive stresses applied was chosen to cover the stresses applied to field soils by agricultural machinery (Panayiotopoulos, 1989).

After compaction the samples were saturated with tap water under vacuum (2 - 3 kPa) and allowed to equilibrate for 10 days on tension tables at 10 kPa matric suction. During saturation no volume increase of the soil samples was observed. After equilibration of the soil samples, two holes, about 40 mm apart and 10 mm deep, were made in the surface of each sample with a needle (1 mm diameter). The root of a pre-germinated maize (*Zea mays*, var. Rustica majority) seed was positioned in each hole. The surface of the soil and the seeds were covered with loose soil at the same moisture content as that in which they were planted.

The maize seedlings were allowed to grow for 1, 3 and 7 days while the pots were kept on tension tables at 10 kPa matric suction and the room temperature was kept constant at 20 ± 1 ^{0}C. The experiment was conducted in a laboratory where the relative humidity ranged from 55 - 60 %, the photoperiod was around 11 h and no extra light was provided. At the end of each time interval studied, the pots were emptied and the maize roots were carefully separated from the soil under flowing water, washed and dried on blotting paper. The number and length of seminal axes as well as fresh and dry (70 ^{0}C) root mass of each seedling were measured. Total root length was also calculated as the sum of the lengths of all seminal axes of any individual seedling. All root parameters studied were expressed on a plant basis. The rate of root elongation was calculated as the average increase in total length of seminal axes of each seedling per unit time.

Bulk density and penetration resistance of the soil samples were also determined 1, 3 and 7 days after equilibration at 10 kPa matric suction using pots prepared and treated in an identical manner but without plants. Bulk density was calculated from the dry mass and the volume of the soil samples while penetration resistance was determined in a manner similar to that mentioned earlier. Three replicates were used for both root and the bulk density and penetration resistance measurements, for any soil and for any compaction and time interval studied. Relative values of soil properties or root growth parameters used in this work are expressed as fractions of the controls (i.e. those under zero applied stress on the same day).

3. From four soils (two Entisols, an Alfisol and a Vertisol), typical of agricultural soils of Greece and of varying basic properties, undisturbed samples were taken by means of stainless steel cylinders (57 mm in diameter and 40 mm in length). The cores were water saturated under vacuum (2 - 3 kPa) and allowed to equilibrate at a series of matric suctions namely 0, 1, 10, 100, 1000 and 10^5 kPa. After equilibration, the cores were stressed uniaxially and continuously from zero to 300 kPa by static loading. A compression test machine (Wykeham Farrance Eng. Ltd, Slough, UK) was used for the experiments, and two rates of straining were applied (0.38 and 1.52 mm min^{-1}, respectively).The range of stresses applied was chosen to cover the stresses applied to field soils by agricultural machinery. Porous ceramic plates were put at the top and the bottom of the cores before stressing. During the compression tests both the load applied and the deformation (decrease of the sample length) were recorded, and more than ten load-deformation values were taken for each test. The stress applied was calculated as the load divided by the area of the sample base while the deformation values recorded were converted to % deformation on an initial sample length basis. Three replicates were used for each soil, strain rate and matric suction studied.

4. From three locations of Northern Greece, namely Kerasia, Xyloupoli and Galatista, undisturbed soil mini-cores (20 mm in diameter and 40 mm long) were sampled by means of a mini-corer (Young et al., 1990) at the surface (0 - 5 cm) and in the subsoil, just below the plough layer (25 - 30 cm), corresponding to the mean effective rooting depth of the main

crops (i.e. cereals). During sampling the soils were near field capacity and no cracks were present at the surface. The selection of soils, which were under natural vegetation and classified as Alfisols according to Soil Survey Staff (1975), was based on their abundance under Mediterranean climatic conditions and their different parent material. After sampling, each mini-core was immediately transferred to a cylindrical split plastic mould, with two halves held together with adhesive tape and plastic caps were placed on either end of each mould.

The samples were saturated under vacuum at 2 - 3 kPa with distilled water over a period of 6 - 7 hours and then equilibrated at matric suctions of 0.001, 0.01 (tension table), 0.1, 1 (pressure plate) and 100 MPa (air-dry). Blotting paper was placed between each sample and the porous plate of both the tension table and pressure plate to maintain good hydraulic contact. Equilibrium was considered to have been reached when a batch of 20 samples released less than 0.1 cm^3 of water over a period of 24 h. Equilibrium time ranged from 2 to 13 days. After equilibration, the ends of each sample were leveled with a spatula, the split moulds were removed and each sample was placed in a sealed plastic container and stored at 20^0 C for an hour before testing for any re-equilibration after removal of the moulds. Before testing, the samples were weighed (± 0.1 mg) and their dimensions were measured (± 0.1 mm). After testing, the moisture content of the samples was determined by oven drying (105^0 C) overnight and the dry bulk density was calculated.

Unconfined compressive strength (UCS) and indirect tensile strength (ITS) were determined using a compression test machine (Wykeham Farrance Eng. Ltd, Slough, UK) at a deformation rate of 0.38 mm min^{-1}. During testing, the load and the sample deformation were measured with electronic transducers and recorded automatically.

UCS tests were performed by applying a load across the ends of a cylindrical sample and UCS was calculated as the load at failure divided by the sample's cross-sectional area at failure (A_f) which was estimated as (Koolen and Kuipers, 1983)

$$A_f = A_0 (1 - \varepsilon_f)$$

where A_0 and ε_f represent initial cross-sectional and longitudinal strain at failure, respectively. Failure was taken to have occurred when an abrupt and permanent decrease of load applied was observed. Where a failure plane was evident the angle ϑ between this plane and the major principal plane was measured and the angle of friction φ was calculated as $\varphi = 2\vartheta - 90^0$.

Young's modulus (E) was calculated as $E = \sigma/\varepsilon$, where σ is normal stress and ε is deformation per unit length, by using the values of stress and deformation recorded during UCS tests. The deformation of the samples during equilibration at the different matric suctions was not measured.

ITS testing was performed in a similar manner to UCS, but in this case the sample was loaded along two diametrically opposed generators. In most cases the samples were deformed at the loading points although packing strips for distributing the load were placed between the samples and the plates of the test machine. This resulted in a creation of flattened contact zones near the load points. Failure was taken to have occurred when fracture was evident at both ends of the samples. ITS (Y) was calculated from a modified equation proposed by Frydman (1964)

$$Y = 2Fg(\sigma)/\pi dL$$

where F, d and L stand for load at failure, sample diameter and sample length, respectively and g(σ) is a function of the ratio (width of flattened zone)/(distance between flattened zones) given graphically by Frydman (1964).

For both UCS and ITS tests as well as for Young's modulus measurements five replicates were used for each soil, depth and matric suction applied.

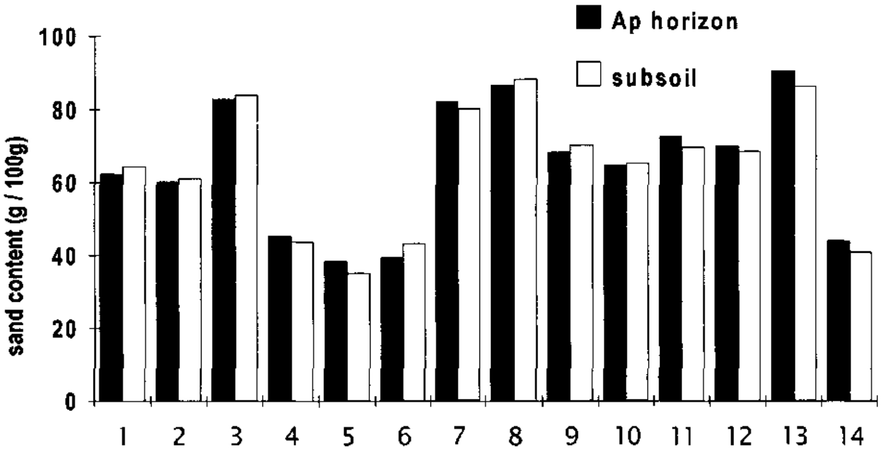
Results and discussion

The results of the works No 2, 3 and 4 have already published in scientific Journals and Conference proceedings (Panayiotopoulos, *et al.*, 1994a; Panayiotopoulos, *et al.*, 1994b; Panayiotopouls, 1996). Thus, only some results of the work No 1 will be presented in this paper.

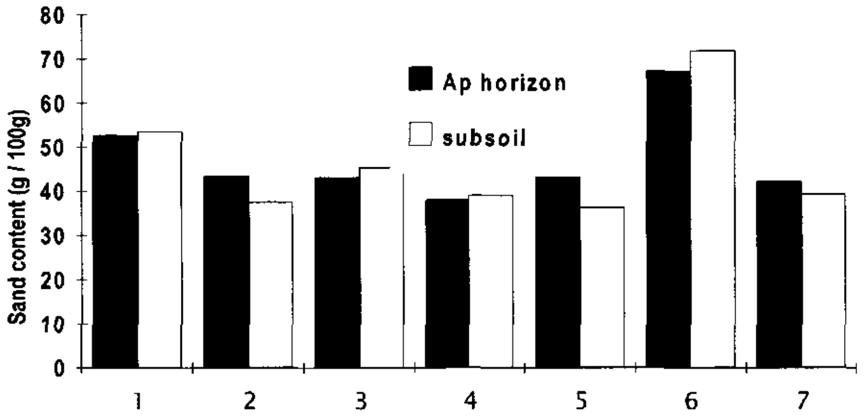
The soils were classified (Soil Survey Staff, 1975) as Entisols (14 sites), Alfisols (7 sites) and Inceptisols (8 sites). The differences in particle size distribution between the Ap and the subsoil were negligible (Figs. 1 and 2). In most of the cases, greater values of bulk density, field capacity, weight mean aggregate size and smaller values of porosity, air-field capacity, and saturated hydraulic conductivity were found in subsoil as compared to Ap horizons. As an example, the results of saturated hydraulic conductivity of the Ap horizons and the subsoil of all soils studied are presented in Fig. 3. Significant differences of the above properties were found in some cases between Ap horizons and subsoil. The penetration resistance, at any soil water matric suction applied, was always greater in subsoil than in Ap horizon (Fig. 4) and in most cases significant differences were found between the two depths studied.

The above mentioned results clearly show the occurrence of compaction in the soils studied.

ENTISOLS



ALFISOLS



INCEPTISOLS

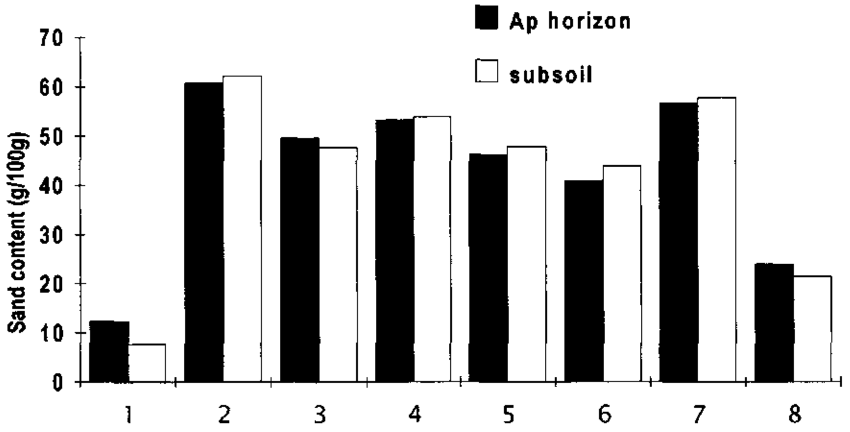


Fig. 1. Sand content of the Ap horizons and the subsoil of the soils used.

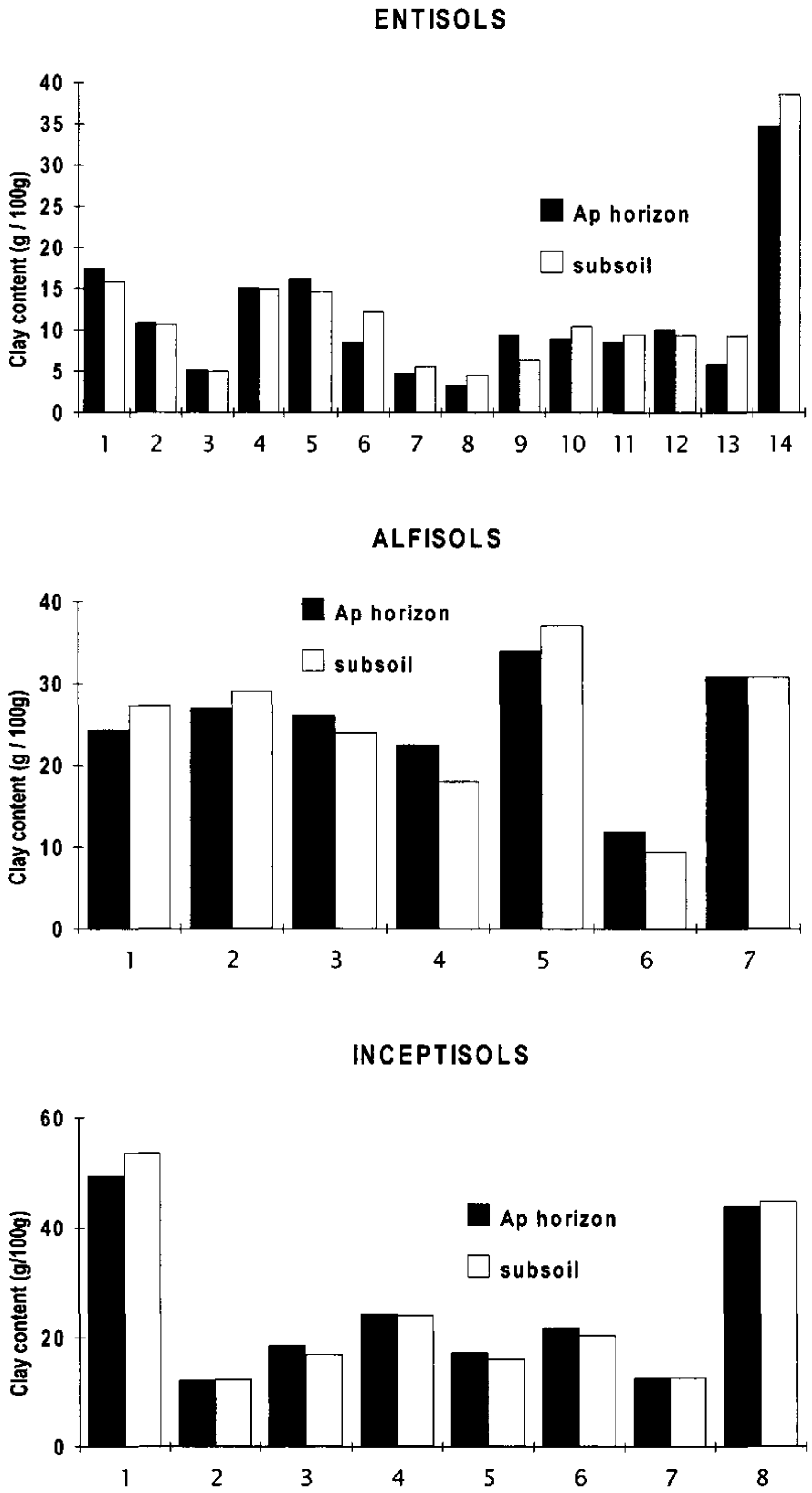


Fig. 2. Clay content of the Ap horizons and the subsoil of the soils used.

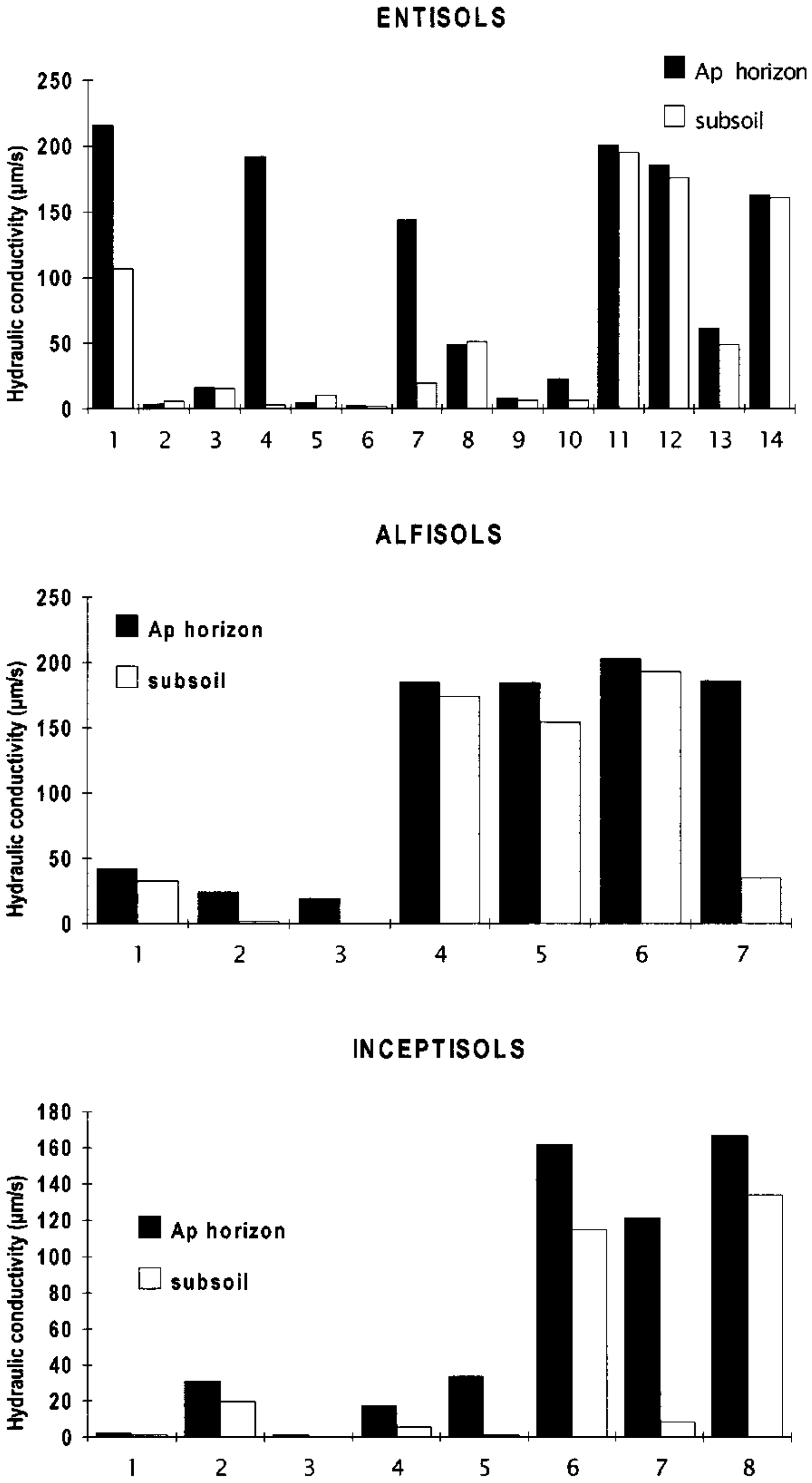


Fig. 3. Saturated hydraulic conductivity of the Ap and the subsoil of the soils used.

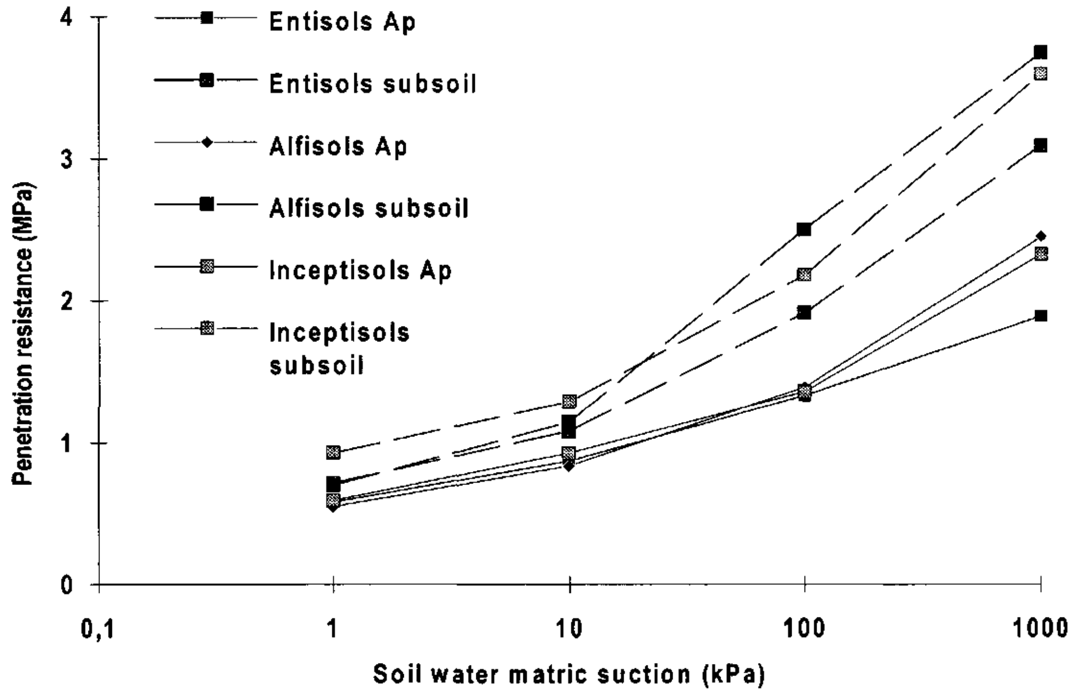


Fig. 4. Penetration resistance at different soil water matric suctions

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SURVEY ON SOIL COMPACTION IN ITALIAN PADDY FIELDS

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Abstract

Wheeled tractor efficiency in paddy fields is very low and it is necessary to improve vehicle mobility performance. Among other solutions, Italian narrow steel wheels are used on tractors operating in flooded fields for broadcasting seed and for carrying out crop protection operations when mobility rather than draught power is needed.

In Northern Italy rice cultivation is repeated for many years (in some cases more than 20 years) as a monoculture. Some operations are carried out on dry fields, and tractors often travel repeatedly over the same site. The result is a high soil compaction, both of the top-soil, and above all of the sub-soil, due to the high loads of the machinery and to the repeated passes. In addition, a very hard plough pan is often present, as a result of the above mentioned intensive monoculture. On the other hand, it should be noted that this hardpan acts in some way as a water controller and, in addition, it is a useful support for the narrow steel wheels equipping the tractor in order to develop a traction pull.

Different soil and machinery parameters have been taken into account at different stages of crop growth in paddy fields in order to investigate soil conditions in rice cultivation : soil granulometry ; moisture content ; cone penetrometer resistance ; water depth ; type of implements used for previous soil tillage (plough, harrow, chisel) ; type of previous levelling (traditional or laser controlled) ; mean ground contact pressure of combine harvesters front tracks and rear tyres; rut(s) width and depth.

The results show that in paddy fields both the top- and the sub-soil compaction have to be viewed differently in comparison with other crops. Because of the upper layer flooding in the growing season and the heavy traffic of the machinery equipped with tyres in the dry period (above all the laser levelling), there is a high reduction of the vertical pore system. On the other hand, traditional tillage only partially improves the (top)soil structure, due mainly to the prevalently poor weather conditions in the tillage period, and so ploughing and harrowing are carried out when the soil has a high moisture content.

Introduction

European and North American agriculture is normally practised in dryland conditions. The working capacity and the mobility limits of tractors and implements are well known. Wheeled vehicles are extensively used, with a minor utilization of crawler tractors (from almost nil up to about 20 % in Italy). In both cases extensive investigations have shown the effects of the various design and operating parameters on field performance.

In almost all the areas of the developing world however, in which rice is the staple food, dryland farming is not possible and wet cultivation techniques must be applied. Two problems arise. First, by mobility is sometimes almost impossible and locomotion aids valid for all conditions are not available. Second, by the requirements for tractor and implement mobility in wet fields are not the same as those for dryland conditions and the well known principles found in dry fields cannot be applied to wetland agriculture. Meanwhile, wheeled tractor efficiency in paddy fields is very low and it is necessary to improve vehicle mobility performance in this specific sector (Gee-Clough, 1985).

Since conventional or very wide section tyres and open lug cage wheels could not be considered, other solutions were proposed and investigated, ranging from retractive lugged cage wheels (Verma *et al.*, 1988) to hovercrafts (Maresca, 1989) or to specific air cushion vehicles for wetland paddy fields (Raheman 1991 and 1992). In Italy two prototypes of hovercraft are being tested on paddy fields; several problems arise from the large vehicle surface which is necessary and from the drift during turning.

Italy is the largest paddy producing country in Europe (215,000 ha in 1990, about $1.2 \cdot 10^6$ t of rice production in 1989, with an average of about 5.5 t ha^{-1}). Cropping is concentrated in the colder but wetter North (about 45° N latitude) and fully mechanized (labour has been reduced from 700-800 h ha^{-1} to 30 h ha^{-1} in 40-50 years mainly by mechanizing planting, weed control and harvest). The soil is prepared dry and laser levelling is extensively used. Puddling is becoming an obsolete technique. No transplanting is done, the seed being broadcast in April by tractor trailed or mounted spinners onto flooded fields. Low level flying to seed and apply pesticide is forbidden, but would be however impractical (small basin size; large number of varieties); so pesticides are applied by trailed or mounted sprayers. The soil is drained in August and the rice is harvested in September-October using combine harvesters fitted with front half tracks and rear floatation tyres.

Mechanization of rice cultivation in Italy

Tractors using narrow steel wheels are used in flooded fields only for broadcasting seed and for carrying out crop protection operations when mobility rather than draught power is required. To allow satisfactory yields from broadcast seed, fields must be adequately levelled and large ruts avoided.

Soil preparation

Mouldboard ploughing with a tractor fitted with normal tyres to 200-250 mm depth is used for weed control and **to preserve a hard pan**. In addition to normal tyres, typical Italian folding strakes are often used to achieve extra traction as the land is still soft (**fig. 1**). These strakes are about 100 mm high and 400 mm wide and, being mounted on a pivoted arm, stick out across the whole width of the tyre. These are sold throughout Italy and are not only for use in the rice producing areas. They are not used in flooded soils because they make large ruts. The strakes total mass is about 150-230 kg per wheel and when folded back they interfere very little with normal tyre use.

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Secondary tillage, again with a tractor fitted with normal tyres, is commonly carried out with a vertical axis powered harrow.

Flooding and seeding

Repairs to bunds, especially cross-bunds, which would generally have been destroyed during the harvest and ploughing operations, are carried out with offset ploughs and angled rollers or with powered ditchers. No significant levelling is done before flooding.

Seed is soaked for one day, so that it will sink and not be blown about on the surface, and is then broadcast with a fertiliser spinner. Generally the spinner is converted into a trailed machine using large, smooth, narrow, steel wheels while the tractor is fitted with lugged wheels.

Crop protection

Considerable quantities of herbicides and other pesticides are used and applied using trailed sprayers again fitted with smooth, large diameter, narrow, steel wheels (**fig. 2**).

Fig. 1 - In addition to normal tyres, typical Italian folding strakes are often used to achieve extra traction as the land is still soft.

Fig. 2 - Herbicides and other pesticides are applied using trailed sprayers fitted with smooth, large diameter, narrow, steel wheels.

Harvesting

Combine harvesters fitted with an open grouser half track and floatation rear tyres are used. Grain carting is carried out with a tractor and trailer.

Levelling

Levelling is a cultivation practice of remarkable importance, at present extensively used in Northern Italy for different crops. Regarding rice cultivation in particular, farmers consider it very important to render their fields perfectly levelled, in order to facilitate a regular water flow through fields sited at different levels, avoiding lenghty stagnation which may cause widespread growth of algae. In any case, each levelling operation is carried out during the winter, when the soil is dry and a laser technique is used for highly accurate results.

This operation is actually executed by using large blades (> 6 m wide), operating horizontally within the field, and continuously moving soil from given zones to others, in order to obtain a flat terrain (**fig. 3**) . Because of the extremely high traction pull needed to move a large amount of soil, very high powered and heavily weighted tractors (>150 kW, >80 kN) are used. Moreover, tractors are often travelling for a long time over the same site, especially in cases of big difference in level, and consequent transportation of soil carried out at more than one time.

Both factors cause high soil compaction, as in the top-soil, but above all in the sub-soil, due to the high loads of machinery and to their numerous passes.

Optimal topsoil structure is normally recovered by tillage, *whilst the problem of subsoil remains unsolved.*

Fig. 3 - The laser levelling is actually executed by using large blades, operating horizontally within the field, and continuously moving soil from given zones to others, in order to obtain a flat terrain.

Main traction aids used on rice cultivation machinery

Narrow steel wheels

2 WD or 4 WD tractors equipped with narrow steel wheels are normally used. They are hand crafted, with the diameter, width, number and shape of lugs designed according to the farmer's requirements. A wide range of lug shape and size can be found, selected by farmers in order to minimize wear, rather than to improve tractive performance (**fig. 4**). Steel wheels have rim widths varying from 60 to 120 mm and diameters (excluding lugs) typically 1.2÷1.3 times normal tyre diameter. The lugs tend to be triangular, about 150 mm tall and spaced at about 200-250 mm apart on the rear wheels, and are smaller and closer for front driven wheels. Apart from triangular lugs, there are also "U" shaped and bar-ended lugs for some

hard track use, and a "W" shaped type often used on sandy soil to reduce sinkage. The wheel rims are made of sheet steel and the hub is generally offset, to allow the wheel to run outside the mudguard, due to its larger diameter by comparison with that of the corresponding tyre.

On very soft soils a dual wheel can be used, the outer wheel having a smaller diameter and being typically mounted 350-400 mm from the inner wheel (**fig. 5**).

Smooth steel wheels (with no lugs) are used on the front axle of 2 WD tractors and on trailed implements.

In general, a typical tractor used for rice cultivation would appear to be 4 WD, 80 kW, fitted with four lugged wheels. The tractor is generally carried on low loading trailers when transported on roads, although road rings have been used, particularly on 2 WD tractors.

It is estimated that there are at present 8,000÷10,000 tractors equipped with these wheels, provided by 4 or 5 manufacturers. It should be noted that a set of 4 wheels for a 4 WD tractor has a total mass of around 750 kg, increasing by about 10 % the mass of the corresponding tyred tractor.

Narrow steel wheels are successfully used in Northern Italy for rice cultivation for the following reasons :

- in order to facilitate the mechanization of the cultivation, broadcast seeding is necessary, but this requires well levelled fields. Narrow wheels only form small ruts, leaving the soil surface levelled. For crop protection narrow wheels also reduce the amount of plants damaged by wheeling ;
- water control : these wheels cut through water control bunds and the damaged area can be filled in very quickly by foot ;
- others : the extra ground clearance using larger diameter wheels may help in negotiating banks and ditches as well as generally increasing the clearance to avoid bogging down and to reduce damage to the crop when spraying.

Half tracks

30-40 days before harvesting operations, rice fields are drained, leaving a soil moisture content ranging between 20 and 30 %. This figure is still high and can cause serious mobility problems for combine harvesters which therefore have to be especially equipped with half tracks on the front axle, while normal lugged tyres (in order to improve the steering of the vehicle) are fitted on the rear axle (**fig. 6**).

These tracks are generally made for the Italian market by a small number of companies, their width ranging from 700 mm to 1100 mm, depending on the mobility problems encountered in the various fields. For road use, the tracks are fitted with rubber inserts. Similar tracks can be supplied for tractors for use on marshy ground.

Soil tillage and compaction in wet soils

Machinery operations carried out on wet fields can result in very dense subsoil (Soane, 1970). These resultant hard, impervious subsoils obstruct water flow and root penetration, to say nothing of increasing the runoff and erosion losses.

Compaction also increases soil strength which impedes root growth, and poor root growth results in low crop yields (Taylor *et al.*, 1964). The purpose of tillage in agriculture is to restore the physical condition of the soil for optimum plant production from an utilitarian and economic standpoint (Cooper, 1971). This change in physical condition usually involves a change in the structure of the soil, and the soil structure has an overriding influence on plant growth since it governs the fluxes of water and air to the roots.

An analysis of the aforementioned effects of machinery traffic and tillage operations on soil structure, hydraulic properties and plant growth is shown schematically in **fig. 7.** (Negi *et al.*, 1980).

Fig. 4 - A wide range of lug shape and size equipping narrow steel wheels can be found, selected by farmers in order to minimize wear, rather than to improve tractive performance.

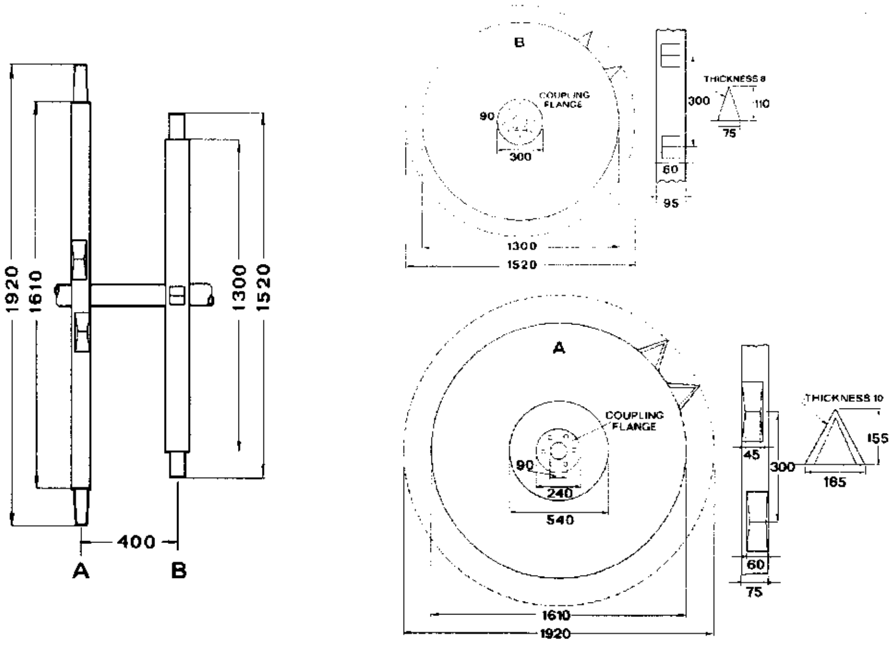

Fig. 5 - On very soft soils a dual narrow steel wheel can be used, the outer wheel having a smaller diameter and being typically mounted 350-400 mm from the inner wheel.

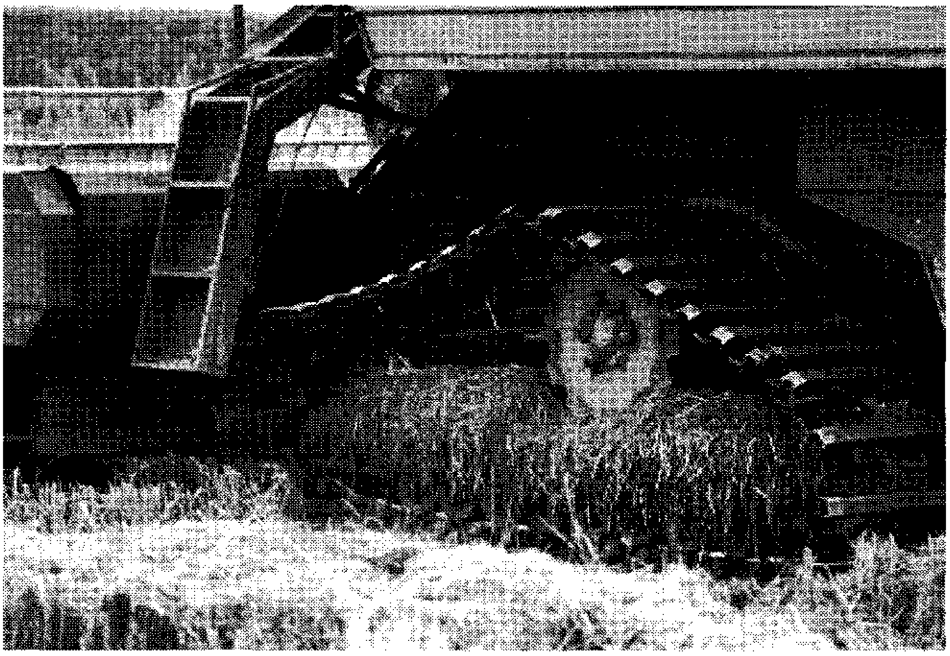

Fig. 6 - To avoid mobility problems during harvesting, combine harvesters have to be especially equipped with half tracks on the front axle, while normal lugged tyres (in order to improve the steering of the vehicle) are fitted on the rear axle.

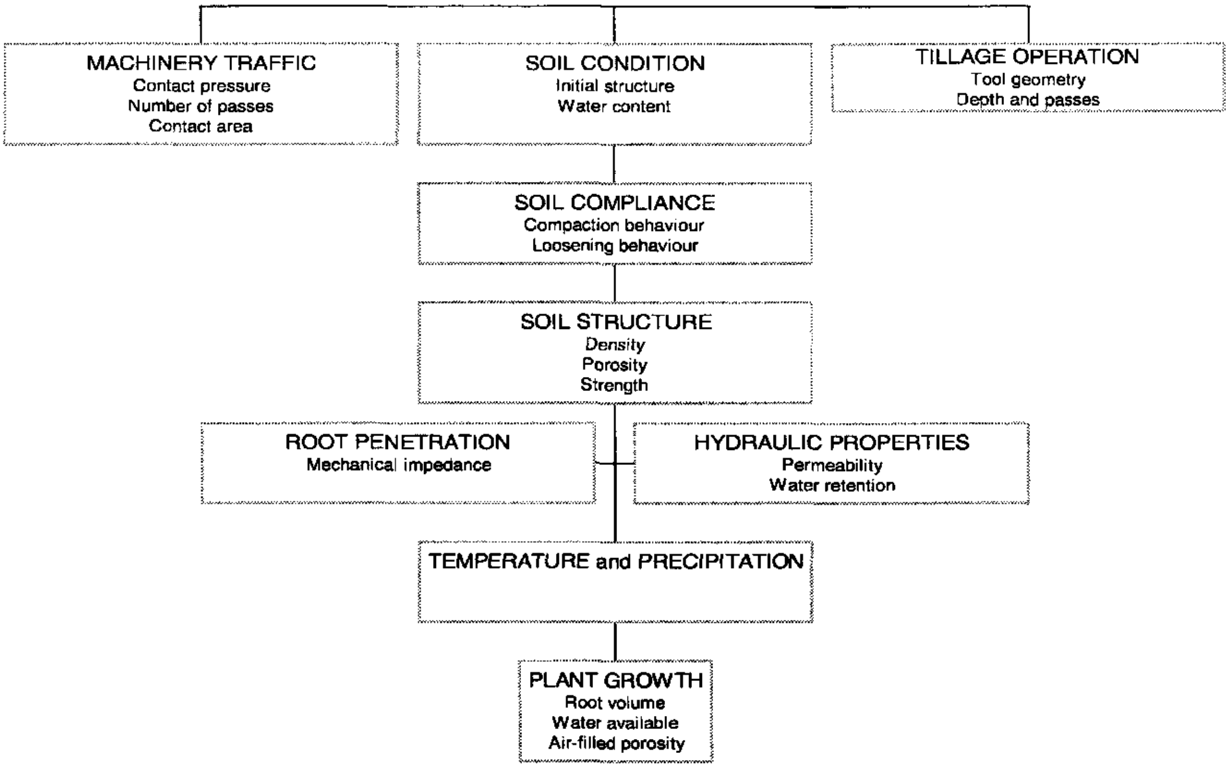

Fig. 7 - Analysis of the various effects of machinery traffic and tillage operations on soil structure, hydraulic properties and plant growth (from Negi *et al.*, 1980).

In rice cultivation all these factors have a significant effect on compaction, taking into consideration that this crop is usually repeated for many years (in some cases more than 20 years) as a monoculture.

Ploughing and harvesting damage the sub-soil structure in particular because, due to bad spring and autumn weather, these operations sometimes have to be carried out when the soil has a high moisture content.

On the other hand, the soils cultivated for rice in Northern Italy are high in silt and when dry showed no signs of cracking, although the whole area varies from sandy to clay soil. As the ploughing depth is fixed at 200-250 mm, and this operation is repeated year after year, a very considerable hard-pan (plough-pan) is probably formed.

It is however to be underlined that in rice cultivation, the presence of a hardpan is useful for controlling the water consumption in flooded fields, especially in sandy soils. Narrow steel wheels also cross the flooded layer very easily and partially penetrate the hardpan, so creating a "gear effect" and allowing a relatively high traction force, useful in overcoming the rolling resistance of the tractor itself and the implement being towed.

The walls of the narrow steel wheels are not perfectly vertical, but they appear convex, having the maximum width at their centre. Particularly in very soft soils, this shape is thought to facilitate a degree of wheel floatation, limiting the sinkage but at the same time allowing the gear effect.

Methods

Different soil parameters have been taken into account in paddy fields at different stages of growth (mainly in the mid-growing season and after harvesting), in order to investigate the soil condition in rice cultivation.

After the definition of the soil granulometry, the moisture content (when achieveable), the cone penetrometer resistance and the cone index were measured in 16 paddy fields, sited in the district of Vercelli, the most typical Italian paddy area.

Usually, Italian paddy fields are filled with water during the first fortnight of April and the mid-growing season is at the end of May. Consequently the water has been present for 45-50 days. At this stage of the crop, the following data were collected for every field:

- fields granulometry ;
- type of tools used for previous soil tillage (plough, harrow, chisel) ;
- type of previous levelling (traditional or laser controlled) ;
- water depth ;
- cone penetrometer resistance.

Further measurements were carried out after the rice harvesting to compare, when possible, the results obtained with those recorded in the mid-growing season, to investigate the compaction of the different soils due to machinery traffic. Soil moisture content tests and new cone penetrometer resistance recordings were then carried out.

A hand held semi-automatic electronic penetrometer, designed and manufactured at IIA, was used for measuring the cone penetrometer resistance (**fig. 8**). This improved and simplified the processing of the penetration resistance readings. The data were collected at first on paper and then processed using a digitizer ; in following measurement sets, a strain gauge cell (2000 N full scale) was used for measuring the penetration force, while the depth was recorded by a linear cable potentiometer. The data were stored in a data logger, and later transmitted via the serial port to the computer.

Readings were taken every second at a penetration speed of approximately 30 mm s^{-1}, using a 30° cone (base size 323 mm^2, 20.3 mm diameter) and 15.9 mm diameter shaft, according to ASAE 5313.2 standard. In each field examined, about 15 penetration resistance tests were carried out continuously from 0 to 600 mm depth, consistently with the soil resistance.

Fig. 8 - The hand held semi-automatic electronic penetrometer, designed and manufactured at IIA, used for measuring the cone penetrometer resistance (of a flooded field, in the photograph).

Four combine harvesters fitted with half tracks on the front axle and lugged tyres on the rear were used to study mobility problems on 7 of the surveyed fields during the harvesting period, taking into account the following parameters :

- mean ground contact pressure of front tracks ;
- mean ground contact pressure of rear tyres ;
- rut width ;
- rut depth.

Rut width and depth in particular can be considered a useful index of the mobility problems encountered by the combine harvesters. Moreover, rut depth is related more to rolling resistance and rut width to steering problems.

Results and discussion

Soil granulometry

Table 1 shows the soils granulometry and for 12 of 16 surveyed fields, the moisture content during the harvesting period only (October), as the fields are flooded in the mid-growing season. As expected, the soil composition was quite constant : in fact, according to the U.S.D.A. classification chart, 13 fields were sandy loam, 1 loamy sand, 1 sandy clay loam and, lastly, one clay.

Table 1 - Soil granulometry and moisture content in the harvesting period of the 16 surveyed fields.

Field name		Soil granulometry		Classification	Moisture content
	clay (%)	sand (%)	silt (%)	(USDA)	(%)
Capannina	13	60	27	sandy loam	26.3
Albero	9	63	28	sandy loam	28.7
Marcita	12	70	18	sandy loam	29.5
Campagnina	12	64	24	sandy loam	28.0
Praino	16	60	24	sandy loam	23.0
Olmette	10	62	28	sandy loam	29.5
Rabusello grande	4	76	20	loamy sand	12.0
Rabusello piccolo	17	56	27	sandy loam	26.5
Valassa	14	60	26	sandy loam	22.5
2-15 e 40	10	66	24	sandy loam	23.0
San Giacomo	20	62	18	sandy clay loam	21.0
Baraggia	42	40	18	clay loam	23.0
Rovere 1°	10	64	26	sandy loam	-----
Rovere 2°	14	60	26	sandy loam	-----
Rovere 3°	16	58	26	sandy loam	-----
Rovere 4°	24	50	26	sandy clay loam	-----

Cone penetrometer resistance

Cone penetrometer resistance measurements vs. depth below the soil surface (thus not considering the water surface as zero) were carried out in the mid-growing season. Each measurement is normally taken to be the average of 9÷14 recordings.

In **fig. 9** two examples are given, to highlight that, below the depth indicated with the marker, the penetrometer resistance is the average of fewer readings, because the penetrometer resistance was too high to operate manually. **This proves the presence of a considerable hardpan, sited roughly at the same depth as ploughing.**

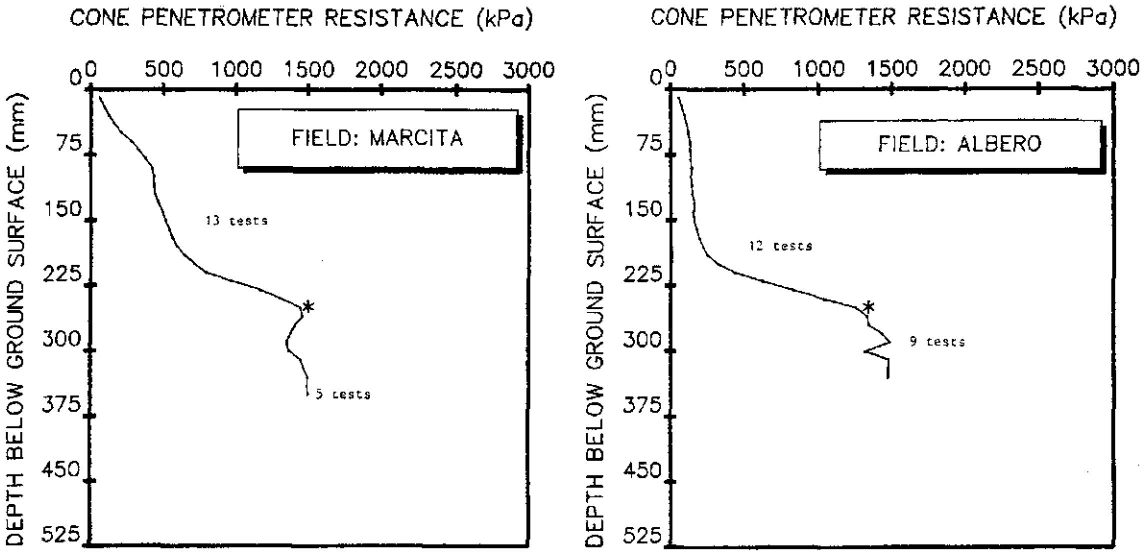

Fig. 9 - Below the depth indicated with the marker, the penetrometer resistance is the average of fewer readings, because the penetrometer resistance was too high to operate manually. This proves the presence of a considerable hardpan, sited roughly at the same depth as ploughing.

Of 3 out of 16 of the examined fields the surface was levelled using the laser technique instead of the traditional system. The use of blades controlled by laser could theoretically increase the sub-soil compaction, because the accurate levelling of the surface achievable in this way requires several passes of heavy machinery on the field. Nevertheless, no significative differences were found in maximum cone penetrometer resistance values measured in fields with similar soil granulometry but levelled with the two systems.

On the contrary, in the tilled layer (but especially in the first 150 mm) the fields which were laser levelled showed a slight increase in average values. This could be caused by a degradation of the soil structure, and in particular of the continuity of the pore system in the vertical sense, in particular inside each clod.

On the other hand, it could be noted that in order to protect against extreme temperature variations the crop during its first growing period and so to keep it below the water level, accurate levelling should allow a reduction of the water height. At the moment, farmers do not seem to take advantage of this opportunity, because the recorded water height values ranged from 30 to 200 mm, showing no correlation with the levelling system.

In **fig. 10** an example is given of the comparisons between the cone penetrometer resistance data collected in the mid-growing season and after harvesting, for two fields characterized by different soil granulometry : Olmette (sandy loam) and Baraggia (clay loam).

In the sandy loam field, in wet as well as in dry conditions a clear increase of the cone penetrometer resistance was recorded at ploughing depth ; in dry conditions, no data were obtained below 250 mm; on the contrary, in clay loam soil there is no evidence of a compacted layer up to a depth of about 400 mm ; as expected, the resistance slightly increases with deepening, but its maximum value is 40 % lower than that of the sandy loam field at the same depth.

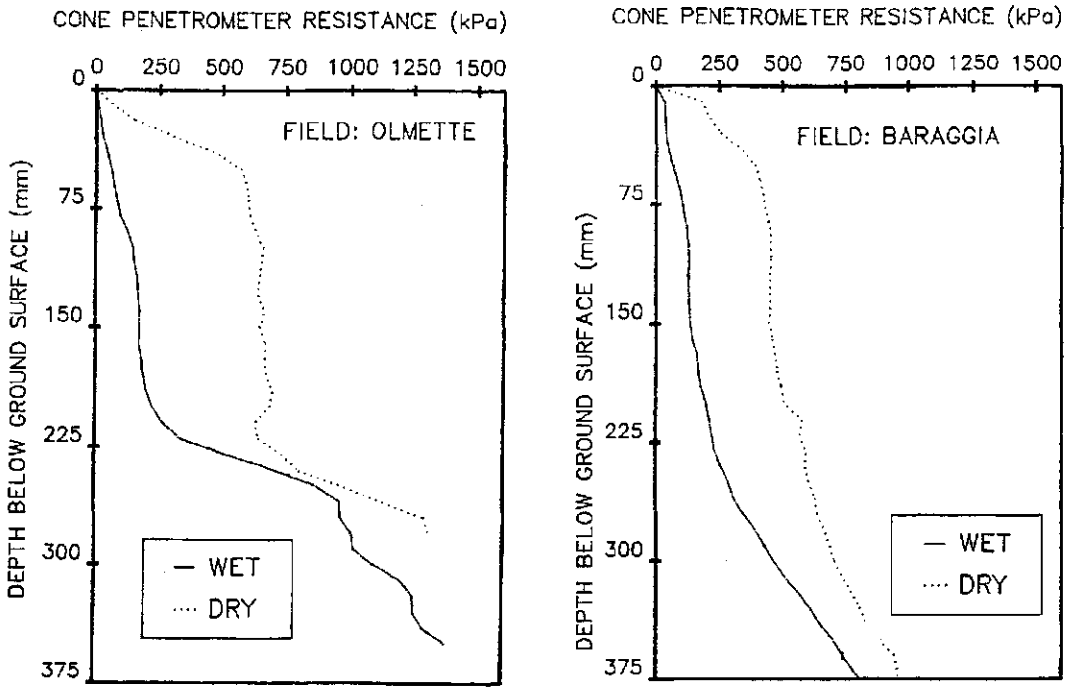

Fig. 10 - Comparisons between the cone penetrometer resistance data collected in the mid-growing season and after harvesting, for two fields characterized by different soil granulometry : Olmette (sandy loam) and Baraggia (clay loam).

Combine harvester mobility problems

Table 2 summarises the main data of the combine harvesters used for the tests, related to each field. An example of the rut width and depth left by the tracks and the rear tyres is shown in **fig. 11**.

Table 2 - Main data of the combine harvesters used for the tests, related to each field.

Make and model	Tracks		Rear	tyres	Mass	(at full load)	Theoretical ground contact pressure		Field(s) harvested
	Width	Contact lenght	Type	Inflation pressure			Front tracks	Rear tyres	
	mm	mm		kPa	kg	kg	kPa	kPa	
Laverda M120R	650	1800	8.3-24 4 p.r.	210	10210	1930	43	225	Capannina Abero
Claas Dominator 114 CS	800	2160	19.5R24 138 A8	90	13280	2590	38	97	Praino
Claas Commandor 116 CS	900	2160	19.5R24 138 A8	95	14040	2720	35	101	Olmette
Lova 1800 Commandor	900	3310	12.4-24 8 p.r.	200	12100	2380	20	215	Valassa S.Giacomo Baraggia

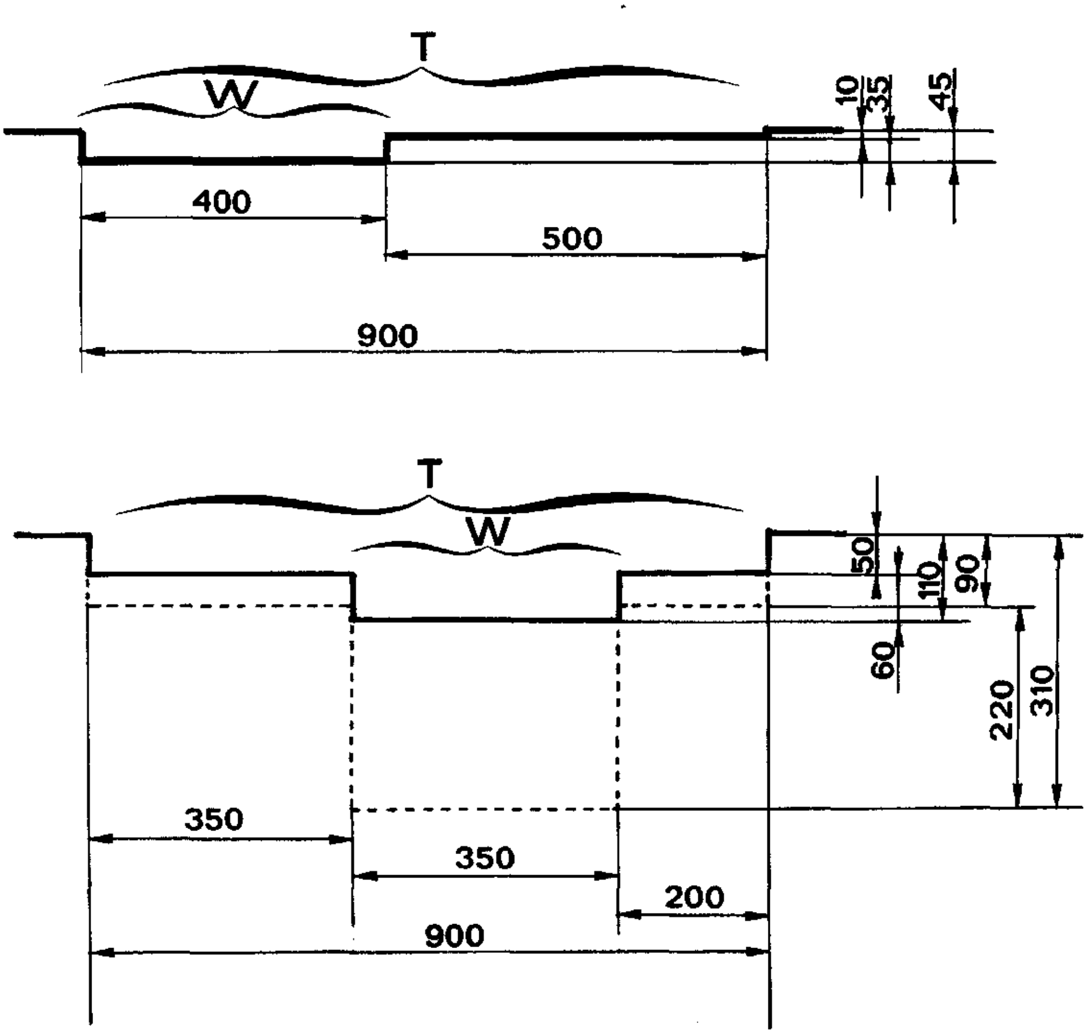

Fig. 11 - Examples of the ruts width and depth left by the tracks and the rear tyres of the combine harvester in two of the fields surveyed : Olmette (top, sandy loam) and Baraggia (bottom, clay loam). T : front track rut ; W : front track + rear tyre rut ; ---- : rut in Baraggia critical area.

The results in general highlight the influence which soil granulometry has on mobility. Deeper ruts were created in the fields with a high clay content (S. Giacomo and Baraggia, as shown in fig. 11). The ground contact pressure of the tracks and tyres is also important, as is soil moisture content, altough the latter did not show a significant influence on combine mobility during the study. This is probably due to the fact that the measured moisture contents were similar for all the fields examined.

In the only clay loam field surveyed a critical area was found, where the ruts formed were very deep (up to 310 mm). In comparison with an average moisture content of 23.0 %, in this area the figure found was 40.5 %. This confirms the principle that heavy soil with a high moisture content creates the worst mobility conditions.

The size and inflation pressure of the lugged rear tyres have a remarkable influence on localized compaction. On the other hand, with narrower tyres inflated to a high pressure, steering problems may arise.

Conclusions

In paddy fields, soil compaction has to be considered differently from that of other crops. In the growing season the upper layer is flooded and no, or very low, cone penetrometer resistance is then measurable. On the other hand, the traffic of machinery equipped with tyres in the dry period, especially laser levelling, may cause high reduction of the vertical pore system. Moreover traditional tillage improves the soil structure only partially, mainly due to bad weather conditions when ploughing and harrowing are carried out, and when the soil therefore has a high moisture content. In almost all cases a very hard plough pan is present, as a result of intensive monoculture ; on the other hand, this hardpan acts to a certain extent as a water controller and, in addition, it is a useful face for the narrow steel wheels equipping the tractor in order to develop a traction pull. Finally the machinery used in the paddy fields of Northern Italy during the flooded period use narrow steel wheels, designed to cross the flooded layer with minimum damage and not to float on it (as done, for example, by cage wheels typically used in Far East paddy fields).

Greater efforts are needed to measure (sub)soil compaction in paddy fields, to consider its consequences on crop yield, machinery mobility, water consumption and so on the control of pesticides used against weeds and algae.

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SOIL COMPACTION UNDER DRY MEDITERRANEAN CONDITIONS IN CENTRAL SPAIN

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Abstract

This paper describes the research work carried out, both in laboratory and in field experiments, at the Polytechnic University of Madrid in relation to soil compaction. In the first case, the confined uniaxial compression test was used to assess the response and the viscoelastic behaviour of five soils from different agricultural areas of Spain to compaction at different moisture contents and compression stresses. The variables taken into account in evaluating this response and behaviour were void ratio, air permeability and stress relaxation. In the second case, four compaction treatments, 0, 2, 4 and 6 passes with a 2 WD tractor, were applied inmediately after sowing on the plots of a long-term tillage trial were three tillage systems: conventional tillage, minimum tillage and direct drilling, have been compared for fifeteen years. The objective was to evaluate the extent to which this induced compaction affected the soil physical conditions and the crop establishment and yield on a three year winter wheat-vetch rotation.

The compression index of the soil was affected by the moisture content at compaction Air permeability was conditioned both by moisture and by the compression stress applied. These two variables also affected the relaxation rate of the soil and its residual elastic modulus.

The effects of the passage of the tractor did not extend beyond a soil depth of more than 15 cm. The higher the number of passes of the tractor the lower the plant estblishment of both winter wheat and vetch. The tillage system least affected by compaction was direct drilling, since the highest productions of vetch were obtained with 0, 2 and 4 passes.

Introduction

Soil compaction refers to the process of increasing the bulk density of an unsaturated soil by means of the applied forces to it. These forces may be either natural in origin, for example those arising as a result of the impact of rain drops, processes of evapotranspiration, swelling and shrinking and freezing and thawing, or applied by man since mechanized agriculture has become a reality for crop production. These latter forces are caused by heavy machinery traffic and by the action of the tillage implements.

The adoption of intensive agricultural production systems has led to the need for field equipment with a higher working capacity and greater weight, requiring higher traction power. All of these factors have given rise to soil structure degradation, reflected in a higher degree of soil compactness and a greater susceptibility to compaction. Nowadays, it is recognised that soil compaction is a problem in the humid, temperate climates of nothern Europe and North America (Soane and Van Ouwerkerk, 1995). Furtheremore, Oldeman et al. (1991) have estimated that in Europe some 33 million hectares are affected by problems of topsoil and sub-soil compaction.

In humid, temperate climates most tillage for seedbed preparation is carried out when the soil is moist, and therefore most susceptible to compaction. In those areas in which dry or semi-arid Mediterranean climates prevail, such as most of the regions of Spain devoted to rain-fed cereal crop production, rainfall is scarce and, despite its irregular distribution, concentrated on autumn and spring, the winters are dry and cold and the summers dry and either hot or very hot. The sowing of winter-sown cereal crops takes place after the topsoil has been wetted by the first autumn rains, while spring-sown cereals are sown once the soil has dried to field capacity after the winter rains. In both situations, seedbed preparation and other cultural practices are performed when the moisture content of the soil is low – except in the upper part of the soil profile in the first case and in the subsoil in the second – as a result of which the soil shows high mechanical resistance to the external forces applied. These circumstances have led to very little attention having been given to the problem of soil compaction due to machinery traffic. In other geographical regions with a Mediterranean climate, however, for example southern Australia, Holloway and Dexter (1990) have observed that the problems due to compaction are steadily increasing, in spite of the fact that the traffic intensities associated with extensive grain and pasture production are much lower than those of the intensive cropping systems of those areas with a humid climate. This lack of attention to the problem of compaction extends also to those areas in which irrigation is practiced. In this latter case, the moisture content of the soil is not a limiting factor and machinery traffic at sowing and even at harvesting occurs when the soil is moist enough to be unable to withstand the external forces applied.

This paper summarises our experience on the study of the problem of soil compaction. To date, two different experimental works have been carried out. The first one was performed in the laboratory and its objective was to use the uniaxial compaction test to assess the response and the viscoelastic behaviour of five soils from different Spanish agricultural areas when compacted at different normal stresses and moisture contents. The response was evaluated in terms of void ratio, air permeability and stress relaxation. The other experimental work consisted of a field trial carried out at El Encín experimental station (Alcalá de Henares, Madrid). The objective was to evaluate to which extent the seedbed induced compaction by machinery traffic affected the soil physical conditions and the crop development and yield on a three year winter wheat-vetch rotation.

Methods

Laboratory experiments

Five soil samples with textures ranging from sandy-loam to clay and with different organic matter contents were considered. Three of these soil samples were selected from three representative soils of the Spanish semi-arid regions devoted to cereal growing under dry-farming conditions. A common property of these soils is the low organic matter content of the topsoil. The other two samples were collected from a representative soil of the humid areas of northern Spain. The topsoil of this soil has a high organic matter content. Samples A and B were obtained from the topsoil (0-300 mm) and subsoil horizon (300-600 mm) of an Alfisol (Udalf) in Castro-Gayoso (43°01' N, 7°33' W). Sample C, of loam texture, was collected from the topsoil horizon (0-100 mm) of an Alfisol (Xeralf) at El Encín Research Station, Alcalá de Henares, (40°29' N, 3°22' W). Finally, samples F and Z were obtained from the topsoil horizon (0-100 mm) of a Vertisol (Xerert) of clay texture and from an Entisol (Fluvent) of silt-loam texture, respectively. The former was located in Numancia de la Sagra (40°5' N, 0°11' W) and the latter in Ejea de los Caballeros (21°7' N, 2°35' E). The first two samples were collected in the humid area of Galicia (NW Spain), with a mean annual precipitation 1018 mm, from a soil devoted to grassland production and fodder corn. The third sample belongs to a typical terrace soil from the semi-arid, 470 mm mean annual rainfall, rain fed cereal growing area of central Spain. In relation to the last two samples, the first is also located in central Spain, 430 mm mean annual precipitation, and has a high clay content. The second comes from the dry area of Aragón (NE Spain), mean annual rainfall of 480 mm, where dry-farming cereal crops are predominant. Details of selected characteristics of the five soil samples are summarized in Table 1.

Table 1. Selected properties of the soils.

Soil depth	Soil A 0-30 cm	Soil B 30-60 cm	Soil C 0-10 cm	Soil F 0-10 cm	Soil Z 0-10 cm
Soil particle distribution (g kg^{-1})					
Sand (2000-50 μm)	650	460	390	190	150
Silt (50-2 μm)	320	230	400	280	590
Clay (< 2 μm)	30	110	210	530	260
Texture	SL	SCL	L	C	SiL
Organic matter (g kg^{-1})	77	4.4	15	12.8	20
Specific gravity of solids	2.54	2.85	2.64	2.69	2.65
Consistency limits (g kg^{-1})					
Liquid	520	400	270	560	190
Plastic	440	240	190	310	230
Plasticity index	80	160	80	250	120

Textural classes: SL, sandy loam; SCL, sandy clay loam; L, loam; C, clay; SiL, silt loam

The soils were air-dried to constant moisture content and sieved through a 2 mm mesh. Samples were taken from the fraction that passed through this mesh, and mixed with water until gravimetric moisture contents of 5, 10, 15, 20 and 25% were achieved. The moisture content of soil A was raised to 35% and that of soil F to 30% due to their high plastic limits. The samples were prepared in plastic containers containing the amount of distilled water required to obtain the desired moisture in 50 g of air-dried soil. The great difficulty experienced in preparing the soil samples with moisture contents equal to or greater than 25% (w/w) made it necessary to use a different methodology to moisten the soil. This methodology consisted of filling with dry soil the stainless steel rings used to prepare the probes which were compacted. The soil was then saturated by capillarity and taken to the desired moisture content in a pressure plate extractor for 24 hours.

For the compaction tests, cylindrical stainless steel rings measuring 50 mm in internal diameter and 20 mm in height, were used. The rings were filled with soil and care was taken to prevent compaction. To ensure that the air filled porosity of the probe was within a range of 50-60%, the ring was placed on a balance to weigh the amount of soil transferred. The uniaxial compaction of the soil probes was accomplished using a universal testing machine. The maximum compression stresses applied to the soil by the piston in the moving head were 50, 100, 200 and 400 kPa. The moving head of the universal testing machine was lowered at a constant rate of 0.83 mm s^{-1} . The resulting strain in the probe was registered as a function of the stress applied by a computer interfaced to the testing machine. As soon as the preset compression stress was reached, the head movement was inverted. On completion of the compaction process, the air permeability of each soil probe was determined using an air permeameter.

The viscoelastic behaviour of the soils was assessed by means of stress relaxation tests. The procedure applied was the same as for the compression tests except that once the preset compression stress was reached, the crosshead of the universal testing machine was stopped and held for 45 seconds. The alleviation of the stress imposed was recorded during this time period.

Data were analyzed as a complete randomized three factor, soil, compression stress and moisture content, factorial design with four replications.

Field experiment

The field experiment was performed at El Encín experimental station, Alcalá de Henares, (40°29' N, 3°22' W) on a Calcic Haploxeralf soil (Soil Survey Staff, 1992) of loamy texture. Details of some properties of this soil can be seen in Table 1. Four compaction subtreatments, 0, 2, 4 and 6 passes with a 2 WD tractor, were applied inmediately after sowing on a long-term tillage trial were three tillage systems: conventional tillage (T1), minimum tillage (T2) and direct drilling (T3), have been compared for fifeteen years. The experiment lasted three consecutive growing seasons (1992/95) and the crop rotation followed was winter wheat (cv. Talento) (2 years)-vetch.

The T1 treatment consisted of mouldboard ploughing to 300 mm depth, followed by one or two passes with a cultivator for seedbed preparation. In the T2 treatment, primary tillage was chisel plowing to 150 mm depth and seedbed was prepared as in the T1 treatment. The T3 plots were no tilled and seeded with a no-till drilling machine. Weeds were sprayed before sowing. The experimental design was a 3x4 factorial arranged as a complete randomized split-block with four replications. The dimensions of the experimental plots were 20 m x 40 m. The sowing rate of the wheat was 160 kg ha^{-1} and that of the vetch 100 kg ha^{-1}. Following sowing, the compaction treatments were applied, these consisting of passing with a 2WD tractor such that in each plot there were three track ruts, each of them comprising two crop rows, with 2, 4 and 6 passes. The rear and the front tractor track widths were 1620 mm and 1710 mm, respectively, and the weight being 41229 N. The average soil contact pressure was estimated at 85 kPa.

Bulk density was determined to a depth of 40 cm using a γ-ray transmission equipment. Data acquisition was accomplished on selected dates, with three replications for each sub-treatment.

Penetration resistance was recorded to a depth of 40 cm, using a penetrometer with a 30° cone base and 1cm^2 cross-section. Ten replicates per sub-treatment were performed.

Crop establishment and crop yield were determined in each crop season.

Results and discussion

Laboratory experiments

Void ratio, e, decreased linearly with the log of the applied stress, σ. The results fitted the logarithmic model developed by Bailey and Vanden Berg (1967), which is expressed as

$$e = e_1 - c \log \sigma$$

where e_1 is the void ratio at a normal stress $\sigma = 1$, and c is the slope of the line.

The effects of the type of soil and moisture content, as well as that of the interaction between these two factors, on the compression index, c, are reflected in Table 2. Soil samples A, B and Z exhibited the lowest compression indices, 0.45, 0.43, and 0.41, respectively, and soil samples C and F the highest, 0.50 and 0.51, respectively. The average compression index for the five soils considered increased with increasing moisture content from 5% to 20% (w/w), where it peaked at 0.71. At a moisture content of 25%, the average compression index decreased to 0.56, which is very similar to that obtained at 15% moisture content, 0.55.

The decrease in the pore space of the soil as a function of its moisture content and the compression stress applied was analyzed in terms of the relative void ratio, *i.e.* the ratio of the soil void ratio at a given compression stress to its void ratio at zero compression stress. Figure 1 shows the variation of the relative void ratio with soil moisture content at each compression

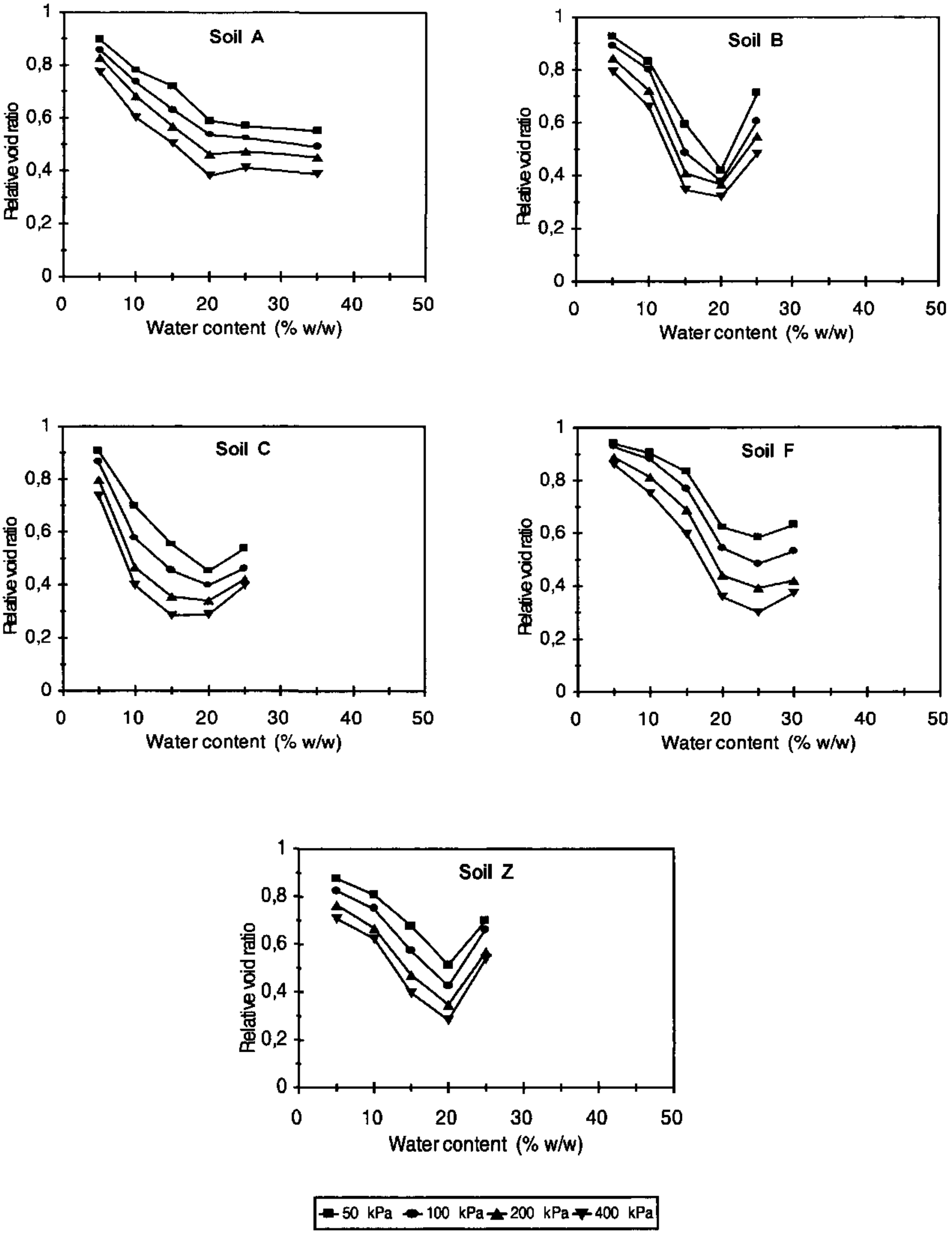

Figure 1. Relative void ratio as a function of moisture content at the different compression stresses applied to each soil. (textural classes: soil A, sandy-loam; soil B, sandy-clay-loam; soil C, loam; soil F, clay; soil Z, silt-loam).

stress considered. All the soils except A behaved similarly. The relative void ratio decreased with increasing water content at compaction to a minimum at 20% (w/w) for soils B, C and Z.

Table 2. Soil and soil moisture content effects on compression index, *c*.

Soil sample[a]	Average compression index	Soil moisture content (% w/w)	Average compression index
A	0.45	5	0.16
B	0.43	10	0.32
C	0.50	15	0.55
F	0.51	20	0.71
Z	0.41	25	0.56
LSD ($p<0.001$)			
Soil (S)	0.008		
Moisture content (MC)	0.008		
S x MC	0.019		

[a] Soil textural classes: A, sandy-loam; B, sandy-clay-loam; C, loam; F, clay; Z, silt-loam

The minimum value for soil F was obtained at a moisture content of 25% (w/w). Moisture content above the previous two resulted in increased relative void ratios. The value for soil A also decreased with increasing moisture up to 20% but remained constant beyond that point. At a given moisture content, the relative void ratio decreased with increasing compression stress. As the compression stresses were applied over a very short time period, moisture content played a central role in soil compaction. As moisture was raised, relative displacements among the soil mineral particles was favoured and soil compactability increased as a result. However, when the moisture content at compaction was very high, water saturated part of the pore space and, being non-compressible, withstood part of the compression stress applied. Consequently, the relative void ratio increased and the compactibility of the soil was reduced. The moisture content at which the former trend was reversed may be considered around the plastic limit of the soils.

The application of different compression stresses to the five soils following equilibration at the water contents considered had marked effects on air permeability. Soil F exhibited the highest air permeability, 57 μm^2, and soil A the lowest, 3.68 μm^2. The other three soils had permeability values closer to the former, 8.81 μm^2 for soil Z, 10.78 μm^2 for soil B and 13.55 μm^2 for soil C. As the moisture content of the soils increased, their permeability decreased and the average permeability fell from 27.79 μm^2 at 5% (w/w) water content to 7.79 μm^2 at 25% (w/w) water content. Likewise, air permeability was found to be inversely related to compression stress. For example, the average air permeability was 32.69 μm^2 at a compression stress of 50 kPa but decreased to only 8.81 μm^2 on raising the stress to 400 kPa. Figure 2 illustrates the effect of the interaction between stress of compaction and soil moisture on air permeability. At constant soil moisture content, the higher the compression stress the lower the air permeability. At a given compression stress, the higher the moisture content of the soil the lower its air permeability. However, at a compression stress of 50 kPa, air permeability was almost constant below 20% moisture content but decreased as moisture content was raised to 25%. With the other compaction stresses, values of air permeability less than the limiting value of 10 μm^2 were reached with water contents which were the lower the greater the stress applied, for example 23, 17 and 13% (w/w) for 100, 200 and 400 kPa.

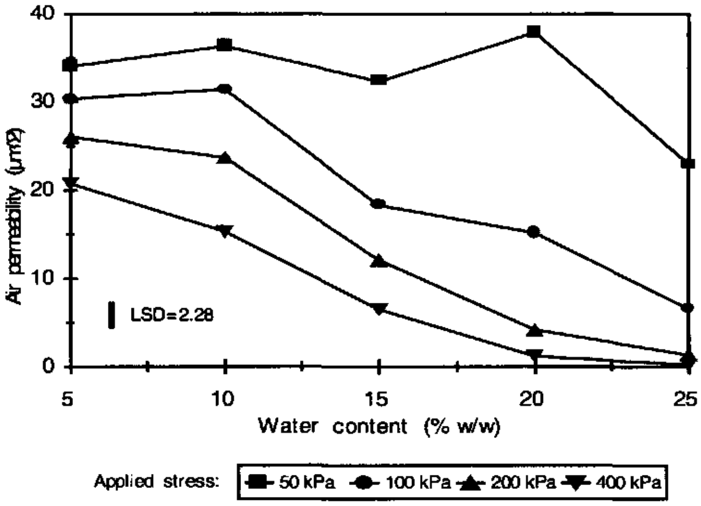

Figure 2. Effect of water content on the mean value of air permeability in each soil considered.

The time relaxation of the stress induced after having subjected the soils to constant deformation was fitted to the mathematical expression corresponding to a model consisting of a spring coupled in parallel to two Maxwell elements. This expression is as follows:

$$E(t) = E_R + Ae^{-Bt} + Ce^{-Dt}$$

where E(t) is the elastic modulus of the soil at a given moment (kPa), E_R is the residual elastic modulus, (kPa), A and C are the elastic moduli of the springs of the two Maxwell elements and B and D are the inverse of the relaxation times of these two elements.
This paper does not include the values obtained from each soil at each of the compression stresses and moisture contents considered for the coefficients of this equation. Nevertheless, it is worth to mention that the values for parameters B and D hardly varied with moisture content, but while the first decreased in value as compression stress increased, the second remained practically constant.

The relaxation rate at time t=0 expresses the rate at which the soil begins to dissipate the stress induced by the deformation to which it is subjected. The analysis of variance (Table 3) underlined the effects of soil type, moisture content and compression stress on the value of this relaxation rate.

Table 3. Effect of soil type, compaction stress and moisture content on the relaxation rate at time t=0..

Source of variation	Level of significance	LSD
Soil, S	****	121
Compaction stress, σ	****	108
Moisture content, MC	****	121
Interactions		
S x σ	****	242
S x MC	****	271
σ x MC	****	242

**** p(<0.001); LSD, Least significant difference

The highest value of the relaxation rate at time t=0, 1720 kPa s^{-1}, corresponded to the clay soil, F, followed by the sandy-clay-loam soil, B, 1220 kPa s^{-1}. The sandy-loam, A, silt-loam, Z, and loam, C, soils had the lowest relaxation rate, the value being similar in all cases at 926 kPa s^{-1}. The relaxation rate decreased when soil moisture content increased from 5% (w/w) to 20% (w/w) (Fig. 3a). Nevertheless, at 25% moisture content the former reached a value of the same order of magnitude as that obtained at 15% (Fig. 3a). The effects of compression stress on the value of the relaxation rate at time t=0 are shown in Figure 3b. At both 400 kPa and 200 kPa similar values were reached, 1306 kPa s^{-1} and 1246 kPa s^{-1}, respectively, these being higher than those corresponding to 100 kPa, 1104 kPa s^{-1}, and 50 kPa, 943 kPa s^{-1}.

The residual elastic modulus is a parameter directly related to the stress that the soil has not dissipated after a given relaxation time. The higher the value of this parameter, the lower the stress dissipated. Table 4 shows the analysis of variance that expresses the extent to which the residual elastic modulus is affected by soil type, moisture content and compression stress. The highest value of the residual elastic modulus, 1134 kPa, corresponded to the clay soil, F, followed by the sandy-clay-loam soil, B, with a value of 591 kPa, and by the silt-loam, Z, loam, C, and sandy-loam, A, soils, the residual elastic modulus of which was the same in all cases, at 44 0 kPa.

Table 4. Effect of soil type, compaction stress and moisture content on the value of residual modulus of the relaxation curve.

Source of variation	Significance level	LSD
Soil, S	****	36
Compaction stress, σ	****	33
Moisture content, MC	****	36
Interactions		
S x σ	****	73
S x MC	****	81
σ x MC	****	73

**** (p<0.001); LSD, Least significant difference

The effect of moisture content on the value of residual elastic modulus was similar to that observed for the relaxation rate at time t=0 (Fig. 3a). In the moisture content range between 5% (w/w) and 15% (w/w), the residual elastic modulus decreased sharply, since its value was 1462 kPa at 5%, decreased to 652 kPa at 10% and decreased further to 362 kPa at 15%, but it remained almost constant with moisture contents higher than this last value. For example, with a moisture content of 20% the elastic residual modulus was 270 kPa, this being maintained at the same order of magnitude when moisture content increased to 25%, 300 kPa. As the compression stress applied increased, so too did the elastic residual modulus (Fig. 3b). Indeed, with stresses of 50 kPa and 100 kPa, the values for this parameter were 244 kPa and 399 kPa, respectively. When the compression stress increased to 200 kPa, the residual elastic modulus increased to 681 kPa, the highest value, 1115 kPa, being reached at an applied stress of 400 kPa. In a soil subjected to constant deformation, the stress induced in it decreases with time until the elastic equilibrium condition is reached. This equilibrium is quantified by the residual elastic modulus. The water content of the soil plays an important role in this process, since it affects both the rate at which this stress is dissipated and its residual value. Figure 3a underlines that this rate, expressed as the mean value of the rates of all the relaxation curves corresponding to all the soils considered and all the compression stresses applied, decreases when moisture content increases from 5% to 15%, remaining practically constant at moisture contents higher than this last value. The residual elastic modulus follows a similar trend. If the moisture content is low, the number of menisci retaining water in the soil pores is equally low and, therefore, so is the value of the forces of attraction between the aggregates, but when water content increases the number of menisci also increases, along with the forces of attraction. In the first case, low moisture content, the soil particles reorganize rapidly, but in the second, high water content, they do so only after having overcome the resistance of the water retained in the pores. For this reason, the rate of relaxation decreases sharply when water content increases from 5% to 15%. In the range 15% to 25%, the attraction of the aggregates would appear to stabilize, since relaxation rate remains constant. Once the resistance of the water is overcome, its lubricating action is responsible for the soil reaching elastic equilibrium at lower residual stresses.

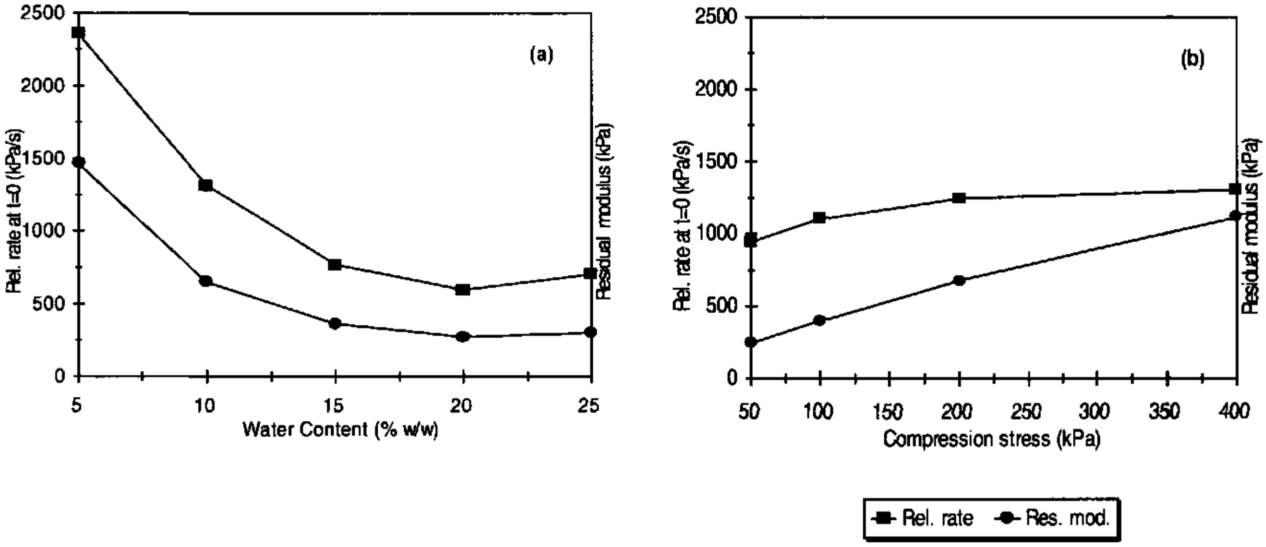

Figure 3. Relaxation rate at time t=0 and residual elastic modulus as a function of (a) moisture content at compaction and (b) compression stress (Rel. Rate, relaxation rate at time t=0; Res. mod. Residual modulus).

Field experiment

Tables 5 and 6 show the values of penetration resistance following soil compaction in the growing season 1992/93. The former table contains the soil strength profile corresponding to each treatment and sub-treatment whereas the latter reveals the impact of each sub-treatment on the values of penetration resistance measured for each tillage system.

Table 5. Values of penetration resistance (kPa) measured in the treatments and sub-treatments considered.

Tillage system	No. passes	Soil depth (cm)							
		5	10	15	20	25	30	35	40
T1	0	220^{b}	330^{c}	560^{b}	710^{c}	1208^{c}	1508^{b}	2236^{b}	2361
	2	1542^{a}	1354^{b}	1225^{a}	1080^{b}	1285^{bc}	1668^{ab}	2657^{ab}	2654
	4	1938^{a}	1574^{ab}	1328^{a}	1440^{a}	1631^{a}	1920^{a}	2748^{ab}	2765
	6	2196^{a}	1630^{a}	1403^{a}	1518^{a}	1554^{ab}	1408^{b}	3405^{a}	2706
T2	0	972^{c}	1124^{b}	1138^{b}	1374^{ab}	1442^{ab}	1621^{b}	2357^{a}	2567
	2	1410^{b}	1284^{b}	1240^{b}	1144^{b}	1171^{b}	1750^{ab}	2000^{b}	2366
	4	1626^{a}	1257^{ab}	1268^{ab}	1297^{ab}	1144^{ab}	2050^{a}	1825^{b}	2269
	6	1698^{a}	1432^{a}	1455^{a}	1522^{a}	1641^{a}	2002^{a}	1985^{b}	2323
T3	0	1372^{b}	1527	1442^{a}	1497	1304	1574	1875^{b}	2139^{b}
	2	1341^{b}	1282	1173^{b}	1079	1280	1849	2367^{a}	2755^{a}
	4	1603^{a}	1269	1142^{b}	1197	1340	1478	1808^{b}	2558^{a}
	6	1334^{b}	1282	1146^{b}	1041	1280	1720	2363^{a}	2801^{a}

In each treatment, the figures in each column followed by different letters differ one from the other ($p<0.01$). The figures not followed by letters are not different.

In the conventional tillage system (T1), and to a depth of 25 cm, the lowest penetration resistance values were those for the sub-treatment with 0 passes, followed by the values measured for 2 passes (Table 5). The highest values corresponded to the sub-treatments with 4 and 6 passes. At depths greater than 25 cm the penetration resistance was similar in all sub-treatments. In the case of the minimum tillage system (T2), the differences in the penetration resistance measured in the sub-treatments were less accentuated than in the former system. For example, only at a depth of 5 cm was it observed that the penetration resistance for 0 passes was lower than that recorded for the other sub-treatments. In these, soil strength increased with the number of passes (Table 5). At depths of 10 and 15 cm, the lowest values of penetration resistance corresponded to the sub-treatments with 0 and 2 passes, followed by those with 4 and 6 passes. At greater depths, the values measured for 0 and 2 passes were lower than those for 4 and 6 passes, but at a depth of 40 cm the penetration resistance was similar in all sub-treatments. With the direct drilling system (T3), the values of soil strength were similar at all depths and with all sub-treatments (Table 5). This underlined the fact that with this tillage system a constant and uniform level of compaction was maintained within the entire soil profile. Likewise, and given that the soil was more consolidated, this system was also the one least susceptible to mechanical compaction.

In the sub-treatment with 0 passes (Table 6), the lowest values of penetration resistance were recorded with the conventional tillage system (T1), and the highest with direct drilling (T3). Nevertheless, at depths of more than 25 cm the three tillage systems exhibited the same soil strength (Table 6). The soil profile showed a high degree of uniformity in all the tillage treatments when compacted with two tractor passes, since in all cases the values of penetration resistance were of the same order of magnitude. When compaction was by four and six passes, however, the penetration resistance measured in the range 5-10 cm depth was higher with the conventional tillage system than in the case of minimum tillage and direct drilling. This situation was reversed as from a depth of 30 cm.

Table 6. Values of penetration resistance (kPa) measured for each tillage system and each of the sub-treatments compared.

No. passes	Tillage system	Soil depth (cm)							
		5	10	15	20	25	30	35	40
0	T1	220^{c}	330^{c}	560^{c}	710^{b}	1408^{b}	1508	2236^{a}	2361^{a}
	T2	972^{b}	1124^{b}	1138^{b}	1374^{a}	1442^{a}	1621	2357^{a}	2567^{ab}
	T3	1372^{ab}	1527^{a}	1442^{a}	1497^{a}	1304^{ab}	1574	1875^{b}	2139^{b}
2	T1	1542	1354	1225	1080	1285	1668	2657^{a}	2654^{a}
	T2	1410	1284	1240	1144	1171	1750	2000^{b}	2366^{b}
	T3	1341	1282	1173	1079	1280	1849	2367^{a}	2755^{a}
4	T1	1938^{a}	1574^{a}	1328	1440	1631^{a}	1920^{a}	2748^{a}	2765^{a}
	T2	1626^{b}	1257^{b}	1268	1297	1444^{ab}	2050^{a}	1825^{b}	2269^{b}
	T3	1603^{b}	1269^{b}	1142	1197	1340^{b}	1478^{b}	1808^{b}	2558^{b}
6	T1	2196^{a}	1630^{a}	1403^{a}	1518^{a}	1554^{ab}	1408^{b}	3405^{a}	2706^{a}
	T2	1698^{b}	1432^{b}	1455^{a}	1522^{a}	1641^{a}	2002^{a}	1985^{c}	2323^{b}
	T3	1334^{c}	1282^{b}	1146^{b}	1041^{b}	1280^{b}	1720^{ab}	2363^{b}	2801^{a}

In each treatment, the figures in each column followed by different letters differ one from the other ($p<0.01$). The figures not followed by letters are not different.

The tillage system and the number of passes applied affected the crop establishment. Table 7 contains the winter wheat estalishment in the 1992/93 season. Direct drilling (T3) was the treatment providing the highest number of plants established, 243 plants m^{-2}, followed by conventional tillage (T1), 186 plants m^{-2} and by minimum tillage (T2), 166 plants m^{-2}. The table also shows that the higher the compaction the lower the number of plants established. If for each treatment the plants established in each sub-treatment are expressed as a percentage of those corresponding to 0 passes (Table 7), it may be seen that for the three treatments there is the same reduction in plants established with the number of passes.

Table 7. Wheat establishment (plants m^{-2}) in the growing season 1992/93.

Tillage system	Number of passes 0	2	4	6	Mean
T1	324 (100)	185 (58)	145 (46)	90 (28)	186
T2	300 (100)	169 (57)	116 (39)	80 (27)	166
T3	391 (100)	257 (65)	200 (51)	126 (32)	243
Mean	338	204	154	98	
LSD ($p<0.01$)					
Tillage	14				
No. passes	8				

For each tillage system figures in brackets are percentages referred to 0 passes.

Table 8 shows the establishment for the vetch crop in the 1994/95 season. On this occasion there was no effect due to the tillage system, but there was a clear effect relating to the number of passes and the interaction between the former and the latter. Establishment decreased with the number of passes. Comparison of the emergence obtained with a given sub-treatment for the different tillage systems shows that the highest number of plants established with 0 passes was attained with the conventional tillage system, followed by minimum tillage and direct drilling. As the number of passes increased, the situation was reversed and the highest emergence was associated with direct drilling and the lowest with conventional tillage.

Table 8. Vetch establishment (plants m^{-2}) in the growing season 1994/95.

Tillage system	Number of passes 0	2	4	6	Mean
T1	139 (100)	66 (47)	31 (22)	17 (12)	63
T2	128 (100)	61 (48)	50 (39)	24 (19)	66
T3	113 (100)	85 (75)	79 (70)	41 (36)	80
Mean	127	71	53	27	70
LSD ($p<0.05$)					
No. passes	21				
Tillage x No. passes	28				

For each tillage system figures in brackets are percentages referred to 0 passes.

The production of fodder vetch (Table 9), with 85% moisture content wet basis, was directly related to the number of plants established. Indeed, this production decreased as the number of passes with the tractor increased. Nevertheless, when analyzing the interaction between the treatments and the number of passes, the response obtained differed between tillage systems. In the case of direct drilling (T3) , for example, the same production was obtained with 0, 2 and 4 passes. In the other two treatments, the production achieved with 0 passes was similar to that corresponding to direct drilling, but this was not the case for other numbers of passes. In this respect, conventional tillage (T1) was the treatment most affected by soil compaction, since the crop productions obtained with 2, 4 and 6 passes were lower than with the other two systems, although it is true to say that there were no significant differences with respect to those obtained with minimum tillage. With 6 passes the lowest crop productions were achieved in the three treatments.

Table 9. Production of fodder vetch (kg ha^{-1}) with 85% moisture content wet basis, in the 1994/95 season.

Tillage	Number of passes				
System	0	2	4	6	Mean
T1	13156	7110	4755	4324	7336
T2	12288	9531	7530	6593	8986
T3	10888	10751	11663	6394	9924
Mean	12111	8320	6142	5770	
LSD ($p<0.01$)					
No. Passes	1723				
Tillage x No. passes	2984				

Conclusions

The confined uniaxial tests revealed the clear dependence that exists between the compression index and the moisture content of the soil when compacted. Moisture content and compaction stress affected the air permeability of the soils compared. With a stress of 50 kPa, air permeability at each of the moisture contents considered was above the limiting value of 10 μm^2. At compression stresses of 100, 200 and 400 kPa, however, this value was reached with moisture contents of 23, 17 and 13%, respectively.

The viscoelastic behaviour of the soil was also conditioned by its moisture and by the compaction stress applied. The relaxation rate at time $t=0$ decreased when soil moisture content increased from 5% to 15% and remained practically constant with moisture contents higher than this latter value. This relaxation rate increased , however, with compression stress. The residual elastic modulus decreased in value as moisture content increased, but increased linearly with compaction stress.

The effects of the compaction induced in the soil by tractor traffic hardly extended beyond depths of more than 15 cm. The greatest increase in the penetration resistance values occurred with the conventional tillage system.

The winter wheat crop establishment was highest with direct drilling, although it decreased with the number of tractor passes. In the case of the vetch crop, plant establishment also decreased with the number of passes, and although significant differences were not always encountered, the establishment obtained with direct drilling was higher than with the other tillage systems in all the sub-treatments considered.

In relation to the production of fodder vetch, direct drilling was the treatment least affected by compaction, since the same yield was achieved with 0, 2 and 4 passes. In the other two systems, crop yields were lower the higher the number of passes, although conventional tillage was found to be less sensitive to compaction than minimum tilling.

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APPENDIX

The experience of our research group concerning soil compaction has been already described in the paper presented to this workshop. Nevertheless, our group has been working for fifeteen years in a related topic: tillage research under rainfed Mediterranean conditions in Central Spain.

Type and number of experiments

Field experiments comparing three tillage systems: conventional tillage, minimum tillage and direct drilling, following different crop rotations: monoculture of winter wheat, monoculture of spring barley, winter wheat in rotation with vetch and winter wheat in rotation with chickpea. This field experiments have been conducted for fifeteen years.

Soils investigated

All the field experiments have been caried out in a Calcic Haploxeralf (Soil Survey Staff, 1992).

Soil properties measurements

Bulk density (+)
Soil textural and structural porosity (+)
Penetration resistance (+)
Soil water content (+)
Unsaturated and saturated hydraulic conductivity (+)
Air permeability (+)
Aggregate stability (+)
Soil organic matter content and soil nutrient distribution (+)

Crop properties

Crop establishment (+)
Crop yields (+)
Crop yield components (for cereal crops) (+)
LAI (+)
Water use efficiency (+)

Laboratory experiments

Uniaxial compaction experiments to assess the behaviour of soil samples representing four main soil types of different Spanish agricultural regions when compacted at different moisture contents and compression stresses.

Soil properties measurements

Modelization of the soil compaction process (+)
Soil tensile strength (+)
Air permeability (+)
Rheological behaviour (stress relaxation) (+)

MECHANICAL PROPERTIES OF DANISH SOILS - A REVIEW OF EXISTING KNOWLEDGE WITH SPECIAL EMPHASIS ON SOIL SPATIAL VARIABILITY

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Abstract

Guidelines for the determination of soil mechanical strength have been suggested in literature with methodology based on classical soil mechanics. Such methods, however, are time-consuming and laborious. There is a need for an evaluation of quicker methods. Further, measuring programmes should take into account the soil spatial variability. This paper presents results from measurements using quick methods for consolidation and for shear strength determination. The results are from seven Danish soils, ranging in textural composition from sand to loamy sand (clay percentage from 4 to 16). Cores of undisturbed soil were sampled from the plough layer soil and the 30-40 cm depth. The sampling procedure allowed evaluation of the spatial variability of the measured parameters at the 0.2-1 m scale as well as at the 20-100 m scale. The sensitivity of soil to compaction for stresses above the pre-consolidation load was derived from quick, strain-controlled consolidation tests without controlling soil pore water pressure. An index of virgin compression appeared to be lower for two sandy soils compared to loamy sands with clay contents above 10%. For the latter soils, no correlation was found with soil textural composition. Even when removing the effect of initial sample bulk density, no general trend in the soil compactibility could be detected. For reference samples of remoulded soil, a positive correlation was found between the index of virgin compression and the soil clay content. Averaged for the seven soils in investigation, the compactibility appeared to have an optimum at a water potential about field capacity. For samples of undisturbed soil, the index of virgin compression was determined with a coefficient of variation of about 25%. When the effect of soil bulk density was taken into account, a residual variability of about 10% still remained. Soil strength parameters were estimated by a quick shear annulus method applied to cores of undisturbed soil drained to predefined potentials. Soil cohesion as well as angle of internal friction increased with increasing clay content. Also the variability of the strength estimates increased for clay-holding soils. Standard deviation of strength estimates ranged from typically 10 kPa for sandy soils to 20-25 kPa for loamy sands. The implications of the variations found are discussed in relation to monitoring programmes for soil strength.

Introduction

The mechanization in agriculture in the past decades has increased the energy input to the soil. The machinery has become larger and heavier, thereby loading the soil to levels never seen before in the history of mankind. Also in tillage procedures, dramatic forces are manipulating the soil matrix. For humid regions like Denmark, much traffic in the field is carried out at soil water contents higher than the lower plastic limit, i.e. when the soil is compressible. Furthermore, legislation controlling the use of animal manures in agriculture in Denmark has pushed the farmer towards more traffic in early spring. Often slurry wagons with loaded weight loads of up to 30 t are pulled along the winter-wet fields with tractors themselves weighing up to 10 t. Axle loads in such situations are often in the range of 10-15 t (up to 20 for a boogie-axle). Even though low to medium pressure tires are often used for these purposes, severe compaction can be expected to reach deeper soil layers.

There is an urgent need for knowledge about the soil mechanical properties as related to the loads applied at the conditions mentioned above. The sensitivity to compaction of the soil should be quantified for conditions of isotropic stress as well as for shearing forces in the soil matrix. Lebert & Horn (1991) suggested a procedure for evaluating the mechanical strength. However, the methods suggested are time-consuming, laborious and therefore expensive. This makes it difficult to manage a measuring programme which aims to quantify the mechanical strength for a large number of soil types and soil depths. There is a need to discuss the potential and problems in using quicker methods. The classical consolidation test adopted from civil engineering purposes involves loading times from 8 to 24 hours. Quicker procedures have been suggested (Larson *et al.*, 1980; O'Sullivan, 1992; Veenhof & McBride, 1996), and loading rates similar to those observed in the field under running wheels have been recommended by Koolen (1974) and Koolen & Kuipers (1983). The argument of simulating the field situation also means a lot in the shearing procedures selected for estimating soil strength. While Lebert & Horn (1991) suggest a shearing rate of 0.003 mm s^{-1}, Olsen (1984) and Schjønning (1986) used shearing rates approximately 300 times higher.

Further, when judging the benefits and drawbacks of different methodological approaches, it is imperative to incorporate knowledge of the spatial variability of the soil mechanical properties. The general variation in soil parameters is well known and to an increasing extent used in soil science and precision agriculture (Bouma, 1989). There is a need of quantifying the variability also in soil mechanical properties and to discuss how future research should optimize the resources employed in combating soil compaction. In this paper, some results and experience gained for Danish conditions are summarized with special emphasis on the effect of soil variability.

Danish soils

Danish soils all are geologically young soils, developed from the morainic deposits from the last glaciation about 12000 years ago. Most soils in the eastern part of the country are sandy loams exhibiting a 'well-graded' texture, i.e. typically 10-15% of clay (< 2µm), 10-15% of silt (2-20 µm) and 70-80% of sand. The clay content is high enough to make the soils plastic, and the combination with the high content of (most often coarse) sand produces very compressible soils. The western part of Jutland exhibits coarse sandy soils derived from the sedimentation in the glacial water running from the border of ice in the glaciation period. Often sandy soils are expected to be non-compressible. However, a field trial has shown that significant compaction can take place also for this soil type (Schjønning & Rasmussen, 1984).

Soil compactibility

Remoulded soil

Only a few studies have addressed soil mechanical properties for Danish soils. Rasmussen (1985) reported results from confined compression tests of remoulded soils. In accordance with results from American soils (Larson *et al.*, 1980), Rasmussen found a higher 'virgin' compactibility for two loamy soils with a clay content of 13-17% than for a coarse sandy soil (3% clay). Jakobsen (1968) analyzed five soils for their response to confined compression when recompacted in cores after a homogenization procedure. Although difficult to interpret, the study seems to support that within the same soil the compactibility at high loads is independent of water content (Larson *et al.*, 1980). Applying triaxial tests to cores of remoulded soils, Petersen (1993) found a steeper slope (λ) of the Normal Consolidation Line (NCL) for a soil holding 27% clay compared to one containing only 13% clay. The water content of the soils appeared to be positively correlated to this index of compactibility up to approximately 20 percent (w/w).

Undisturbed soil

Schjønning (1991) quantified the mechanical properties for seven agricultural soils in Denmark. Some basic characteristics of the soils are given in Table 1.

Table 1. Selected basic characteristics of the soils studied by Schjønning (1991)

Location		Soil type	Depth cm	Texture (% w/w)				CEC^2, m. eqv/kg	Consistency limits^1 (% w/w)		
No.	Name			Org. matter	Clay <2 µm	Silt 2-20 µm	Sand 20-2000 µm		Plastic limit	Liquid limit	Plasticity index
1	Tylstrup	Cumulic	0-20	2.6	3.6	2.9	90.9	107	11.9	30.9	19.0
		Haplumbrept	30-40	1.7	3.6	2.9	91.8	102	12.5	32.7	20.2
2	Borris	Orthic	0-20	2.2	5.2	5.8	86.8	101	12.1	27.6	15.5
		Haplohumod	30-40	1.0	5.2	5.8	88.0	72	9.8	27.2	17.4
3	Tystofte	Not	0-20	2.0	10.5	12.0	76.5	115	10.2	22.4	12.2
		classified*	30-40	1.4	10.5	11.0	77.1	93	9.2	21.1	11.9
4	Årslev	Typic	0-20	2.2	10.6	11.9	75.3	127	10.3	25.5	15.2
		Agrudalf	30-40	1.2	13.6	10.4	74.8	112	9.9	23.2	13.3
5	Roskilde	Typic	0-20	2.6	11.0	13.5	72.9	132	10.0	24.8	14.8
		Agrudalf	30-40	1.9	10.6	12.9	74.6	111	11.7	22.8	11.1
6	Rønhave	Typic	0-20	2.6	12.1	15.4	69.9	158	11.6	29.4	17.8
		Agrudalf	30-40	1.4	15.2	13.3	70.1	131	10.0	25.6	15.6
7	Silstrup	Not classified	0-20	3.2	14.8	13.2	68.8	189	14.1	33.0	18.9
			30-40	2.2	15.7	13.3	68.8	171	14.8	29.8	15.0

$^{1)}$ Drop cone method. $^{2)}$ Cation exchange capacity. * Same origin as 5.

The methodological procedures are presented in detail in the original paper. In short, all measurements were carried out in soil cores of 100 cm^3 volume drained to a predefined matric potential. These cores of undisturbed soil were enclosed in a metal ring also used for sampling, which for each soil included two soil depths (0-20 and 30-40 cm) at six separate plots along the field. A uni-axial, confined compression test - in principle as suggested by Koolen (1974) - with a strain-controlled (1 mm per minute) stress application formed the basis for calculation of the virgin compression index, defined as the slope of the linear part of a plot of void ratio [m^3 m^{-3}] against $\log_{10}$(load, [kPa]). Six replicate soil cores were measured for each of six matric potentials ranging from -30 to -300 hPa. Due to the rapid application of load, no attempt was made to control pore water pressure during the measurements.

Larson *et al.* (1980) suggested soil bulk density as the soil parameter in evaluation compression tests. However, void ratio was chosen by Schjønning (1991) as it is an additive parameter and displayed the same linear relation to $\log_{10}$(normal load) when exceeding the pre-consolidation load. The index gives the numerical value of the change in void ratio when increasing the normal load by a factor 10 at loads higher than the pre-consolidation load.

Table 2. Index of virgin compression, C_v, and soil bulk density and volumetric water content for the plough layer soil of seven Danish soils drained to six different matric potentials. Figures in brackets denote standard deviation (n = 6). Calculated from data of Schjønning (1991).

Location (% clay)	Matric potential, hPa	C_v-index				Bulk density g cm^{-3}	Water content % v/v
		Measured data		Calibrated*			
Tylstrup (4)	-30	9.1	(1.1)	9.1	(0.8)	1.38	41.0
	-50	9.0	(1.1)	9.5	(1.0)	1.40	38.2
	-75	10.5	(2.2)	10.0	(0.8)	1.37	31.2
	-100	9.8	(1.6)	9.6	(0.5)	1.38	24.1
	-160	10.3	(2.1)	9.7	(1.0)	1.37	17.5
	-300	9.5	(2.4)	10.0	(0.6)	1.40	12.7
	LSD_{95}	n.s.		n.s.		n.s.	2.4
Borris (5)	-30	7.4	(2.7)	8.1	(0.4)	1.52	35.2
	-50	8.8	(2.1)	8.6	(0.4)	1.50	32.6
	-75	10.3	(2.0)	10.4	(0.6)	1.50	28.2
	-100	10.1	(2.0)	9.9	(0.6)	1.50	24.4
	-160	10.0	(1.9)	9.2	(0.5)	1.48	20.6
	-300	8.3	(1.9)	8.6	(0.8)	1.51	18.0
	LSD_{95}	1.8		0.7		n.s.	1.5
Tystofte (11)	-30	12.4	(5.6)	11.9	(1.1)	1.52	32.3
	-50	14.8	(3.7)	13.7	(0.8)	1.51	30.1
	-75	11.6	(2.0)	13.6	(0.7)	1.57	26.7
	-100	11.8	(3.7)	14.1	(0.7)	1.58	24.4
	-160	13.9	(4.3)	13.2	(1.1)	1.52	22.2
	-300	15.0	(3.3)	13.0	(1.4)	1.49	20.0
	LSD_{95}	n.s.		1.0		n.s.	1.0
Årslev (14)	-30	13.2	(5.0)	12.0	(2.0)	1.53	31.4
	-50	11.7	(3.6)	14.5	(1.3)	1.60	30.0
	-75	14.1	(1.9)	14.0	(1.6)	1.55	27.4
	-100	13.9	(4.1)	14.8	(1.3)	1.57	26.3
	-160	15.7	(5.8)	14.6	(2.1)	1.54	24.6
	-300	15.0	(5.9)	13.7	(1.8)	1.53	23.2
	LSD_{95}	n.s.		1.4		n.s.	1.3
Roskilde (11)	-30	10.7	(5.8)	10.5	(1.7)	1.58	31.1
	-50	11.3	(3.5)	11.4	(1.0)	1.59	30.3
	-75	10.7	(3.2)	11.2	(1.8)	1.60	28.7
	-100	12.6	(4.1)	11.8	(1.2)	1.57	27.3
	-160	9.0	(2.7)	10.9	(1.2)	1.63	27.2
	-300	12.3	(4.8)	11.1	(1.1)	1.56	24.9
	LSD_{95}	n.s.		n.s.		n.s.	0.9
Rønhave (15)	-30	17.3	(2.9)	15.1	(1.7)	1.43	33.3
	-50	14.7	(2.0)	16.6	(0.4)	1.50	32.4
	-75	17.1	(3.2)	17.3	(1.1)	1.47	29.9
	-100	18.7	(2.3)	18.4	(1.4)	1.46	28.4
	-160	19.3	(4.7)	18.6	(1.4)	1.46	27.0
	-300	16.5	(1.6)	17.2	(1.6)	1.49	25.7
	LSD_{95}	2.8		1.2		n.s.	3.0
Silstrup (16)	-30	9.2	(2.9)	11.3	(1.3)	1.54	35.4
	-50	13.8	(2.7)	13.5	(1.0)	1.50	33.2
	-75	14.0	(3.4)	13.7	(1.3)	1.50	31.7
	-100	15.9	(2.9)	14.8	(1.1)	1.49	29.6
	-160	14.2	(2.5)	13.9	(1.1)	1.50	29.5
	-300	13.3	(2.7)	12.9	(1.0)	1.50	28.4
	LSD_{95}	3.1		1.2		n.s.	1.1

* Calibrated to identical bulk density within each location, see text for details.

Table 3. Index of virgin compression, C_V, and soil bulk density and volumetric water content for the 30-40 cm soil layer of seven Danish soils drained to six different matric potentials. Figures in brackets denote standard deviation (n = 6). Calculated from data of Schjønning (1991).

Location (% clay)	Matric potential hPa	C_v-index				Bulk density g cm^{-3}	Water content % v/v
		Measured data		Calibrated*			
Tylstrup	-30	9.5	(1.2)	8.9	(0.8)	1.39	40.4
(4)	-50	10.0	(3.5)	10.6	(1.9)	1.41	39.1
	-75	9.7	(2.0)	10.8	(1.3)	1.42	31.1
	-100	11.6	(2.5)	11.5	(1.1)	1.40	24.9
	-160	12.7	(3.3)	11.9	(1.9)	1.38	16.9
	-300	12.5	(3.2)	11.9	(0.9)	1.39	11.6
	LSD_{95}	2.2		1.2		n.s.	1.7
Borris	-30	10.1	(1.9)	10.2	(1.8)	1.54	34.5
(5)	-50	11.6	(1.5)	11.7	(0.4)	1.54	31.1
	-75	14.0	(4.0)	12.5	(0.9)	1.51	28.3
	-100	12.8	(3.6)	12.7	(1.4)	1.53	24.2
	-160	11.2	(2.3)	11.7	(0.7)	1.54	18.5
	-300	11.6	(1.0)	12.4	(1.2)	1.55	14.8
	LSD_{95}	n.s.		1.4		n.s.	1.5
Tystofte	-30	11.3	(2.7)	12.8	(1.3)	1.65	31.8
(11)	-50	12.1	(4.2)	13.1	(1.3)	1.64	29.9
	-75	12.7	(2.5)	14.6	(1.8)	1.66	26.8
	-100	17.6	(5.8)	15.3	(0.8)	1.59	24.5
	-160	15.7	(6.0)	14.6	(1.1)	1.61	24.0
	-300	15.3	(6.9)	14.6	(1.8)	1.61	21.2
	LSD_{95}	3.4		1.3		n.s.	1.4
Årslev	-30	11.2	(3.4)	11.5	(1.1)	1.66	31.7
(11)	-50	14.5	(4.0)	12.5	(2.1)	1.62	30.5
	-75	13.5	(3.3)	13.0	(2.2)	1.65	29.5
	-100	12.5	(3.9)	14.5	(1.8)	1.69	27.4
	-160	13.8	(4.1)	13.3	(1.9)	1.65	26.7
	-300	13.8	(3.1)	14.6	(1.5)	1.67	24.7
	LSD_{95}	2.0		1.6		0.03	1.5
Roskilde	-30	11.5	(1.2)	11.1	(2.1)	1.59	32.2
(11)	-50	13.0	(1.6)	13.5	(1.9)	1.61	30.8
	-75	16.5	(4.3)	15.9	(2.3)	1.58	29.0
	-100	17.1	(5.3)	17.1	(0.8)	1.59	27.7
	-160	17.1	(5.6)	17.1	(2.1)	1.59	26.1
	-300	15.8	(5.5)	16.3	(2.1)	1.60	23.2
	LSD_{95}	3.7		2.2		n.s.	n.s.
Rønhave	-30	9.8	(1.6)	10.1	(2.0)	1.70	30.9
(12)	-50	12.0	(2.1)	11.8	(1.1)	1.68	29.7
	-75	12.8	(3.0)	12.4	(2.6)	1.68	23.9
	-100	12.0	(2.6)	12.9	(1.9)	1.71	27.1
	-160	14.8	(3.3)	14.1	(2.5)	1.67	26.9
	-300	13.4	(2.1)	13.4	(1.2)	1.69	25.1
	LSD_{95}	2.9		1.8		n.s.	n.s.
Silstrup	-30	16.8	(4.5)	17.0	(1.3)	1.53	34.6
(15)	-50	17.7	(2.6)	18.4	(0.7)	1.54	31.5
	-75	19.0	(4.5)	18.3	(0.9)	1.52	29.6
	-100	20.2	(1.4)	19.6	(1.8)	1.52	28.3
	-160	22.1	(4.1)	21.9	(1.0)	1.53	27.6
	-300	20.7	(2.8)	21.4	(1.0)	1.54	25.6
	LSD_{95}	2.2		1.3		n.s.	0.9

* Calibrated to identical bulk density within each location, see text for details.

Throughout this paper, the calculated values are presented multiplicated by a factor 100. The smallest load that should take part in the calculation of the slope of the virgin compression index, C_V, was judged by eye when plotting the results from each individual test.

The results from the compression tests are summarized in Tables 2 and 3, which include information from a total of 504 soil cores (7 locations times 6 field plots times 2 soil depths times 6 replicate cores). Although the 'virgin' compression index displays characteristics of the soil matrix that should be little influenced by the (mostly management induced) differences in bulk density of the soil, a significant correlation was found between the bulk density and the compression index. Therefore, data were calibrated to identical bulk densities for each depth and soil type, column two of Tables 2 and 3. The 'raw' data for the C_V-index exhibited a variability among replicate samples in the range of 10-55% (overall average of all soil types and water potentials: 25.4%) for the plough-layer soil, and 7-40% (overall average of all soil types and water potentials: 23.8%) for the 30-40 cm soil. When calibrated to identical bulk densities, the variability range decreased to 2-16% (average 9.2) and 4-20% (average 11.4) for the plough-layer and 30-40 cm soil depths, respectively.

For the plough layer soil, the coefficient of variability for the bulk density parameter was found to be about the same (approximately 3%) for the 0.2-1 m as well as the 20-100 m range (data not shown). For the 30-40 cm soil depth on the other hand, averaged across soil types, a fifty percent higher variability was detected for the 20-100 m scale compared to the 0.2-1 m scale. This means that for subsoil horizons, sampling for soil parameters ought to include the large-scale variation, considering the effects of bulk density detected in this study.

Table 4. Index of virgin compression, C_V, for the 0-20 and 30-40 cm depth of seven Danish soils as averaged across soil types for six different water potentials. Calculated from data of Schjønning (1991).

Matric potential	C_V-index			
	0-20 cm depth		30-40 cm depth	
	Measured data	Calibrated*	Measured data	Calibrated*
-30	11.4	11.2	11.2	11.4
-50	12.1	12.6	13.0	13.1
-75	12.6	12.9	14.1	14.0
-100	13.3	13.4	14.9	14.8
-160	13.2	12.9	15.4	15.0
-300	12.9	12.5	14.8	15.0
$LSD_{.95}$	n.s.	0.6	1.3	0.9

* Calibrated to identical bulk density within each location, see text for details.

The index of compactibility is rather stable across water contents, considering the range in water potential and quantity (Tables 2 and 3). This is in accordance with the results of Larson *et al.* (1980), who found no influence of soil water content upon the index of virgin compression. On the other hand, statistically significant differences could be detected for most soil types, see the Tables. Generally the lowest compactibility was found for the wettest soil. Considering this, it should be remembered that the tests were rather quick and with no attempt to regulate pore water pressure. Although the loading was stopped when water expelled from the sample, air entrapped in dead-end pores and restrictions in the hydraulic conductivity might have affected the results. This is a condition, however, that can be interpreted as realistic and compares to running a vehicle across the agricultural land. Averaged for all soil types, it appears that the compactibility had an optimum at the matric potential of -100 hPa for the 0-20 cm soil layer and -160 to -300 hPa for the 30-40 cm soil layer (Table 4).

Considering soil type differences, the most sandy soils, Tylstrup and Borris, clearly display the lowest compactibility (Table 5). For the loamy sands with clay contents in the range from 11 to 16%, no distinct relation could be found between compactibility and clay content or other soil characteristics such as CEC (Table 1). For most soils, a higher compactibility was observed for the 30-40 cm compared with the 0-20 cm soil layer. This may be interpreted as a strengthening effect of the soil organic material present in higher amounts in the upper soil layer.

Table 5. Index of virgin compression, C_V, for the 0-20 and 30-40 cm depth of seven Danish soils as averaged across water potentials for seven Danish soil types. Calculated from data of Schjønning (1991).

Location	C_v-index			
	0-20 cm depth		30-40 cm depth	
	Measured data	Calibrated*	Measured data	Calibrated*
Tylstrup	9.7	9.7	11.0	11.0
Borris	9.2	9.2	11.9	11.9
Tystofte	13.3	13.3	14.2	14.2
Årslev	14.0	14.0	13.3	13.3
Roskilde	11.2	11.2	15.2	15.2
Rønhave	17.3	17.3	12.5	12.5
Silstrup	13.4	13.4	19.6	19.6
$LSD_{.95}$	2.9	1.1	3.4	1.3

* Calibrated to identical bulk density within each location. Due to the averaging for each soil type, the mean will be identical to uncalibrated data while the variability is reduced.

Comparing remoulded and undisturbed soils

In the study of Schjønning (1991), extra tests were also performed using remoulded soils packed in metal cylinders of the same size and with the soil drained to specific matric potentials. The soil samples were allowed to equilibrate for the same time period (~2 weeks) in order to allow the same conditions for 'age hardening' of samples at different water potentials.

Generally, the index of virgin compression was much higher for the remoulded samples than for the corresponding undisturbed soil cores. This may be due to differences in water content and/or bulk densities obtained for the two groups of samples. In order to facilitate a comparison, the measured index from all samples was calibrated to an average bulk density for all samples tested (Table 6).

Table 6. Index of virgin compression, C_v, for the 0-20 cm layer, undisturbed samples, for the 30-40 cm layer, undisturbed samples, and for the 0-20 cm layer, remoulded samples. Averaged across water potentials studied (-30—-300 hPa for undisturbed samples and -30—-700 hPa for remoulded samples) for seven Danish soils. Calibrated to identical bulk density for all samples tested. The average water content (% w/w) is given in brackets. Calculated from data of Schjønning (1991).

Location	Sample type		
	Undisturbed		Remoulded
	0-20 cm depth	30-40 cm depth	0-20 cm depth
Tylstrup	6.3 (19.8)	7.9 (19.6)	10.2 (18.0)
Borris	9.0 (17.7)	12.6 (16.5)	13.9 (18.5)
Tystofte	13.9 (16.9)	17.5 (16.2)	17.1 (22.7)
Årslev	15.3 (17.5)	17.4 (17.2)	18.2 (24.6)
Roskilde	13.3 (17.9)	17.6 (17.7)	18.5 (24.3)
Rønhave	16.2 (20.1)	17.5 (16.2)	21.6 (27.0)
Silstrup	13.3 (20.8)	20.2 (19.1)	23.6 (27.9)
$LSD_{.95}$	1.6	2.1	1.7

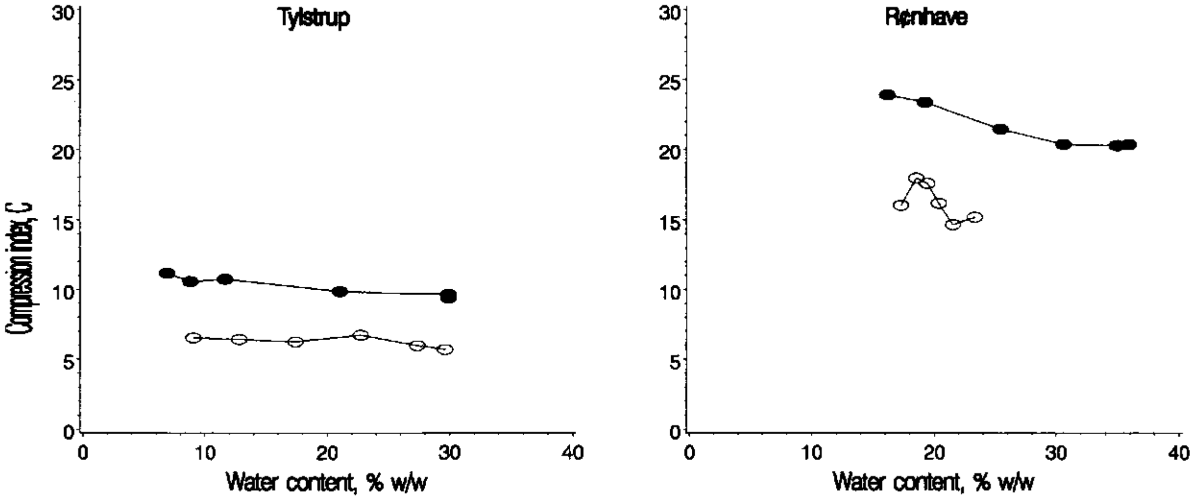

Figure 1. The virgin compression index, C_v, for plough layer soil from the sandy soil at Tylstrup and the loamy sand at Rønhave. For the undisturbed soil (open symbols), the water potentials studied were -30, -50, -75, -100, -160 and -300 hPa, while the remoulded soil (closed symbols) was measured at potentials of -30, -50, -100, -160, -300 and -700 hPa.

The way of presenting data for the tests on undisturbed samples only to some extent changes the relative compactibility of the soils studied. Still, there is no clear correlation to textural differences for soils holding more than 10 percent clay. This means that the lack of correlation for un-calibrated data is not due only to differences in soil bulk density. On the contrary, for the remoulded samples, the virgin compression index seems to be correlated to soil content of clay, which is in accordance with Larson *et al.* (1980).

The water contents reported in Table 6 indicate a higher water-holding capacity of the remoulded soils compared with the undisturbed samples. Due to this, a direct comparison between the undisturbed and remoulded soil as presented in Table 6 is not possible. However, as can be seen from Figure 1, also at comparable water contents, the compactibility was found to be higher for the remoulded samples even though calibrated to identical bulk

densities. This indicates inter-aggregate bonds as well as intra-aggregate strength to be responsible for the resistance to severe compaction.

Shear strength

Laboratory methods

The study of Schjønning (1991) also included shear strength measurements on undisturbed soils drained to pre-defined water potentials. For each of six water potentials in the range -30 to -300 hPa, shear strength was determined with a shear annulus method with a shear rate of 45.6 mm per minute, applying six different normal loads to soil cores mounted in a mechanical press (Schjønning, 1986). Due to the rapid application of load and shear, no attempt was made to control pore water pressure during the measurements. Soil was sampled as in the compactibility studies except that here only the plough layer soil was investigated. Two replicate cores were measured for each combination of location, water potential and normal load (a total of 504 soil cores).

The results from the measurements are reported in Table 7. The cohesion and friction components of the soil strength have been calculated from linear regressions of the peak shear strength and the corresponding normal load (Coulomb's equation). The cohesion generally is increasing with increasing soil content of clay. Noticeable is also that the angle of internal friction is lowest for the two sandy soils compared with the soils with a clay content of more than 10%. Averaged for these five loamy soils, the soil cohesion increases with decreasing matric potential (increasing pF-value), Figure 2, while the angle of internal friction appears to be rather constant within the range of matric potentials studied.

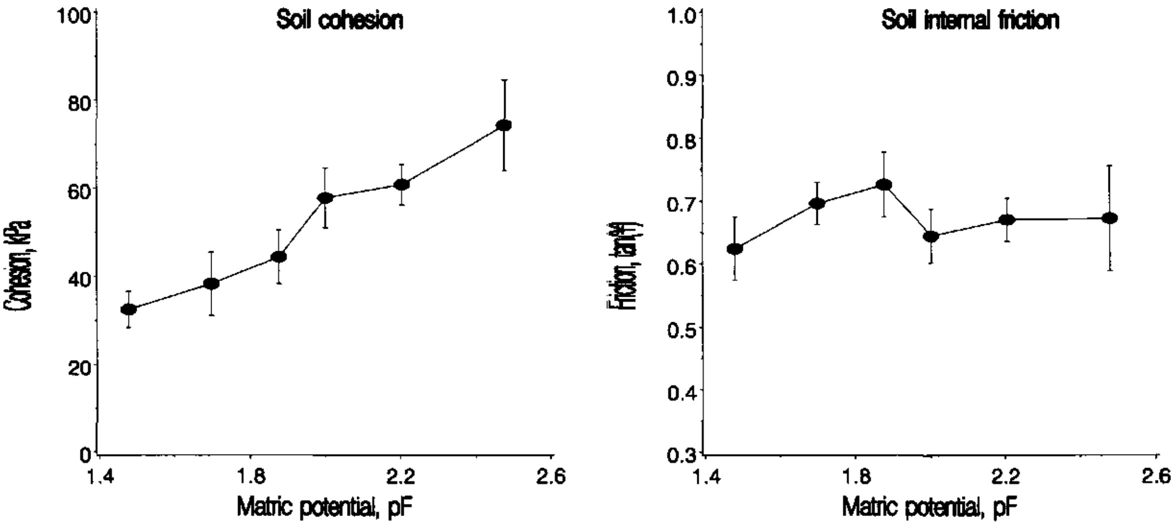

Figure 2. Soil cohesion and internal friction for the plough layer soil as averaged for the five loamy soils with clay content above 10% (cf. Table 1). Bars indicate +/- 1 standard error of the mean.

Table 7. Strength estimates as differentiated to cohesion (C) and internal friction (tan ϕ) in undisturbed soil cores drained to different water potentials. The dry bulk density and volumetric water content are given as well. Calculated from data of Schjønning (1991).

Location	Water potential hPa	Cohesion (C) kPa	Friction (tan ϕ)	Root MS_e (s) from regression. Input to the calculation of confidence limits	Dry bulk density* g cm^{-3}	Water content* % v/v
Tylstrup	-30	23.6	0.37	11.0	1.38	42.8
	-50	17.9	0.46	11.8	1.37	40.3
	-75	28.8	0.49	3.0	1.39	30.8
	-100	25.1	0.55	3.4	1.38	24.7
	-160	25.9	0.58	4.8	1.39	17.2
	-300	19.8	0.74	15.8	1.38	15.2
Borris	-30	25.3	0.49	20.5	1.48	37.8
	-50	28.4	0.51	9.6	1.48	32.8
	-75	34.3	0.52	7.5	1.47	28.1
	-100	44.5	0.55	10.7	1.48	23.4
	-160	51.0	0.48	9.1	1.46	20.1
	-300	68.9	0.47	10.2	1.51	18.4
Tystofte	-30	18.9	0.52	4.9	1.48	32.8
	-50	13.1	0.83	18.5	1.53	28.2
	-75	29.3	0.63	5.3	1.48	25.2
	-100	34.9	0.68	9.9	1.48	23.0
	-160	52.1	0.59	13.3	1.51	21.3
	-300	59.1	0.62	15.3	1.52	20.2
Årslev	-30	32.1	0.63	12.2	1.55	30.9
	-50	40.5	0.67	15.1	1.52	28.0
	-75	45.4	0.73	13.1	1.55	27.0
	-100	56.6	0.63	11.9	1.52	25.1
	-160	66.9	0.61	15.9	1.53	25.8
	-300	98.6	0.54	31.6	1.52	23.9
Roskilde	-30	44.4	0.53	22.3	1.55	33.2
	-50	54.1	0.64	22.1	1.54	29.5
	-75	37.7	0.92	32.5	1.56	28.6
	-100	62.3	0.79	15.7	1.58	26.6
	-160	75.1	0.67	15.4	1.57	25.8
	-300	92.9	0.63	25.2	1.56	25.5
Rønhave	-30	33.7	0.64	10.1	1.48	33.1
	-50	34.4	0.67	12.2	1.47	31.3
	-75	43.4	0.70	22.3	1.45	29.7
	-100	58.2	0.57	10.2	1.44	28.7
	-160	50.4	0.78	23.9	1.45	27.2
	-300	76.9	0.57	12.8	1.45	26.7
Silstrup	-30	33.4	0.80	26.3	1.45	34.6
	-50	49.3	0.67	34.1	1.44	33.7
	-75	66.0	0.65	10.9	1.47	32.7
	-100	77.3	0.55	20.5	1.48	31.9
	-160	59.9	0.70	19.9	1.41	29.6
	-300	43.9	1.00	24.5	1.43	28.6

*Averaged for the 12 samples included in the regression for each combination of location and water potential.

An estimate of the soil shear strength at a given confining stress can be calculated from the Coulomb equation. As an example, the shear strength at a normal load of 100 kPa for the Silstrup soil, -50 hPa matric potential can be estimated to $49.3 + 0.67*100 \cong 116$ kPa (Table 7). If the same soil is loaded with only 20 kPa, the shear strength can be estimated to 49.3 + 0.67*20 ≅63 kPa

There is a trend towards higher variability in the soil strength characteristics with increasing soil content of clay. The root mean square error from the regression, which is an estimate of the standard variation, s, of the soil shear strength, is found to be in the range of 3 to 16 kPa for the sandy soil at Tylstrup while it is in the range of 11 to 34 kPa for the loamy soil at Silstrup. Confidence limits for estimates of soil strength calculated using the Coulomb equation can be obtained using the expression

$$t_{(n-2),1-\alpha/2} * s * \sqrt{\left(1/n + \left(P_i - \overline{P}\right)^2 / SS_p\right)}$$

where n is the number of soil samples measured and SS_P the Sum of Squares for the specific data set. This means that an estimate of soil strength at e.g.P=100 kPa normal load for the Silstrup soil will have 95% confidence limits of 7 to 22 kPa for s-values of 11 and 34 kPa, respectively. If the strength at 20 kPa confining stress is estimated it has a 95% confidence limit of 14 to 42 kPa. Figure 3 gives examples of data for two different conditions of variability, compare to Table 7.

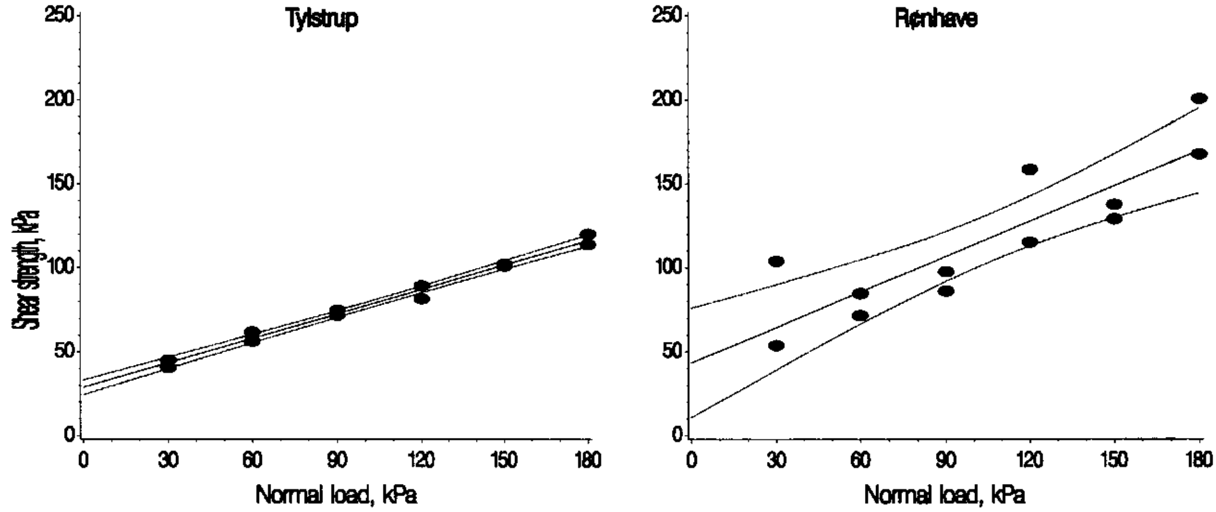

Figure 3. Shear strength measured for a number of normal loads at a water potential of -75 hPa for the sandy soil at Tylstrup and the loamy sand at Rønhave. Dotted lines indicate the 95% confidence interval of the mean.

It is important to realize that the soil strength variability detected demands a rather high number of soil samples in order to obtain a reasonable estimate of soil strength. Further, despite a high number of measurements, the soil strength estimate will still be rather uncertain, especially at low and high normal loads. As an example, it can be concluded from the calculations given above, that the Silstrup soil at a matric water potential of -50 hPa has a shear strength at 20 kPa normal load of 63 +- 42 kPa. Although this perhaps is a 'worst case' (see the s-values in Table 7), it highlights the difficulties in obtaining accurate estimates of soil strength. Finally it should be emphasized that the variability detected here is for plough layer soil. Most probably larger variations are found for deeper soil layers not homogenized through years of tillage.

Field methods

Shear strength can be determined in the field with grousered shear annulus methods (Olsen, 1984) or by the torsional shear box method (Payne & Fontaine, 1952). The latter approach was tested by Schjønning (1991) for the seven Danish soils discussed above. It appears that far lower estimates of soil cohesion were found by the torsional shear box method compared with the laboratory shear annulus method (Table 8). This may be due to differences in the way the shearing device interacts with the soil for the two methods in question. The torsional shear box method allows the soil to shear along the weakest plane of failure, while the shear annulus (like the classical direct shear method) defines the plane of shear. The lower estimates of cohesion detected by the field method may also be due to the lower range of normal loads applied in the field. It is difficult to perform the torsional shear test with normal loads exceeding about 35 kPa. For the present investigation (Table 7), the range of normal loads was from 4 to 20 kPa. Lebert & Horn (1991) have shown, that for aggregated soils, results from shear measurements at a small level of normal load may reflect inter-aggregate strength characteristics rather than bulk soil strength properties. In accordance with this interpretation of data, the estimates of the soil internal friction are higher for the field method.

Another method that may have a potential use in the field (as well as in the laboratory) is the drop cone penetration method originally proposed for estimating cohesional strength of saturated clay (Hansbo, 1957). Preliminary results from measurements with the drop cone apparatus have indicated that this simple and quick method is detecting strength characteristics also obtained by the shear annulus method (Schjønning, unpublished). It is beyond the scope of this paper to present the approach here. Further measurements are currently carried out in order to obtain a full data set allowing a real evaluation of the method.

Table 8. Soil cohesion and internal friction estimated in the field by the torsional shear box and in the laboratory by the shear annulus. Plough-layer soil from seven Danish soils. Calculated from data of Schjønning (1991).

Location	Cohesion, kPa		Internal friction (tan ϕ)	
	Torsional shear box (field)	Shear ann. (lab., -100 hPa pot.)	Torsional shear box (field)	Shear ann. (lab., -100 hPa pot.)
Tylstrup	9.7	25.1	0.91	0.55
Borris	15.3	44.5	0.70	0.55
Tystofte	10.7	34.9	0.89	0.68
Årslev	11.2	56.8	0.83	0.63
Roskilde	12.3	62.3	0.90	0.79
Rønhave	16.5	58.2	0.67	0.57
Silstrup	16.8	77.3	1.04	0.55

Conclusions

The virgin compression index expressing the sensitivity of soils to compaction at loads higher than the pre-consolidation load was found to be lower in sandy soils compared with sandy loams with clay contents above 10%. For structurally undisturbed soil, no correlation could be detected between compactibility for the latter soils and their textural composition. The virgin compression index was influenced by the pre-compression bulk density of the soil specimen. Calibrating this effect out from data did not improve the correlation between the compactibility of undisturbed soil and soil texture. For remoulded soil, the compactibility correlated to soil content of clay. Higher indices of virgin compression were obtained for remoulded soil than for undisturbed soil, also if the effect of bulk density was taken out of the data. There was no strong influence of water content on soil compactibility. Averaged for seven soil types, soil compactibility had an optimum at a water content corresponding to a matric potential of -100 hPa for plough layer soil and of -160 to -300 hPa for soil from the 30-40 cm soil depth. The coefficient of variation for the virgin compression index averaged to approximately 25% independent of soil depth examined. When the effect of soil bulk density was taken out of the data, the variability decreased to approximately 10%, also independent of soil depth.

Soil internal friction and especially soil cohesion of undisturbed soil from the 0-20 cm depth were found to increase with increasing content of clay. The variability of the estimate of soil strength at a given normal load was also highest for loamy soils compared with sandy soils. The 95% confidence limits of the strength estimate at low confining stresses were up to 67% of the strength estimate. The strength estimates derived from field measurements with the torsional shear test method were considerably lower than the values obtained in the laboratory with the shear annulus method.

The high variability of the soil mechanical properties highlights the need for simple and quick methods in order to obtain reliable estimates of the properties within a realistic time-scale and financial budget.

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CONCERTED ACTION ON SUBSOIL COMPACTION

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1 Interest of the research group

The Soil Protection Law (SPL) of the German Federal Government (March 24, 1998) will prompt further intensive discussion about protective strategies needed for legislation and plans regarding advisory assistance for farmers, agricultural engineering and research. Within SPL, three important objectives related to soil protection problems in crop production are mentioned: soil erosion, soil compaction, and soil tillage. These topics are the background of the research done at FAL over the past three decades.

The research of the Institute of Production Engineering is focused now on "managing traffic-induced soil compaction" by using:

- conservation tillage (reduced tillage intensity in comparison with conventional tillage);
- adjusted wheel equipment (number, size, width and inflation pressure of tyres on tractors and combines);
- innovative aspects to control wheel loads on sensitive soils.

2 Experiences of the research group

Some laboratory and several field experiments have been conducted:

- Laboratory experiments on the sensitivity of arable soils to compaction (compression tests, measurements of soil properties: bulk density, saturated hydraulic conductivity, water retention, penetration resistance);
- Field experiments on loamy and sandy soils to study the influence of soil compaction on crop yields (axle loads, conservation tillage with non-inverting soil loosening).

3 Published papers of the research group

Sommer, Zach und Klügel (1969): Untersuchungen über die Bedeutung der Furchenräumung bei Verwendung breiter Schlepperreifen. - Landbauforschung Völkenrode 19 (2), 67-76.

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4 Available data of the research group

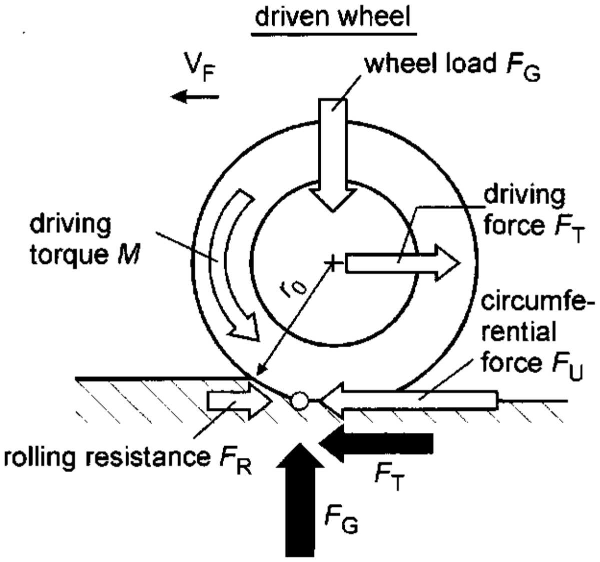
4.1 Type number and duration of experiments:

- Laboratory compression tests with three different soils (1969-1974).
- Several greenhouse experiments with a loam soil (to address the question of how the total root system reacts in terms of water uptake in a soil column in which a compacted middle layer - plough pan - with a contrasting soil matrix potential is set between loose upper and lower layers, 1988- 1990).

- Field experiments with different wheel loads on sand, loam and clay soils (1975-1980).
- Field experiments on subsoil compaction of loam and clay soils with high axle load (total load: 40 t).
- A 6 year field experiment on managing traffic-induced soil compaction by conservation tillage on a sandy soil (1984-1990).
- A 6 year field experiment on a loam soil focusing on how sugar-beet combines with a total load of up to 50 t will influence the yield of wheat the following year, 1995-2000).
- A 3 year field experiment (together with the research group of Professor Horn) on the transformation of tractor performance to traction forces for wheel loads up to 6 t, including soil-protecting traffic on arable sand soil, 1997-1999).

4.2 Measurements

- Soil properties: bulk density, saturated hydraulic conductivity, water retention, penetration resistance, infiltration rate, N leaching
- Crop properties: crop yield (crop rotation: wheat - barley -cover crop - sugar beet), root development.
- Running gear forces: wheel load, wheel slip, driving force, driving torque.



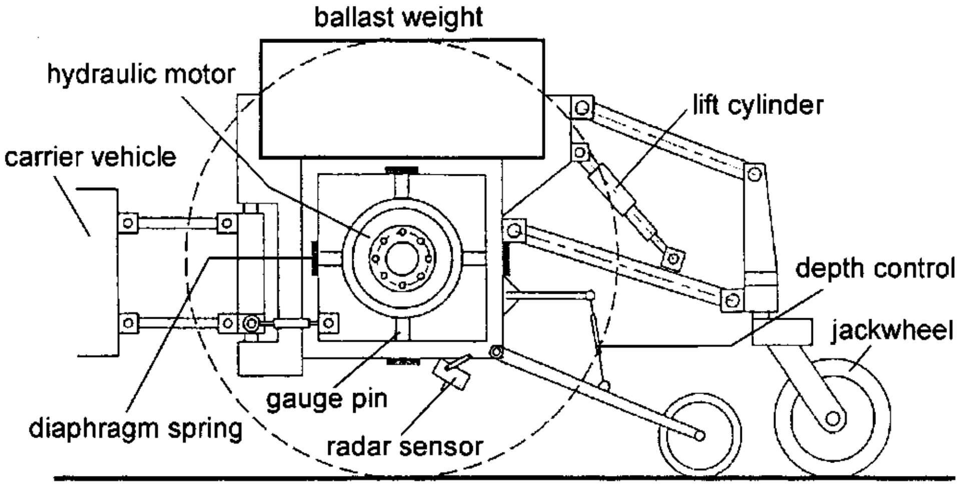
$$F_T = F_U - F_R = M/r_0 - F_R$$

$$F_T = F_G \cdot \chi$$

Wheel forces

5 Methods being used to study the transmission of tractor performance to traction forces in the case of high axle load

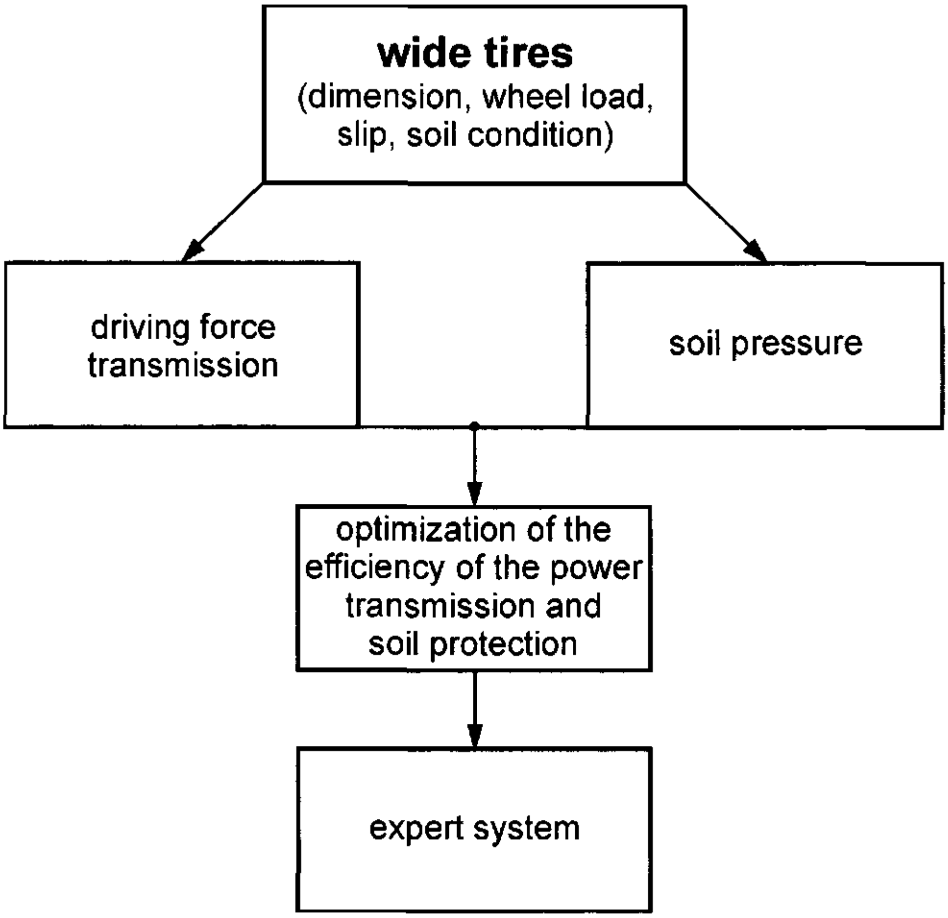
The analysis of wheel forces and soil pressure (research group Horn) is being done by measuring the wheel forces with a single wheel tester.



Single wheel tester for high wheel loads up to 6 t

6 Outlook

The goal of these investigation is to develop an expert system for the use of wide tires and new bogie wheels in crop production. This seems to be the most relevant research from the agricultural engineering point of view against the background of the SPL.


wide tires
(dimension, wheel load, slip, soil condition)
driving force transmission
soil pressure
optimization of the efficiency of the power transmission and soil protection
expert system

MECHANISATION STRATEGIES TO REDUCE TRAFFIC-INDUCED SOIL COMPACTION

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Summary

There is a world wide concern about traffic-induced soil compaction in crop production. Adjustment of field traffic to the prevailing soil strength conditions is a very promising strategy to prevent soil compaction. The use of low tyre inflation pressure and reduction of the number of wheel passes are practical ways to manage soil compaction in the arable layer. Experiments in the Netherlands and in the former German Democratic Republic showed that practical, cost-effective on-farm application of such systems is possible.

Subsoil compaction is very persistent. Nature and mechanisation do not offer a sound solution to loosen an unduly compacted subsoil. Therefore, prevention strategies are needed. Very promising mechanisation strategies are: (1) on-land-ploughing and (2) use of extra wide tyres at low inflation pressure for all transport and harvesting operations.

Introduction

A wealth of publications shows evidence of the negative consequences of traffic-induced compaction for sustainable crop production (Soane and Van Ouwerkerk, 1994). New evidence indicates serious, widespread and long-term negative effects of soil compaction on the quality of the atmosphere, surface waters, ground waters and soil resources of the world (ISTRO, 1993; Soane and Van Ouwerkerk, 1993, 1995; Van Ouwerkerk, 1995). To cope with these effects, methods for the control of traffic-induced soil compaction are needed. This means that practical ways must be developed to prevent tyres to exert too high normal and shear stresses, which induce serious damage to soil structure.

Compaction by agricultural field traffic

From the large amount of empirical data on soil-tyre interaction currently available, some general guidance can be given in quantifying the compactive capability of running gear. Tijink (1994) concluded that the following factors help to reduce the compactive effect of a single pass of a tyre: (1) low inflation pressure; (2) low tyre load; (3) low average ground pressure (i.e., the ground pressure measured on a rigid surface); (4) low tyre stiffness; (5) radial tyre construction; (6) low wheel slip; and (7) low lugs. Among these factors, the average ground pressure on a rigid surface, which under certain conditions is related to the tyre inflation pressure, is the most important. The number of passes of running gear over the same track is an important additional factor. Limitation of the tyre inflation pressure and the number off passes can be considered to be the major mechanisation tools for the control of soil compaction in practical conditions.
Söhne (1953 and 1956) showed the dominant effect of tyre inflation pressure (Fig. 1).

Figure 2 shows that, at the same payload, tyres with a low inflation pressure produced a considerably lower soil compactness in the arable layer compared with a high inflation pressure. Figure 2 also shows that, when transporting a certain payload, a once-over operation with a high-loaded wheel is to be preferred over multi-passes with a low-loaded wheel.

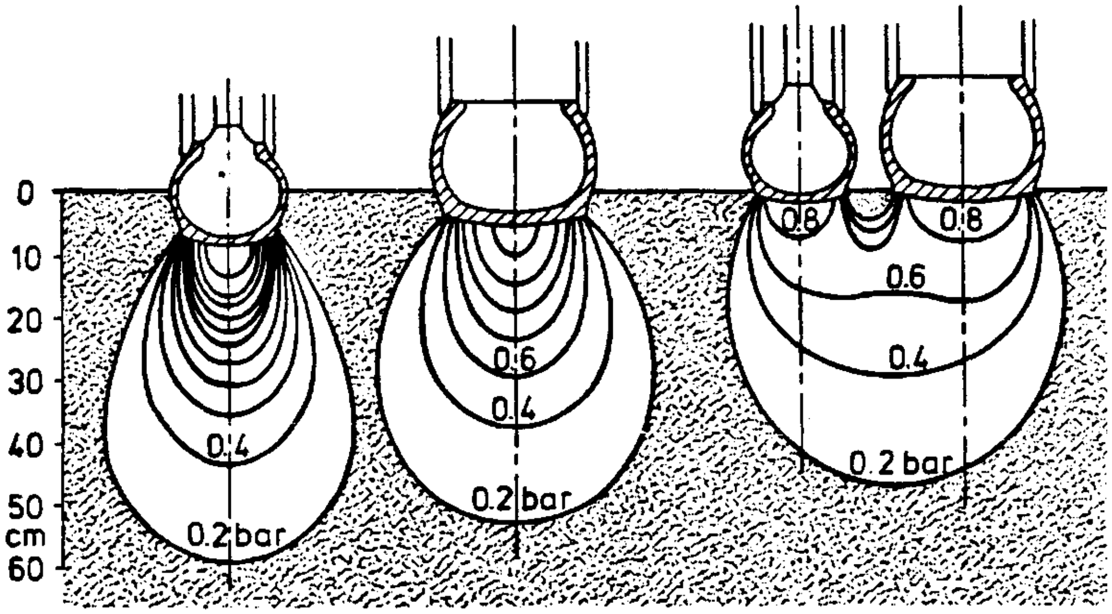

Fig. 1: Calculated pressure bulbs under tyres with 0.7 t wheel loads. From left to right: narrow tyre, wide tyre, and dual trailer tyres at inflation pressure of 300, 150 and 75 kPa respectively (after Söhne, 1956).

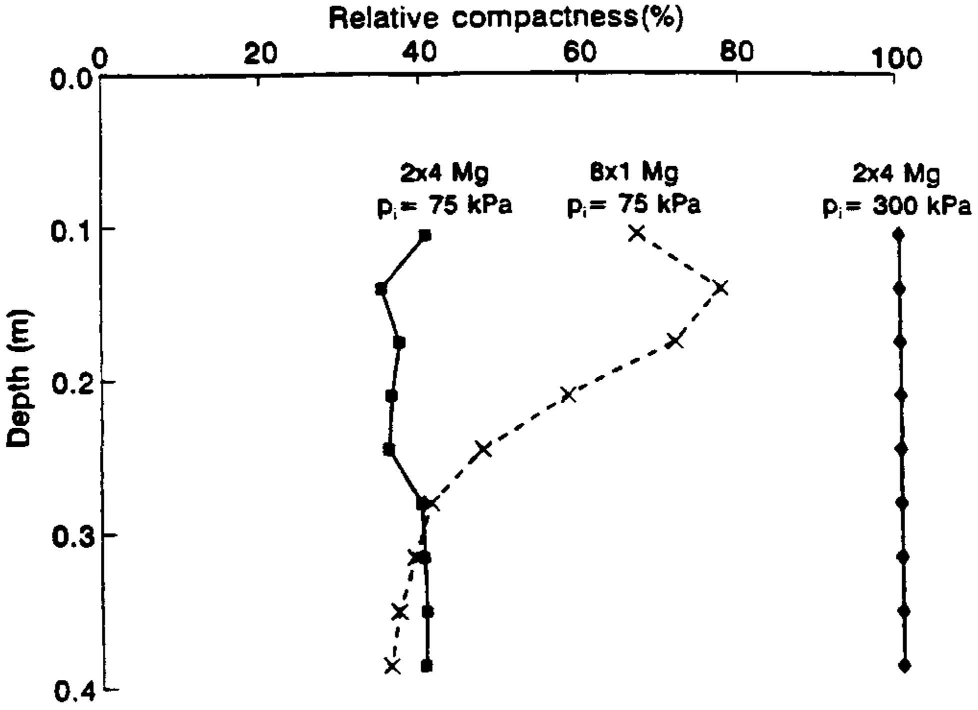

Fig. 2: Cone index (relative compactness) produced by three combinations of tyre inflation pressure and number of passes, used to transport an 8 t payload over a disturbed sandy soil relative to the cone index (compactness = 100%) produced by two passes with 4 t load with an inflation pressure of 300 kPa (after Rudiger, 1989).

Håkansson and Petelkau (1994) showed that extremely high-loaded wheels caused persistent negative effects in the subsoil. In current farming practices, extreme loadings of the upper part of the subsoil may occur during driving in the open furrow at ploughing and when applying high-loaded wheels combined with high inflation pressure when soils are wet (Fig. 3).

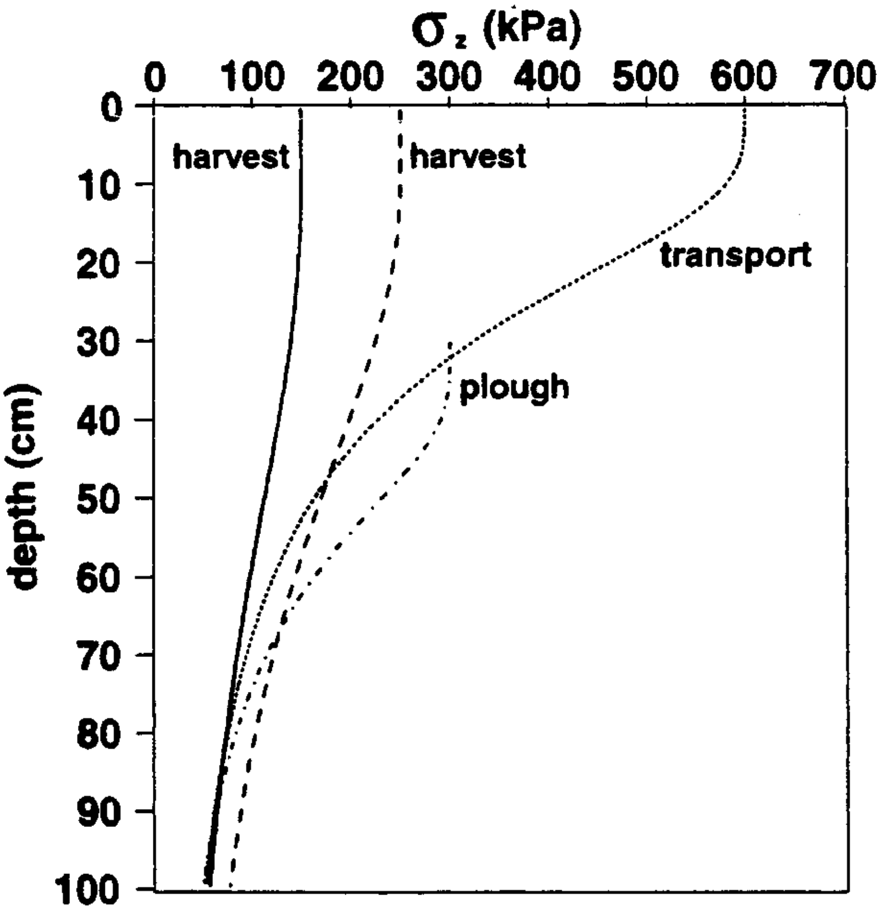

Fig. 3: Vertical soil stresses, σ_z, under 4 typical tyres. Wheel loads are 2 t (ploughing), 4 t (transport), 7.5 t (harvester left) and 10 t (harvester right). Tyre inflation pressures are 150 kPa (ploughing), 250 kPa (transport), 100 kPa (harvester left) and 170 kPa (harvester right). Calculated according to Söhne (1953).

However, little experimental information is available on the actual bearing capacity of existing subsoil layers that may be considered satisfactory for crop growth and other soil functions. Consequently, allowable stresses at the interface between the arable layer and the subsoil and in deeper soil layers can only be roughly estimated.

Low ground pressure traffic systems

Experimental results with low ground pressure tyre equipment and associated wheel load restrictions were reviewed by Vermeulen and Perdok (1994). Low ground pressure generally has a beneficial effect on soil compactness and crop growth compared with high ground pressure tyre equipment. Technical guidelines to prevent soil overcompaction, expressed in limits for inflation pressure and/or average ground pressure, or vertical soil stress at a certain depth, were given by several authors (Table 1). In the former Soviet Union, low ground pressure was prescribed by State Standard (USSR, 1986). Generally, traffic-induced loading of the rooting zone of the arable layer should preferably be limited to very small values before and during the growing season, when soil strength usually is very low. This requires a (very) low ground pressure, a uniform pressure distribution and a minimum number of vehicle passes. When the soil exhibits a reasonable strength, tyre inflations pressures of 100 kPa or lower are acceptable. Analysis of Tijink *et al.* (1995) show that present-day low ground pressure tyres may prevent soil compaction if the soil is stronger than, for example, 100 kPa.

Table 1: Technical guidelines to prevent soil compaction, expressed in limits for inflation pressure (p_i), average ground pressure (p_c) and vertical soil stress at 50 cm depth (p_{50}) in spring or in summer/autumn.

Reference	P_i (kPa)	P_c (kPa)		P_{50} (kPa)		Remarks
		Spring	Summer/Autumn	Spring	Summer/Autumn	
Söhne (1953)	80					normal moisture conditions
Perdok and Terpstra (1983)	100					
Petelkau (1984)		50	80[1]			sand
		80	150[1]			loam
		80	200[1]			clay
USSR (1986)[2]		80	100	25	30	water content (0-30 cm depth) > 90% of field capacity
		100	120	25	30	water content (0-30 cm depth) 70-90% of field capacity
		120	140	30	35	water content (0-30 cm depth) 60-70% of field capacity
		150	180	35	45	water content (0-30 cm depth) 50-60% of field capacity
		180	210	35	50	water content (0-30 cm depth) < 50% of field capacity
Vermeulen et al. (1988)	40	50				early spring, arable land
	80		100			all other operations, arable land
Vermeulen et al. (1993)[3]	50					bearing capacity = 0.3 Mpa
	100					bearing capacity = 0.4 Mpa
	150					bearing capacity = 0.5 MPa

[1] Moisture content < 70% of field capacity.

[2] Official standard for fine-grained soils, for the whole former Soviet Union. For the undriven wheels the values are 10% higher. For 2 passes in the same rut the values are 10% lower; for 3 and more passes in the same rut the values are 20% lower.

[3] Guidelines to prevent rut formation on peat grassland.

Investigations by Lebert (1989) on 37 typical Bavarian soils revealed that the preconsolidation strength of undisturbed subsoils can vary between 80 and 250 kPa. Stress values that are less than the preconsolidation stress do not result in soil compaction.

Technical feasibility of low ground pressure traffic systems

Reviews on technical means to reduce traffic-induced soil stresses were given by Döll (1989) and Vermeulen and Perdok (1994). The technical feasibility of achieving a ground pressure below the acceptable limit for field traffic without compromising the load on the running gear strongly depends on the available tyre technology and the possibility of mounting wide and/or multiple tyres on the farm machinery (Vermeulen et al., 1988; Grecenko, 1989; Tijink, 1991a, Tijink *et al.* 1995).

Tractor-plough combination

It is common practice to drive in the open furrow during ploughing operations. This practice has caused concern about subsoil compaction effects, because the tractor wheel interacts directly with the upper part of the subsoil (see Fig. 3). When driving on the unploughed surface, the full depth of the arable layer smooths the non-uniform stress distribution under the tyre. This reduces the maximum stresses and is responsible for a considerable decrease with depth of the shear stresses associated with the exertion of pulling forces (Söhne, 1952).

When using large ploughs, with a working width larger than the width of the tractor, it is possible to drive on the unploughed surface. However, this is not possible when working with smaller ploughs because of problems with steering and stability (Tijink, 1991b). For ploughs with up to three bodies, low ground pressure is usually possible by using the largest tyres that fit in the furrow (45 cm wide for wide-furrow ploughs). Tyres of this size provide for sufficient loading capacity and traction to operate a 3-furrow plough at an inflation pressure of about 80 kPa. For 4-6 furrow ploughs, the following technical options and alternatives to decrease the soil stresses in the upper part of the subsoil can be applied. Firstly, the use of tyres up to 65 cm wide in a 45-cm wide furrow is possible without adversely affecting the uniformity of the work and the degree of soil inversion. These wide tyres make it possible to operate 4-furrow ploughs at low ground pressure, albeit at the expense of some recompaction of the freshly ploughed soil (Vermeulen et al., 1987). Secondly, tyres wider than 65 cm can still be used if the last plough share is fitted with an attachment that slices a strip of soil of the required extra width from the landside at about half the ploughing depth and deposits it in the furrow, so that a wide, flat surface is prepared for the tyre. Thirdly, "slit tillage" (i.e., a tillage operation to loosen the furrow bottom after the tyre has passed) can be practised in combination with ploughing. Finally, p.t.o-powered tillage machinery, such as a crankshaft digger, which allows for driving on the surface can be used.

Transport and harvesting vehicles

Currently, wheel loads of tipping trailers and slurry tankers range from 2-6 t and, when equipped with the standard tyre size (16/70-20), the average ground pressure is far above 100 kPa. Tijink (1991a) described possibilities to reduce the ground pressures for these vehicles, based on technology (tyres and trailers) that was available within the EC in 1990. He concluded that trailers of up to 30 t gross vehicle weight can be equipped to reduce the average ground pressure to 100 kPa. Maximum loads for single-, tandem- and triple-axled trailers are summarized in Table 2.

Nowadays, six row tanker harvesters for sugar beet can have wheel loads up to 12 t. When using the biggest tyre size (1050/50 R 32) wheel loads up to 7.5 t are possible at a tyre inflation pressure of 100 kPa. This means that a very heavy tanker harvester with an empty mass of 25 t and a 20 t tank capacity can operate at 100 kPa inflation pressure, provided that six wheels and the biggest tyres are used.

Table 2: Maximum permitted vehicle loads (t) of trailers at an average ground pressure of 100 kPa

	Single axle	Steered tandem axle	Steered triple axle
Maximum payload	8.5	15	22
Maximum gross vehicle weight	10	20	30
Maximum axle load	10	10	10
Maximum wheel load	5	5	5

Economic feasibility of low ground pressure traffic systems

To evaluate the benefits of a traffic system, the economic feasibility of complete traffic systems integrated in a farming system needs to be studied. Two experiments on low ground pressure farming systems will be discussed shortly, one representing a typical, intensive West European arable farm and the other representing a typical Central European arable farm.

60-ha arable farm in the Netherlands

During the period 1986-1989, the effects of a full-scale low ground pressure traffic system were compared with the commonly used high ground pressure traffic system and a zero-traffic system (Vermeulen and Klooster, 1992). The experiment was carried out on a marine clayey loam soil with a crop rotation consisting of winter wheat, sugar beet, onions and ware potatoes. The soil was tilled annually to a depth of 25 cm. Annual rainfall is about 700 mm.

Tyres for the low ground pressure system were selected on the basis of tyre inflation pressure and average ground pressure (Table 1; Vermeulen et al., 1988). Low ground pressure resulted in an average yield increase of 4% for root crops; for winter wheat no significant yield effects were found. Economic analyses performed by Janssens (1991) showed that when a representative fleet of machinery has been converted to low ground pressure there is a marginally better profitability at the farm level. This means that on-farm use of a low ground pressure traffic system has potential to reduce overcompaction and associated effects on the environment, without negative effects on farm income. Another potential economic benefit, which was not included in the analysis, may result from a gain in timeliness of field operations with low ground pressure as compared to current high ground pressure running gear.

3200-ha arable farm in the former German Democratic Republic

Since 1976, a gradual shift to low ground pressure running gear was made on a 3200-ha arable farm in the former German Democratic Republic. During the research period (1976-1990) the following measures were taken: (1) from 1976 onwards all ploughing operations were changed from in-furrow driving to driving on the unploughed surface; (2) from 1980 onwards tractor drivers were advised about the best way of trafficking the fields; (3) from 1987 onwards all tractors were equipped with dual tyres.

From the results of extensive research on this farm and on 7 other farms in the same region with a conventional traffic regime, Döll and Mührel (1991) concluded that the new traffic regime resulted in a 30% increase in the average yield of grain crops. The main explanation for this phenomenon was the use of low inflation pressure (< 80 kPa), which resulted in less soil compaction and/or in increased timeliness of field operations. For this relatively dry region (annual rainfall about 500 mm), timely execution of the field operations is of great importance, especially in spring. Döll (1989) concluded that on this type of farm the financial advantages are large because of the relatively small investments for the low ground pressure running gear (dual tyres).

Conclusions

From a practical mechanisation point of view, the tyre inflation pressure and the number of passes are the main factors causing soil compaction in the arable layer (0-30 cm depth). Low ground pressure has been shown to be very useful to reduce traffic-induced topsoil compaction. Selecting such equipment is greatly facilitated by using the parameter tyre inflation pressure.

Driving in the open furrow during ploughing is a major cause of subsoil compaction (> 30 cm depth). If the subsoil has a reasonable strength, low ground pressure tyres may prevent subsoil compaction.

Limits for wheel and axle loads based on maximum acceptable ground pressure, strongly depend on available tyre technology. Currently, axle loads up to 10 t are acceptable for tractors and transport purposes, provided low ground pressure running gear is used. For tankers harvesters axle loads up to 15 t are acceptable, when using the biggest available tyres. It may be expected that in the near future novel tyres will allow still higher wheel and axle loads at the same maximum acceptable ground pressure.

On-farm low ground pressure management practices are technically and economically feasible, which promotes sustainable crop production.

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FIELD EXPERIMENTS TO DETERMINE SOILS COMPACTION

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Introduction

Variations in dry bulk density and in the cone index of clayey soil in southern Spain were measured after passes with the three types of tractor most widely used in the area (tracked, single-drive and four-wheel-drive). Sinkage of the running gear of these tractors was measured using a laser micro relief profile meter after each of the five successive passes over the same surface.

Variations of these parameters are of crucial importance when planning fieldwork, and for determining the trafficability of tractive equipment. Many studies have underlined the link between these variations and dramatic decreases in crop yield.

Methods and Materials

Trials were performed at the "Tomejil" Experimental Farm in Vega de Carmona, Seville (Spain). The terrain in this area comprises clayey soil on Miocene beds, defined under the USDA classification system as ENTIC PELOXERERTS.

The most widely-used tractors in the area were tested:

1. A mid-heavy weight four-wheel-drive, the characteristics of which were as follows: power 76 kW, weight 57820 N, 8 x 28" steel-rimmed front wheels with 13.4R x 28" tyres, 14 x 38" steel-rimmed rear wheels with 18.4R x 38" tyres, front tyre pressure 1.4 bar and rear-tyre pressure 1.1 bar. Effective front-wheel diameter was 1.26 m and rear-wheel diameter was 1.66 m.
2. A tracked tractor, the features of which were as follows. power 58.8 kW, weight 44492 N and running gear comprising two 37-plate tracks, with a track-wheel diameter of 0.625 m and a track- plate width of 0.4 m.
3. And a mid-range two-wheel drive, the characteristics of which were as follows: power 46 kW, weight 27710 N, front wheels 7.50 x 16" and rear wheels 16.9 x 30". Front-tyre pressure was 2.5 bar and rear-wheel pressure 1.0 bar; effective front- and rear-wheel diameters were 0.68 m and 1.20 m, respectively.

In order to calculate dry bulk density, a prototype sampling device was designed to allow soil samples to be extracted with as little alteration to the soil as possible. The mechanism comprised a cylindrical support frame and a sampling cylinder measuring 81 mm in height and 47.5 mm in diameter (i.e. 143 cm3 in volume). Handles were fitted at one end of the frame to facilitate embedding of the lubricated sampling cylinder, which was fitted to the lower end of the frame to collect the soil sample. Measurements of dry bulk density were taken at the surface and at a depth of 30 cm.

An electrical penetrometer (fig. 1) was designed for measuring penetration resistance, recording cone index values at 5 mm- intervals up to a maximum depth of 30 cm. This device homogenizes trials, thus reducing sources of error in the measurements recorded.

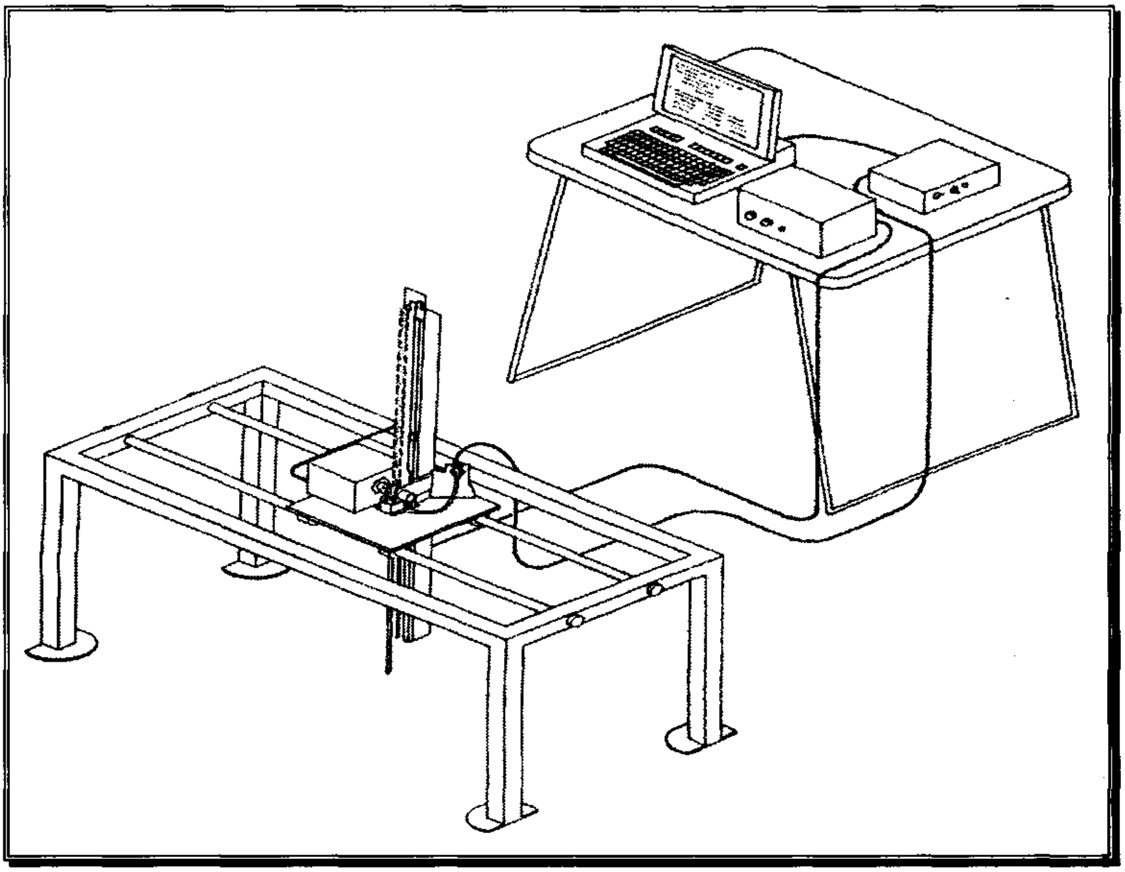

Figure 1. Electrical penetrometer.

The sinkage of the tractor in the soil was measured using a laser micro relief profile meter (Valera *et al*, 1994). This device (fig. 2) can be used to record the coordinates (x,y,z) of up to a maximum 14,000 points situated within 1 m^2 of the trial surface. Sinkage was measured as the difference between initial soil surface volume (soil prior to vehicle passes) and soil volume after tractor passes.

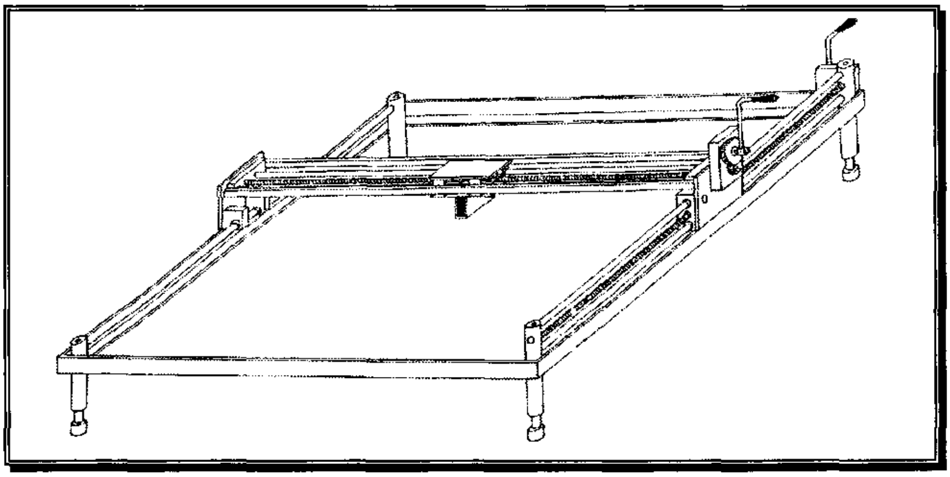

Figure 2. Laser micro relief profile meter.

Results

For all tractor types tested, dry bulk density at the surface increased with each pass, becoming asymptotic by the third pass (table 1). In all cases, the greatest quantitative increase was recorded between initial density and after the first pass. Nevertheless, mean dry bulk density at a depth of 30 cm was not affected by the number of passes or the type of tractor involved.

Table 1. Multiple Range Tests for dry bulk density at the surface by pass.

Method: 95% LSD

Pass	Count	LS Mean	Homogeneous Groups
0	21	1135.93	X
1	21	1245.32	X
2	21	1285.31	X
3	21	1287.18	X
4	21	1307.01	X
5	21	1320.83	X

No statistically significant differences were observed in penetration resistance with the three types of tractor. Successive passes over the same surface caused a significant alteration in soil penetration resistance with the first pass. However, no statistically significant differences were recorded for penetration resistance after the first, second, third, fourth and fifth passes i.e. all the tractors in the trial produced the maximum alteration in this type of soil during the first pass (table 2).

Table 2. Multiple Range Tests for Cone Index by pass.

Método: 95% LSD

Pases	Observaciones	Valor medio observado	Grupos homogéneos
0	21	0.982757	X
1	21	1.26304	X
2	21	1.27257	X
3	21	1.29861	X
4	21	1.31047	X
5	21	1.31076	X

It is worth highlighting that the alterations in penetration resistance (cone index) were observed in the top 10 cm of soil (fig. 3).

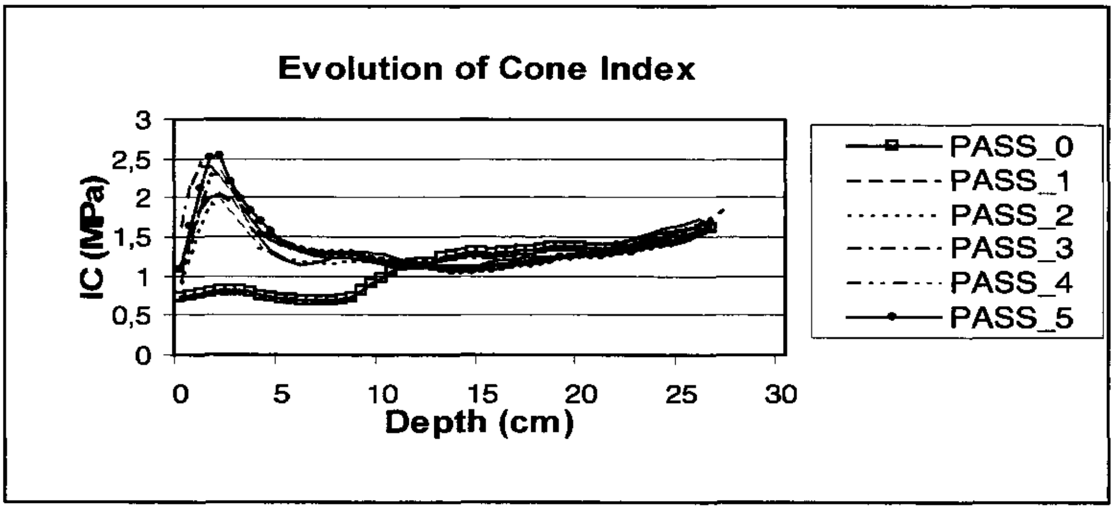

Fig. 3: Evolution of penetration resistance by number of passes.

Greater sinkage occurred during the first pass, with significant increases in the third and fifth passes (fig 4). The sinkage of the tractors increased at greater moisture contents.

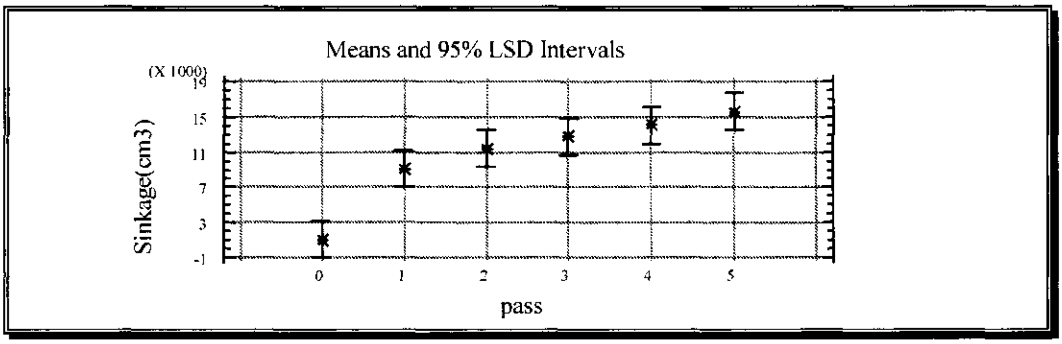

Figure 4. Means and 95.0 Porcent LSD Intervals.

For all the tractors and soil conditions studied here, the first pass provided the greatest increase in dry bulk density and resistance to penetration and sinkage, as compared with the second to fifth passes.

The four-wheel-drive tractor produced the greatest increase in dry bulk density, resistance to penetration and sinkage, when compared with the tracked tractor and the two-wheel-drive tractor. No statistically significant differences were observed between the latter models. This may be accounted for by reference to the weight/load-bearing surface ratio for each tractor.

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DEVELOPMENT, VERIFICATION AND USE OF THE SUBSOIL COMPACTION MODEL SOCOMO

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Abstract

Intensification of crop rotation and increasing use of machinery with high wheel loads are clearly related to compaction of the subsoil. Subsoil compaction is persistent and the effect of natural and artificial loosening has been disappointing. Therefore prevention of subsoil compaction is the best way to preserve the quality of the subsoil. In addition to field studies, there is an increasing need for analytical tools to develop and evaluate measures for preventing subsoil compaction. The objective of the research was to develop such a tool in the form of a computer model suitable for educators and extension workers, professional advisers, agricultural engineers and scientists. The analytical Soil Compaction Model (SOCOMO) was developed to calculate soil stresses under wheel loads. In specific cases the calculated stresses are compared with soil strengths measured in the laboratory. The calculated stresses were compared with known soil strengths or soil strengths determined with help of pedotransfer functions. Subsoil compaction and deformation is prevented if the stresses exerted remain smaller than the actual strength of that subsoil. To verify the model, traffic experiments were performed and methods developed to measure stress, compaction and deformation in the subsoil caused by wheel load. Verification was successful and the model has been used to compare stresses under normal and low pressure tyres, as well as under tandem and dual-wheel configurations. SOCOMO was also used to construct a wheel-load bearing-capacity map of the Netherlands. The model is easy to use and requires only minimal input. However, it is not yet as user friendly as it could be. Weak points of the model are that the rut depth must be estimated and that the shape of the pressure distribution exerted by the tyre on the bottom of the rut is based on rules of thumb. The use of the concept that subsoil compaction can be prevented by keeping the exerted stresses on the subsoil below actual strength is frustrated by the fact that data and pedotransfer functions of soil strength are scarce. More measurements and development of pedotransfer functions are required.

Introduction

The increasing wheel loads of agricultural machinery are the cause of soil compaction occurring at deeper depths. Although the topsoil of arable land is loosened every year, the subsoil is often left undisturbed. This means that every time the maximum load bearing capacity is exceeded, additional subsoil compaction will occur. As a result, root growth in the subsoil will be impeded and permeability to air and water, gas (oxygen) diffusion and nutrient availability will be reduced. Compacted subsoils lead to lower quality crops and reduced yields (Håkansson, 1994; Håkansson et al., 1987) and are a threat to the environment (Soane and Van Ouwerkerk, 1994, 1995). Moreover, the effects are persistent and the results of natural and artificial loosening of the soil disappointing (Håkansson, 1994; Kooistra et al., 1984). This implies that subsoil compaction should be prevented from occurring in the first place, and that it should be the limiting factor in determining the size of wheel loads. Soil compaction can be prevented by adjusting the number, size, width and tyre inflation pressure of the wheel load to match the prevailing soil strength conditions (Lebert and Horn, 1991; Håkansson, 1994; Soane and Van Ouwerkerk, 1994; Van den Akker, 1994). The wheel-load bearing capacity is defined as the maximum wheel load exerted by a specific tyre type and tyre inflation pressure that does not exceed the strength of the subsoil.

The objective of the research described was to develop a computer model as a tool for agricultural engineers and scientists to investigate ways of preventing subsoil compaction and to make it possible for advisors to make well founded and more precise recommendations. In addition, the model should be suitable for educational purposes, so the model must be easy to use, needing limited amounts of input data because data on soil strength and soil deformation characteristics is generally scarce.

The use of low tyre pressures is a possible measure for preventing subsoil compaction (Chamen et al., 1988; Vermeulen and Klooster, 1992). The effectiveness of this solution was investigated in field tests in which vertical stresses in the subsoil, compactions and deformations were measured (Van den Akker et al., 1994). The soil compaction model SOCOMO (Van den Akker, 1988, 1992, 1994) was developed to calculate whether the subsoil will be over-stressed by a particular wheel load. This makes it possible to calculate the allowable wheel load by taking into account the tyre size, inflation pressure and the prevailing soil strength, which depends on soil texture and structure, bulk density and moisture conditions. The model was verified with results of field experiments (Van den Akker, 1994). The strength of the subsoil was measured from soil samples with standard triaxial testing equipment and used as input for the model. The model was then used to calculate the bearing capacity of the major subsoils of the Netherlands under soil-water tension of pF2.5 (Van den Akker, 1997). This was the basis for the construction of a wheel-load bearing-capacity map, which can be used as a tool to prevent subsoil compaction. This first attempt of constructing such a map will be used to determine the requirements for compiling the final map.

Theoretical basis of the model

The model is based on the theory of Boussinesq (1885), which describes the distribution of stresses in a homogeneous, isotropic, semi-infinite solid mass due to a force being applied at a point on the surface of that mass. On any volume element of the semi-infinite solid, vertical, horizontal and tangential normal stresses and vertical and horizontal shear stresses are operative (Figure 1). Fröhlich (1934) proposed to set the Poisson ratio at 0.5 in the formulas of Boussinesq. This means that no change in volume of the soil occurs. In practice the influence of this assumption on the results is small. Fröhlich also introduced a concentration factor (ν) in the Boussinesq formulas to account for the tendency of the soil to concentrate the stresses around the load axis. The resulting equations for the stresses are:

$$\sigma_z = \nu\, P\, (2\, \pi\, r^2)^{-1} \cos^{\nu}\theta$$

$$\sigma_h = \nu\, P\, (2\, \pi\, r^2)^{-1} \cos^{\nu-2}\theta \sin^2\theta$$

$$\sigma_t = 0$$

$$\tau_z = \tau_h = \nu\, P\, (2\, \pi\, r^2)^{-1} \cos^{\nu-1}\theta \sin\theta \qquad (1)$$

where: σ_z, σ_h, σ_z = vertical, horizontal and tangential stress, respectively
τ_z, τ_h = vertical and horizontal shear stress
P = vertical point load
r and θ = polar coordinates

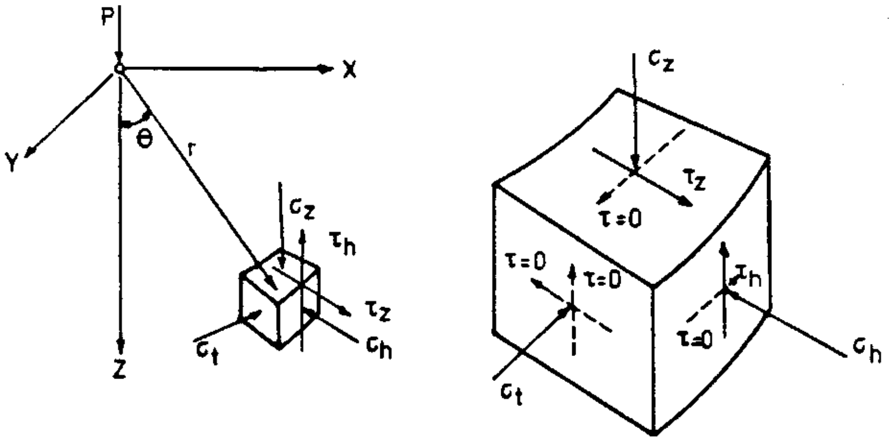

Figure 1. Composition of stresses acting in a volume element due to a point load on a semi-infinite solid.

The value of v is greater when the soil is softer. Koolen and Kuipers (1983) give values of v of 3, 4 and 5 for a hard, normal and soft soil, respectively. When v = 3 the formulas of Boussinesq are obtained with a Poisson ration of 0.5. Because the equations of Boussinesq and Fröhlich are based on a linear elastic material, it is possible to superimpose the stresses on a certain soil element that are the result of several point loads. Of course only stresses with the same direction can be added. This is the case with the vertical stresses σ_z. The horizontal and shear stresses must be first broken down into their x- and y-components. By dividing the vertical stress distribution in the wheel-soil interface into separate point loads, it is possible to compute the stress distribution in the soil caused by a vertical wheel load. In SOCOMO the stress distribution at the soil-tyre interface is projected onto a horizontal rectangular grid and the stresses are concentrated in the grid points. Analogous to the vertical wheel load, the same procedure is followed for the horizontal wheel load in the driving direction (Johnson and Burt, 1990). The input of the wheel load in SOCOMO consists of a matrix with the vertical point loads on the coordinates of the grid and a matrix with the same dimensions for the horizontal point loads. Even for very erratic stress distribution, such as those under a tractor tyre with lugs, can be easily converted into point loads on a rectangular grid (Hammel, 1994). In addition to the dynamic stresses due to the wheel loading, it is necessary to account for the effect of the weight of the soil on the vertical and horizontal stresses. The vertical stress can be easily calculated from the bulk density of the soil. According to Tschebotarioff (1951) the horizontal static stress is 0.5 times the vertical static stress. From all the dynamic and static stresses the principal stresses, S_1, S_2 and S_3, and their directions, can be derived (Timoshenko and Goodier, 1980). The stress at a certain point in the soil is completely represented by these three principal stresses. In this way SOCOMO can calculate the stress at any point in the soil for any given horizontal and vertical stress distribution in the soil-tyre interface.

Soil stress can be converted by the model into compactions with the aid of stress-volume change relations (Van den Akker, 1988; Van den Akker and Van Wijk, 1987) determined with triaxial tests. However, triaxial tests are very time consuming and many tests are required. Moreover, SOCOMO is based on a linear elastic behavior of soil without volume change. Nevertheless it is justifiable to use SOCOMO, mainly because subsoil is being considered, and normally compactions and plastic deformations are limited there. However, the time-consuming and expensive determination of the stress-volume change relations is in conflict with the aim of developing a model that is easy to use. For this reason an other approach was chosen. It was considered that the main goal was to prevent subsoil compaction and not to calculate to what extent the subsoil would be compacted by a certain wheel load. The main part of soil compaction occurs during plastic deformation. Therefore subsoil compaction can be prevented to a great extent by taking into account the soil stresses exerted on the subsoil by a wheel load do not exceed the strength of that subsoil. There are two causes of failure to prevent soil deformation:

1. The structural strength is exceeded by the soil stresses so that aggregates are `crushed' or flattened, resulting in a collapse of the inter-aggregate pore system. Under these conditions the intra-aggregate pore system, which is finer and denser, would govern plant growth and crop yield. The structural strength of the soil is represented by the preconsolidation load and can be measured with uni-axial tests (Lebert and Horn, 1991).
2. The soil shear strength represented by the Mohr-Coulomb failure line is exceeded and shear strength failure occurs. Inter- and intra-aggregate pore systems would be destroyed and the structure-dependent pore system would deform and become a texture-dependent one, which would result in a very tortuous pore system.

Especially soil deformation caused by the soil-shear strength failure reduces soil physical qualities (Dawidowski and Koolen, 1987; Dawidowski and Lerink, 1990; Kirby, 1991). No failure of the subsoil with subsequent compaction would occur if:

$$S_1 \leq S_S \qquad (2)$$

and

$$S_3 \geq K_a S_1 - 2 C \sqrt{K_a} \qquad (3)$$

Where:
S_S = structural strength (preconsolidation load)
K_a = $\tan^2 (45° - \varphi / 2)$
φ = angle of internal friction
C = cohesion

The wheel-load bearing capacity of a subsoil can be defined as the maximum wheel load exerted by a specific type of tyre and tyre inflation pressure that does not exert stresses in the subsoil that exceed the strength of that subsoil. The lowest of the two strength criteria determines the wheel-load bearing capacity.

Verification of the model

By comparing measured and calculated soil stresses under a tyre, Van den Akker (1988) proved that the prediction of soil stresses with SOCOMO was satisfactory. This paper concentrates on the verification of SOCOMO as a tool for calculating the wheel-load bearing capacity of a subsoil. Field traffic experiments were performed and the area of plastic deformation under the tyre was determined and compared with the outcome of model computations. Soil stresses at the subsoil-topsoil interface were measured with pressure cells. Deformations and compactions were measured by photographing a vertical point grid positioned in the soil profile perpendicular to the driving direction. The stress-strain curves and the strength of the subsoil were determined with triaxial tests. The depth to which plastic deformations occurred was determined by combining the derived stress-strain curves with the measured deformations in the field traffic experiment. The plastic area identified under the wheel load in the traffic experiment was compared with the plastic area calculated with SOCOMO.

Materials and methods

The field traffic experiment is part of extensive research being done in cooperation with IMAG-DLO and Wageningen Agricultural University (Van den Akker et al., 1994) to test the use of low pressure tyres as a measure to prevent subsoil compaction. The results of the traffic experiment were ideal for verifying SOCOMO. Moreover it would demonstrate how SOCOMO could be used to analyze the results of traffixc experiments. Two tyres were tested:

- Test A: Special Ribbed (SR) 16.0/70-20 inflated to a pressure of 240 kPa, width of 0.41 m and outer diameter of 1.08 m.
- Test B: Special Ribbed (SR) 20.0/70-20 inflated to a pressure of 80 kPa, width of 0.51 m and outer diameter of 1.22 m.

Both tyres have a rather smooth profile and are common in the Netherlands for towed trailers and slurry tankers. The tests were executed with the tyres mounted 0n a single-wheel device with a controlled wheel load of 32 kN in both tests. The main difference between the tests was that in test A the inflation pressure was 240 kPa and in test B 80 kPa. The used speed was 0.33 m/s. The experiments were conducted on a fine sandy soil containing 4.6% organic matter and 6.6% $CaCO_3$. The particle size distribution was: 2.9% < 2 μm, 31.1% between 2-50 μm, 64.4% between 50-150 μm and 1.6% > 150 μm. The thickness of the topsoil was 0.35 m. The vertical stresses induced by the wheel load at the interface of the loose topsoil and the firm subsoil were measured simultaneously with five pressure cells in a section perpendicular to the driving direction. One cell was installed underneath the centre of the (future) rut and the other cells at distances of 0.125, 0.250, 0.375 and 0.500 m from this centre cell. The cells had a diameter of 76 mm and a height of 17 mm. In order to install the cells the topsoil was removed from an area approximately 1.5 x 1.5 m. In the firm subsoil, five holes were made with a special apparatus. The holes were of the same diameter as the pressure cells and had a depth equal to the height of the cells. In this way stress concentration on the stiff cell was avoided as much as possible, because the cell was embedded under the soft topsoil (i.e. in the firm subsoil) with its surface in plane with the topsoil-subsoil interface. After installation of the cells the topsoil was returned and lightly compacted. In this way a homogeneous topsoil was created over a wide area above the pressure cells. From the five measured stress curves, the vertical stress distribution on the subsoil could be approximated and by integration of this distribution the reaction force could be calculated. This was to check the reliability of the measurement, because the reaction force had to equal the applied wheel load. The procedure had been tested by Van den Akker and Carsjens (1989) and proved to be highly reproducible, although the calculated reaction force was somewhat lower than the exerted wheel load.

Deformation and compaction were measured by stereo photographing a vertical point grid that was positioned in the soil profile perpendicular to the direction of wheel passage. To install the grid, a pit was dug and the wall of the pit used for the grid was smoothed to create a flat surface. Aided by a perspex mould, plastic tracer pins were positioned in the pit wall in a grid pattern of 50 x 50 mm. The width of the grid was 1.0 m; the lowest row of pins was situated at a depth of 0.62 m. The reference points totaled 15-20 on the upper part of two piles of a diameter of 25 mm and a length of 2.5 m, which was installed to the left and right of the grid. Wide plastic tubes 1.0 m long around the upper part of the piles prevented any displacement during wheel passage. The grid was photographed before and after the test and the x, y and z coordinates of each gridpoint before and after the test were measured by standard stereo-analytical photogrammetric procedures, after which compactions and deformations were calculated (Van den Akker and Stuiver, 1989; Van den Akker et al., 1994).

Modeling traffic experiments with SOCOMO

SOCOMO was used to calculate the stresses under both wheel loads in the traffic experiments and to determine whether the bearing capacity of the subsoil had been exceeded. The loosened topsoil was a soft soil with a concentration factor $\nu = 5$ (Koolen and Kuipers, 1983). The mean normal stress in the soil-tyre interface of tyre A was assumed to be 1.2 times tyre inflation pressure, in accordance with a rule of thumb of Koolen and Kuipers (1983). For tyre B, a rule of thumb for low pressure tyres was used, which takes into account the increased influence of the carcass stiffness on ground pressure that results from the great deformation of low pressure tyres: mean ground pressure is equal to inflation pressure plus 50 kN (Van den Akker, 1992). A parabolic vertical pressure distribution over the tyre `footprint' was assumed using a modification of the formula of Johnson and Burt (1990):

$$p_i = [A+(B - A)\,(y/y_{max})^n]\,[1-(x/x_{max})^m] \qquad (4)$$

$$B = r\,A \qquad (5)$$

$$A = p_m\,(n+1)\,(m+1)/[m\,(n+r)] \qquad (6)$$

where A = maximum vertical pressure at tyreprint centre
B = maximum vertical pressure at tyreprint sides
r = ratio of B to A
p_m = mean vertical pressure over the tyreprint
x, y = x and y coordinates point i, x in direction of travel
x_{max}, y_{max} = one-half of footprint length and width, respectively
m, n = power for parabola in x and y direction

Next, parameter values are used: $r = 0.8$, $m = 2$ and $n = 3$. An uniform distribution of the horizontal pressures is assumed. The calculated and measured vertical stresses on the subsoil were compared to derive a parameter set with a good fit and an acceptable pressure distribution.

Determination of the subsoil strength with triaxial tests

The strength parameters angle of internal friction φ and cohesion C, and the strain at failure, were measured with triaxial tests. Drained and undrained triaxial tests were performed on 20 samples of height 100 mm and diameter 50 mm, taken from the upper 0.20 m of the subsoil. The samples were stored on a suction plate at a water pressure of -10 kPa. Average soil moister content was 25.1% (w/w^{-1}), about the same as in the field traffic experiments. The range of the dry bulk densities was 1190-1370 kg m^{-3}. The deformation velocity in the triaxial tests was 0.00435 m s^{-1}; peak strength was reached in 0.6-1.8 s, comparable with the traffic experiments, where after approximately 1.5 s the stresses on the subsoil reached their peak value. The cell pressures used were 5, 10 and 20 kPa, fitting the range of the minor principal stresses in the subsoil calculated with SOCOMO. The structural strength S_S of this soil is known to be much higher than the shear strength and is therefore not considered.

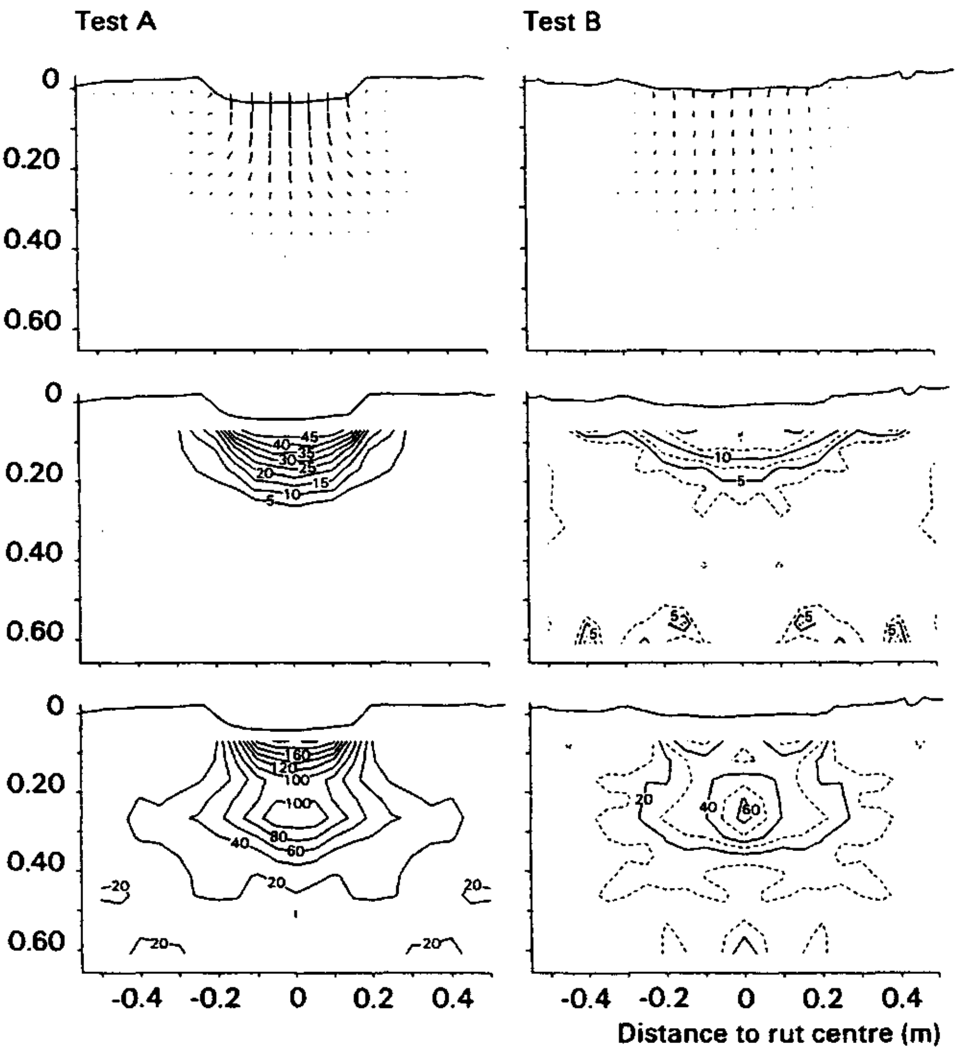

Figure 2. Deformation and compaction in tests A (tyre SR 16.0/70, inflation pressure 240 kPa) and B (tyre SR 20.0/70, 80 kPa). Wheel load was in both tests 32 kN. Top: displacements in a section perpendicular to driving direction. Middle: displacements in driving direction in mm. Bottom: increase in dry bulk density in kg m^{-3}.

Results and discussion

First, the results of the field traffic experiments will be discussed. The horizontal wheel load was 4.0 kPa in test A and 2.6 kPa in test B. The results of the vertical stress measurements are presented in Table 1. Peak stress beneath the tyre inflated to 80 kPa was about two-third of that exerted by the tyre inflated to 240 kPa (test A). The differences between tests A and B can be attributed chiefly to the difference in inflation pressure. The effect of low pressure tyre on rut depth was more pronounced than for the soil stresses. In test B the rut depth was about 50% less than in test A. Figure 2 shows the deformation and compaction observed. Theoretically deformation and compaction must be symmetrical. This proved to be true to a large extent and the symmetry was used to derive a better presentation. Deformation beneath the normal pressure tyre (A) was two to three times greater than under the low pressure tyre (B). This is consistent with the differences in rut depth presented in Table 1. Increase in dry bulk density corresponds to the deformation, the compaction caused by a normal tyre being much more severe than that caused by a low pressure tyre.

Table 1. Measured peak stresses and rut depth after one wheel passage. The calculated reaction force is compared with the exerted wheel load (32 kN).

Test	Tyre	Inflation pressure (kPa)	Cell depth (m)	Rut depth (m)	Peak stress (kPa)	Reaction/ load (-)
A	SR 16.0/70-20	240	0.346	0.039	182	1.08
B	SR 20.0/70-20	80	0.352	0.019	122	1.04

The peak in the stress - strain diagrams of the drained triaxial tests was more pronounced and was reached after a somewhat smaller deformation than in the undrained tests. However, peak stresses were almost identical, so the results were combined to derive the angle of internal friction φ and the cohesion C in relation to dry bulk density (Figure 3). In most tests, peak stress was reached at a deformation <5%. After unloading, a recoil of approximately 1% occurred, resulting in a permanent deformation of 4%. By combining the relation in Figure 3 with the dry bulk density profiles of tests A and B in Figure 4, the strength parameters φ and C were derived for each depth. These are needed as input for SOCOMO. The strength parameters of the loosened topsoil were determined in earlier triaxial tests, resulting in φ = 25° and C = 7.5 kPa. In test A, the subsoil at a depth of 0.50 m below surface was very loose and we were forced to extend the lines in Figure 3 below the measured bulk density range to derive φ and C. In tests A and B, the ratio between reaction force calculated by integration of the measured `pressure bulb' on the subsoil and wheel load applied was 1.08 and 1.04, respectively (Table 1). In the verification of the model, this ratio was used to correct the measurement. Moreover, the measured stresses increase with the vertical pressure induced by the weight of the soil on the pressure cells. A good match was derived without being forced to use an unrealistic stress distribution at the tyre soil interface as input in SOCOMO. The calculated minor stresses S_3 agreed with the cell pressure range used in the triaxial tests. The area calculated to undergo plastic deformation, where soil strength is exceeded in Figure 5, shows that in test A the wheel load was too high in comparison with the bearing capacity of the subsoil. The loose layer at a depth of 0.5 m below surface was too weak and yielded. In test B the bearing capacity of the subsoil was sufficient. The resulting principal strains from wheel load were calculated using the coordinates measured with the photographed point grid. The major principal strain ε_1 in the field tests and the vertical deformation in the triaxial tests could be compared, because in a triaxial test the vertical deformation of the sample is the major principal strain. The triaxial tests showed that a remaining major principal strain after loading >4% is a strong indication that the strength of the soil has been exceeded and that plastic deformation has occurred. Figure 5 shows that in test A major principal strains ε_1 >4% occurred in the upper 0.10 m of the subsoil, proving that the bearing capacity of the subsoil was exceeded. In test B, this is the case for a very small part of the subsoil in the centre. As the grid has a pattern of 50 x 50 mm, this may be attributed to the smoothening effect of the interpolation procedure between the grid points in the topsoil and the subsoil, because in that interface a strong discontinuity in deformation can be expected. We conclude that in test B the bearing capacity was sufficient and no plastic deformation occurred in the subsoil. Comparison of Figure 5 and Figure 6 shows that in test A SOCOMO overestimates the area of plastic deformation. In test B both measured and calculated area of plastic deformation was limited to the topsoil. With SOCOMO, maximal wheel loads allowed can be calculated for tyre A (SR16.0/70-20, 240 kPa) on the soil profile of tests A and B. This was 10 kN and 16 kN, respectively, much lower than the wheel load of 32 kN exerted in the field experiment.

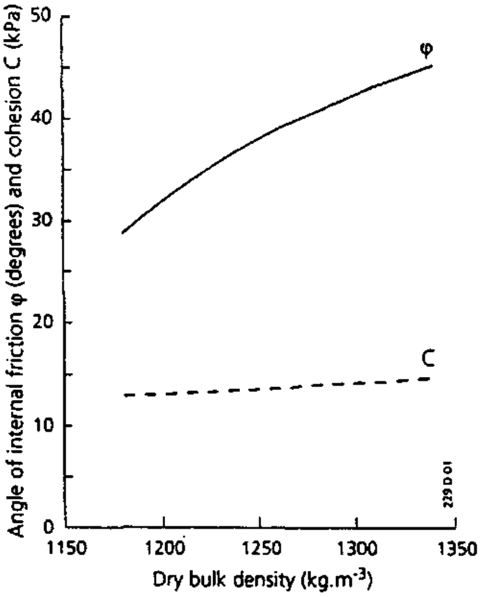

Figure 3. Angle of internal friction φ (°) and cohesion C (kPa) in relation to the dry bulk density (kg.m-3); average soil moisture content 25.1% (g.g-1); soil water suction 10 kPa.

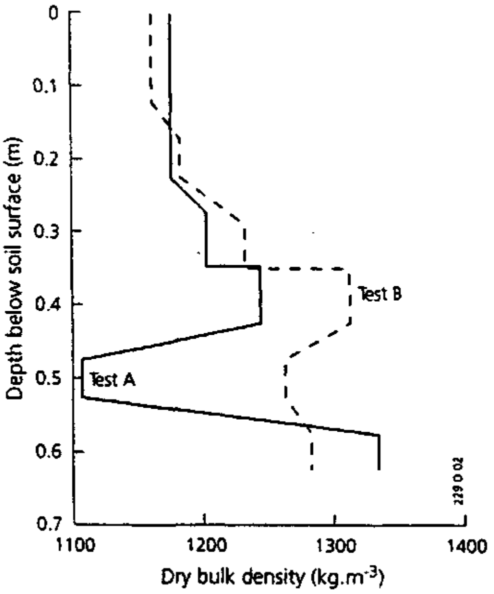

Figure 4. Initial dry bulk density in tests A and B. The soil was loosened to a depth of 0.35 m.

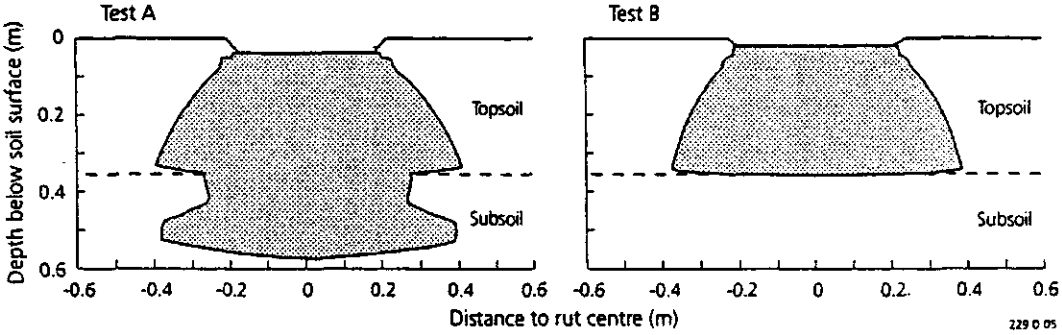

Figure 5. Calculated area with plastic deformation, where the soil strength is exceeded in tests A (tyre SR 16.0/70, inflation pressure 240 kPa) and B (tyre SR 20/70, 80 kPa). Wheel load in both tests 32 kN.

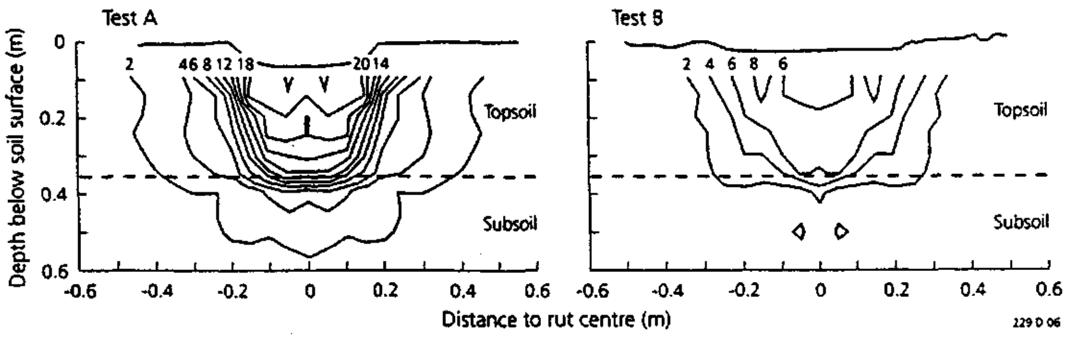

Figure 6. Remaining major principal strain ε_1 (%) calculated from soil deformations measured with a point grid. Strains larger than 4% indicate that soil strength was exceeded and plastic deformations occurred.

Conclusions of verification process

Results of using SOCOMO agreed well with the measurements in the field tests. Computations with SOCOMO offer good indicators for adjustment of wheel equipment (number, size, width and inflation pressure of tyres) and wheel load to the bearing capacity of the subsoil. This makes it possible to design and select wheel equipment to prevent subsoil compaction. SOCOMO proved to be a good tool for analyzing the traffic experiments. Results from the model support the conclusion that the use of low pressure tyres is an effective way of preventing subsoil compaction.

A comparison of Terra tyres and tandem and dual-wheel configurations using SOCOMO

To prevent soil compaction and deformation by heavy wheel loads, wide low-pressure (Terra) tyres can be used. Alternatively, the load could be divided over two smaller tyres in a dual-wheel or tandem configuration. The stresses and the minimal required strength of the soil to prevent plastic deformations have been computed for these three alternatives and a tyre with normal inflation pressure. Towed wheels were considered.

Model input

A Terra tyre (code TT) of 1.10 m width was loaded with 50 kN. This tyre was compared with two low ground pressure tyres of 0.50 m width and a wheel load of 25 kN. Three distances between the dual wheels were considered: 0.10 m (code DW10), 0.20 m (code DW20) and 0.50 m (code DW50). A single tyre of 0.50 m width and a wheel load of 25 kN was considered (code TA) in case of the tandem configuration because the stress distribution under tyres in a tandem configuration will not interfere eachother. The normal tyre of 0.60 m width had a wheel load of 50 kN (code NT). The inflation pressure of the Terra tyre was 60 kPa. To bear the wheel load of 25 kN, the dual and tandem tyres must be inflated to 80 kPa. The normal tyre was inflated to 200 kPa. Just as in the section **Verification of the model,** for the normal tyre we used a rule of thumb derived by Koolen and Kuipers (1983). This states that the mean normal stress at the contact surface is 1.2 times tyre inflation pressure, which gave in this case a mean ground pressure p_m of 240 kPa. For the mean ground pressure at the contact surface under low pressure tyres, we assumed that mean ground pressure was equal to inflation pressure plus 50 kN. This gave mean ground pressures p_m of 110 (TT) and 130 kPa (TA, DW10, DW20 and DW50). A uniform (UNI) and a parabolic (PAR) vertical pressure distribution over the tyre print were considered. For PAR, the modified formulas of Johnson and Burt (1990) already presented, i.e. Eqs 4, 5 and 6, were used with the parameters $r = 0.8$; $m = 2$ and $n = 4$, so the maximum vertical pressure at footprint centre was $A = 1.56\ p_m$. In all cases, a uniform distribution of the horizontal pressures was assumed, i.e. 9% of the vertical wheel load in the case of low ground pressure tyres and 12% in the case of the normal tyre. A normal soil stiffness with a concentration factor $v = 4.0$ was assumed.

Results

A selection of the computation results is given in Figures 7 and 8. The graphs commence at a depth of 0.075 m because the results between 0 and 0.075 m are not reliable. This depth is related to the grid size of the mesh of point loads on the tyreprint used in SOCOMO. The dual wheels spaced at 0.50 m (DW50) acted as two single wheels, with the same results as for the tandem configuration (TA). Figure 7a shows that at a depth of 0.10 m, the major principal stress under the normal tyre was approximately twice that under a Terra tyre.

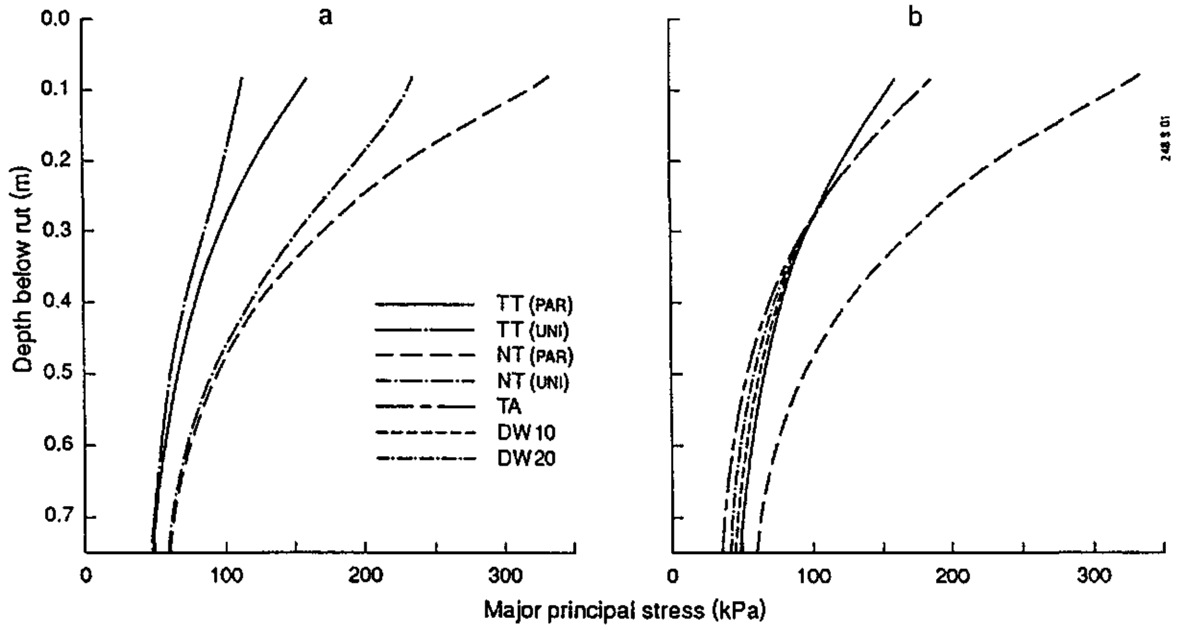

Figure 7. Highest major principal stresses at a certain depth under (a) a Terra tyre (TT) and a normal tyre (NT) with an assumed uniform (UNI) or parabolic (PAR) vertical pressure distribution over the tyre tyreprint. These tyres were (b) compared with tyres in tandem (TA) and dual-wheel configurations with spacings of 0.10 m (DW10) and 0.20 m (DW20). A parabolic vertical pressure distribution was assumed.

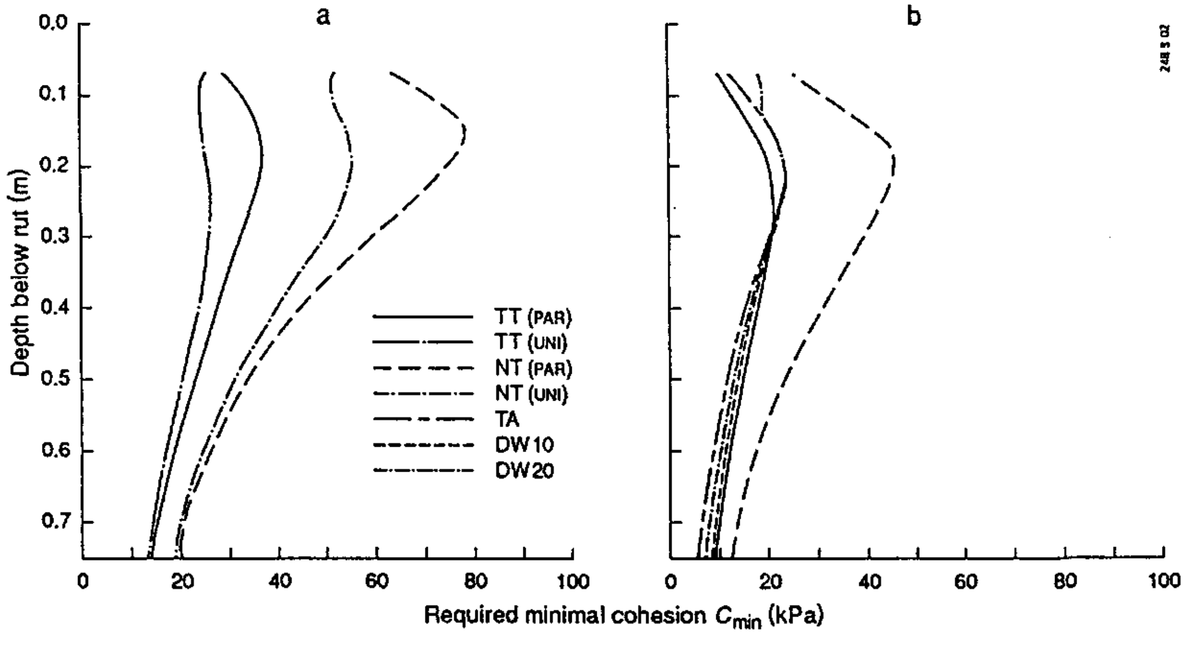

Figure 8. The needed minimal cohesion C_{min} to prevent plastic deformation at a certain depth under the tyres and with the pressure distributions mentioned in Figure 7 in case of (a) an angle of internal friction $\varphi = 15°$ and (b) $\varphi = 30°$.

At a depth of 0.75 m this difference had decreased to approximately 25%. The major principal stresses were markedly influenced by the pressure distribution; at 0.10 m depth the stresses under PAR were 40% higher than under UNI. This difference decreased strongly with depth. Figure 7b shows that at a depth of 0.10 m the stresses under the Terra tyre (TT) were due to the lower inflation pressure, approximately 15% smaller than those under the other low-pressure tyres configurations (TA, DW10 and DW20). At a depth of 0.75 m the stresses under a single wheel of a tandem configuration (TA) were 75% of those under a Terra tyre (TT).

The major principal stresses under the dual wheels (DW10 and DW20) at this depth were in between to those of TT and TA. Figure 8a shows that the minimal cohesion C_{min} needed under NT was twice as high as under TT. At a depth of 0.75 m the difference was still 33% of TT. In the topsoil C_{min} was 43% higher for PAR than for UNI. Comparison of TT and NT in Figure 8b ($\varphi = 30°$) with those in Figure 8a ($\varphi = 15°$) shows a major influence of φ on C_{min}. For C_{min} with $\varphi = 15°$ it was almost twice that needed with $\varphi = 30°$. In the topsoil, C_{min} under the Terra tyre was 88% of that needed under the other low-pressure tyre configurations (TA, DW10 and DW20). At a depth of 0.75 m, C_{min} under TT was 163% of C_{min} under TA.

Conclusions

- The major principal stresses and in particular the soil strength needed are much higher under a normal tyre than under low pressure tyres.
- The vertical pressure distribution over the tyre tyreprint has a strong effect on the major principal stress and the soil strength needed.
- Replacing a Terra tyre by two smaller tyres will result in slightly higher stresses and soil strength needed in the topsoil, and much lower stresses and soil strength needed in the subsoil. This positive effect strongly depends on the distance between the tyres.

Construction of a wheel-load bearing-capacity map

SOCOMO was used to calculate the allowable wheel loads of a tyre with a width of 0.50 m and an inflation pressure of 80 kPa on soils of arable land in the Netherlands in autumn. The moisture tension of these soils is moderate, with a soil-water suction of pF2.5. The values of the concentration factor þ used were the same as those of Horn and Lebert (1994) and the Deutscher Verband für Wasserwirtschaft und Kulturbau e.V. (DVWK, 1995). The rule of thumb to calculate the mean ground pressure at the soil - tyre interface based on a heavily deformed tyre with a wheel load of 32 kN was modified to account for lower wheel loads and therefore diminished tyre deformation: mean ground pressure is equal to inflation pressure plus (50 x F/32), where F is the wheel load under consideration. The vertical and horizontal pressure distribution over the tyre print was identical to the distribution in the verification of SOCOMO. Table 2 presents the strength properties of the major subsoils in the Netherlands. The set of subsoils presented in Table 2 is based on the soil map of the Netherlands at scale 1 : 250 000. Peat soils were not considered because no data on strength properties were available. The soils were classified according the German soil classification using φ and C (DVWK, 1995). These strength parameters depend on the type of soil and its structure. For each soil, the set of strength parameters with the lowest values, representing the weakest structure, was chosen in order to derive the lowest bearing capacity of that particular soil. Pedotransfer functions found by Lebert and Horn (1991) were used to calculate the structural strength S_S. The effective thickness D was defined as the thickness of the topsoil minus an estimated rut depth of 0.03 m. The ploughing depth in sandy soils is usually deeper than in clay soils.

Results and discussion

Trial and error was used to determine the wheel-load bearing capacity of the soils in Table 2. SOCOMO was used to calculate the area in which the stresses exceeded the structural strength and/or the shear strength. The bearing capacities of sandy soils, sandy loam and clay loam were limited by the shear failure criterion; the bearing capacities of the other soils were limited by the failure of the structural strength. The thickness of the topsoil, and therefore the ploughing depth, proved to be an important factor in determining the bearing capacity. The bearing capacities were split into the following categories: 10-15 kN (sandy loam 2); 16-21

Table 2. Angle of internal friction φ, cohesion C and structural strength S_S of the major subsoils in the Netherlands at a soil-water suction of pF2.5. The table is based on DVWK, 1995 and Lebert and Horn, 1991. D is the effective topsoil thickness.

	Clay content (%)	C (kPa)	φ (°)	S_S (kPa)	D (m)
Sandy soils	< 8	12	28	198	0.32
Coarse sand	< 8	10	32	240	0.32
Sandy loam 1	< 8	10	32	122	0.32
Sandy loam 2	8 - 18	10	32	140	0.27
Clay loam	18 - 25	14	31	79	0.27
Light clay	25 - 35	26	36	118	0.22
Medium clay	35 - 50	26	36	96	0.22
Heavy clay	> 50	34	38	114	0.22
Sandy silt	< 18	15	39	82	0.22
Silt loam (loess)	< 18	26	37	110	0.22

kN (sandy soils, coarse sand, sandy loam 1, sandy silt loam); 22-27 kN (light, medium and heavy clay) and 28-33 kN (silt loam). A wheel-load bearing-capacity map was constructed (Figure 9) based on the soil map 1 : 250 000. The bearing capacities are lower than the wheel loads commonly used during harvest operations. The soil strength properties used in the model simulations were those of either weakly structured soil or of soil with no structure at all. This ensured that the lowest allowable wheel loads were derived. However, the values of the cohesion of sandy soils in Table 2 might be too low. Our own measurements (Van den Akker, 1994), and those of Lebert (1989), gave higher cohesion values. Moreover, soil will often be structured and therefore stronger than assumed in the simulations. Good drainage is common on arable land in the Netherlands and that gives rise to a structured, stronger subsoil.

Conclusions

The bearing capacities determined in the construction of the wheel-load bearing-capacity map were too low. This may have been caused by using rather conservative values for soil strength properties. These can be improved by incorporating the drainage conditions, which are available on the Soil Map of the Netherlands scale 1 : 50 000. If original and specific soil strength data are used instead of generalized data from tables, higher values of strength can be used. It proved to be difficult to use the pedotransfer functions based on German soils, because the German soil classification does not match the Dutch classification. It is not clear whether pedotransfer functions based on German soils can be used to calculate the strength properties of Dutch subsoils. This makes the development of Dutch pedotransfer functions necessary.

Conclusions

The results of SOCOMO agreed well with the measurements in the field tests. The model requires only limited input data and is easy to use for analyzing measures aimed at preventing subsoil compaction. Computations with SOCOMO provide information that is useful for adjusting wheel equipment (number, size, width and inflation pressure of tyres) and wheel load to the bearing capacity of the subsoil. This makes it possible to design and select wheel equipment to prevent subsoil compaction. SOCOMO proved to be a good tool in the construction of wheel-load bearing-capacity maps. However, its use is restricted by the lack of good data and pedotransfer functions on soil strength.

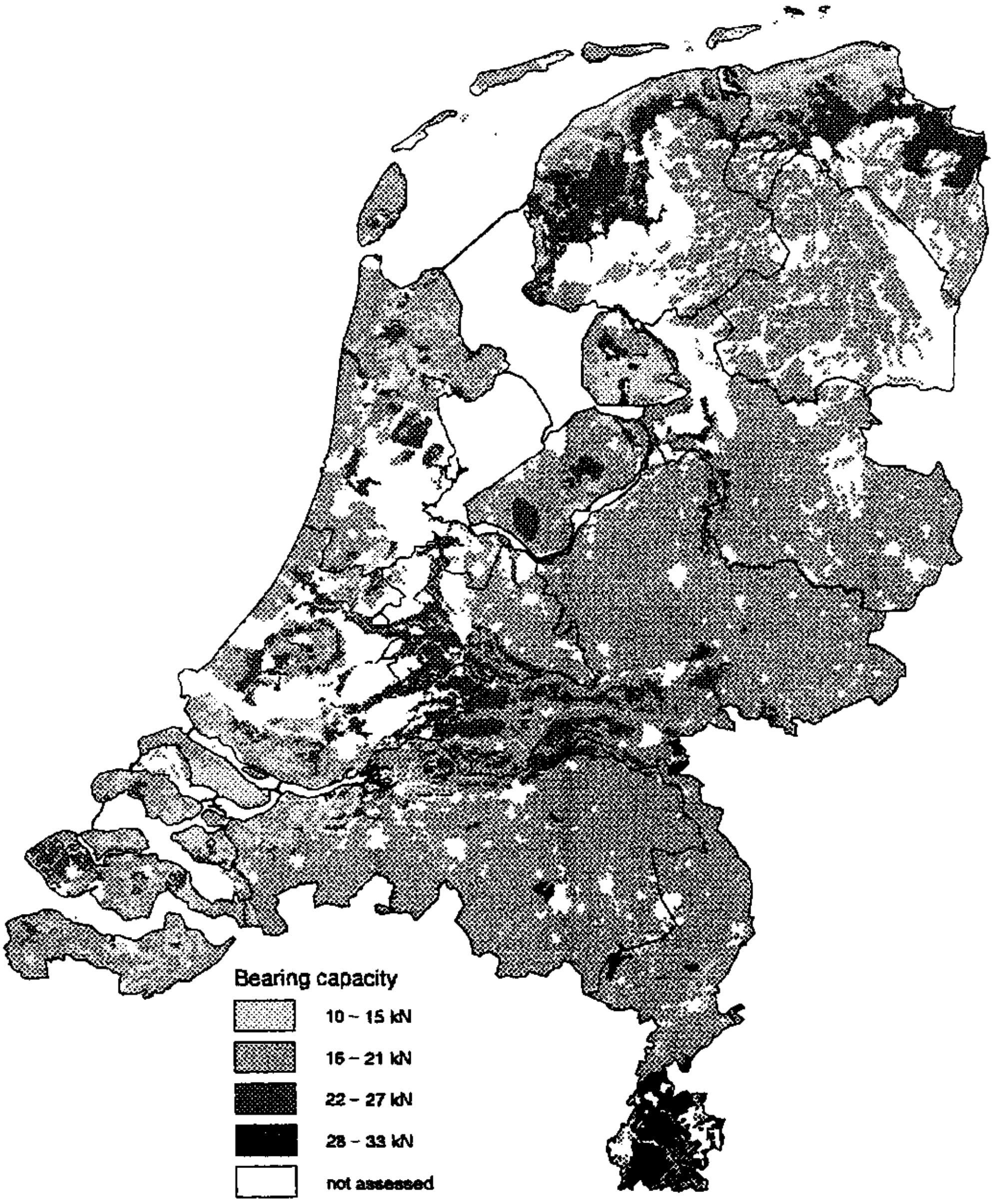

Figure 9. Wheel-load bearing-capacity map of the Netherlands based on tyres with a width of 0.5 m and an inflation pressure of 80 kPa on arable land, and with a soil water suction of pF2.5.

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EFFECTS OF ORGANIC MATTER ON THE PENETRATION RESISTANCE RETENTION ABILITY PORE SIZE DISTRIBUTION AND HYDRAULIC CONDUCTIVITY OF SOIL

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Abstract

Organic matter (compost) was applied in the rates of 0, 75, 150 and 300 m^3ha^{-1} to a loamy and a clay soil to investigate its infuence on the soil physical properties. The experiments were conducted in Attiki and Biotia areas characterised by a semiarid climate. The physical properties of the soils were affected as far as the saturated and unsaturated hydraulic conductivity, water retention ability, pore size distribution, soil resistance to penetration and aggregate stability, were concerned. In the most of the cases the improvements were proportional to the rates of the organic matter applied and they are greater to the loamy soil than to the clay soil.

Introduction

Many physical properties are used to assess soil compaction. Meanwhile, the influence of organic matter on the physical properties of the soil is well known. There are publications concerning the relationship between organic matter and the soil water retention ability (Morel *et al.*, 1978; Kladivko and Nelson, 1979; Kumar *et al.*, 1985; Obi and Ebo, 1995), the saturated hydraulic conductivity (Epstein, 1975; Kumar *et al.*, 1985), the soil resistance to penetration (SRP) (Kumar *et al.*, 1985; Ohu *et al.*, 1985; Ekwue, 1990; Stone and Ekwue, 1993), the aggregation (Pagliai *et al.*, 1981) and the total porosity as well as the pore size distribution (PSD) (Walter, 1977; Pagliai *et al.*, 1981; Mathan, 1994).

The partial reference by several authors on the influence of organic matter to some of the physical properties of the soil at each time as well as our attempt to point out the strong dependence of the physical properties to organic matter gave the reason for this work to be conducted. The objective of this study was to investigate the influence of organic matter by assessing the most important soil physical properties.

Methods

The source of organic matter used in the experiments was a compost produced from a mixture of 17% sawdust, 21% sewage sludge and 62% town wastes by volume, following the Beltsville Aerated Pile Method (Wilson *et al.*, 1980). The heavy metal contents for cadmium, zinc, copper, lead, nickel and chromium are 2.3, 1100, 450, 60.6, 104 and 798 ppm respectively, which are below the safe levels for plant growth. Chardas *et al.* (1994) presented details of the compost production.

The experiments were conducted in two different areas. The first experimental field was established on a deep clay soil (Humic Fluvaquent) and it is located in the area of Aliartos in Biotia, which is characterised by a semiarid climate with a mean annual rainfall of about 590 mm. The second was established on a loamy soil (Typic Xerochrept) and it is located in the area of Kiourka in Attiki with a mean annual rainfall of about 520 mm. Some properties of the soils are presented in Table 1.

Table 1. Some properties of the soils treated with the compost.

Soil mixtures	Particle size %			Organic matter %	$CaCO_3$ %	pH	C.E.C. meq/100 gr
	Clay	Silt	Sand				
Loamy + c0[a]	25	40	35	1.1	0.3	6.8	14.4
Loamy + c75				2.5	1.2	7.1	20.1
Loamy + c150				3.2	2.7	7.2	22.6
Loamy + c150				6.2	3.0	7.2	24.5
Clay + c0	48	31	21	3.2	34.0	7.6	54.2
Clay + c75				4.4	32.2	7.7	55.8
Clay + c150				5.3	30.7	7.7	56.3
Clay + c300				8.2	30.6	7.8	58.2
Compost				31.2	17.5	7.3	61.7

[a] c0, c75, c150 and c300 represent the compost rates of 0, 75, 150 and 300 m^3ha^{-1}

The experimental design was a randomised, complete block with four treatments and four replications. The experimental plots of 18 m^2 (3x6) were separated by 1m wide zone. The compost was applied on October 1994 in the rate of 0 (control), 75, 150 and 300 m^3ha^{-1} (v/v) and it was incorporated (rototilled) into the top 15-20 cm of the soil profile. The fields were rested under grass fallow. Measurements and sampling for this study were made after fifteen months.

The particle size analysis of the soil samples was curried out using the Bouyoucos (1962) hydrometer method. Carbonates were measured by HCl dissolution and measurement of the evolved CO_2. The pH was measured in 1:1 soil and water ratio. The Walkley-Black wet digestion method was used for the determination of organic matter. The soil samples for the above determinations were taken after mixing the four subsamples (replications) of each treatment. The saturated hydraulic conductivity with the constant head method (Klute and Dirksen, 1986), in undisturbed soil samples of a length of 8 cm and a diameter of 6 cm. The unsaturated hydraulic conductivity, $K(\theta)$, was calculated using the Jackson's (1972) procedure. The soil water retention curves (SWRC) were determined by modifying the Haines' Buchner funnel method (Haines, 1930). The modification consists of a removable outflow-inflow system instead of the hunging burette. The undisturbed soil samples were 3 cm in high and 6 cm in diameter. The SRP at the surface was determined in different soil moisture by using a pocket penetrometer (Bradford, 1986). The PSD was obtained from the SWRC by plotting their slopes as functions of the soil water tention (Childs, 1969). The stability of aggregates was determined by using the concept of the instability index b (Valmis *et al.*, 1988).

The experimental data were subjected to analyses of variance (ANOVA) tests and Duncan's multiple range tests estimated statistical differences among treatment means.

Results and discussion

Chemical properties of the soils were affected directly from the compost (Table 1). Organic matter, $CaCO_3$, pH and CEC were increased as the compost rates were increased too.

The SRP in relation to soil water and the rate of applied compost is shown in Figs. 1 and 2. The relationship between SRP and soil moisture was a curve of second order for each treatment. The correlation coefficient R^2 was 0.973, 0.889, 0.921 and 0.963 in the loamy soil and 0.963, 0.99, 0.94 and 0.856 in the clay soil for the compost rates of 0, 75, 150 and 300

m^3ha^{-1} respectively. Generally, SRP was decreased as the soil moisture was increased. As the

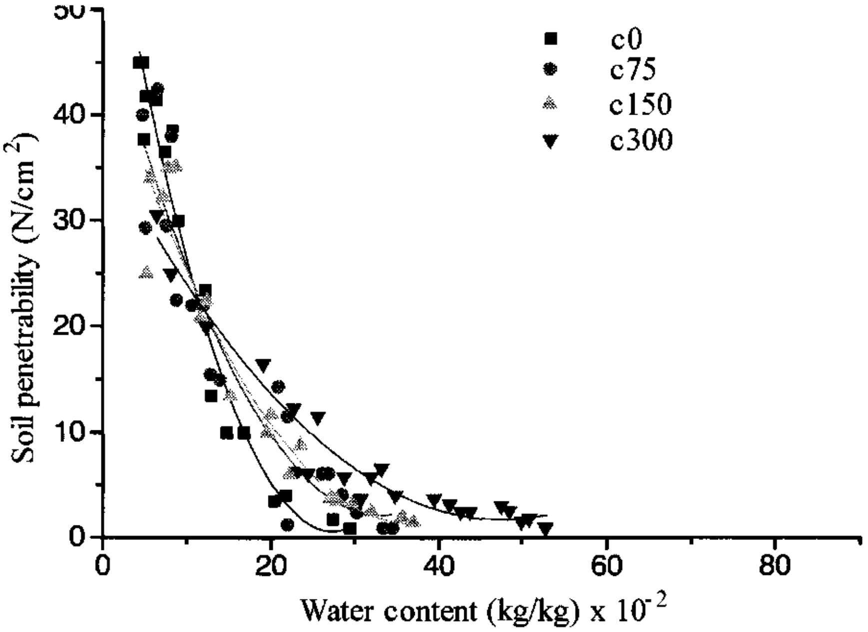

Fig. 1. Soil penetration resistance as related to the soil water. Curves c0, c75, c150 and c300 corresponded to the loamy soil amended with the compost rates of 0, 75, 150 and $300m^3ha^{-1}$.

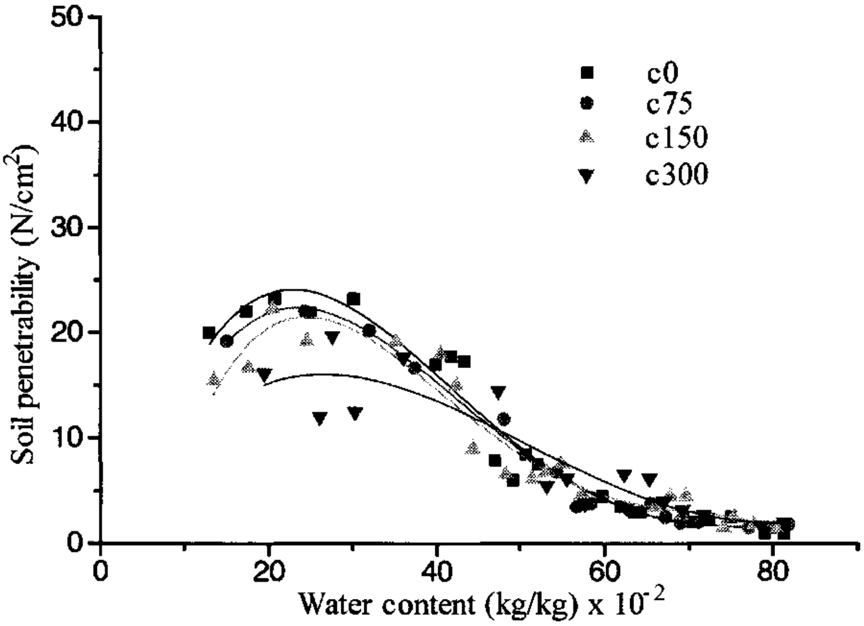

Fig. 2. Soil penetration resistance as related to the soil water. Curves c0, c75, c150 and c300 corresponded to the clay soil amended with the compost rates of 0, 75, 150 and $300m^3ha^{-1}$

compost rates were increased, the slope of the curves giving the relationship between the SRP and soil moisture was decreased.

Increasing the moisture contents, in the loamy soil (Fig. 1), the high compost rates gave smaller SRP values than those with lower rates up to some values (22 - 25 Ncm^{-2}), after which soils with high compost rates have greater SRP than those with lower rates. Similar soil behaviour, after addition of organic matter, has been reported by other researchers including Ohu *et al.* (1985), Ekwue and Stone (1995), in soils where SRP was measured in the laboratory after the soils had been compacted using standard proctor blows.

SRP in clay soil (Fig. 2) showed almost the same behaviour. The slopes of the curves representing SRP versus moisture contents for the clay soil treatments gave lower values than the corresponding values of loamy soil treatments. As in the case of loamy soil increasing the moisture contents the high compost rates gave smaller SRP values than those with lower rates up to some values (7-12 Ncm^{-2}) after which compost affected SRP in a opposite way. A different observation in clay soil treatments is that SRP is increased as the soil moisture is decreased up to some peak values were reached after which the values of SRP declined with further decrease in moisture contents. The letter has been observed in soils previous compacted in the laboratory (Ayers and Perumpral, 1982; Ewkue and Stone, 1995).

The total porosity (0.418 and 0.585 for the loamy and clay soils) was improved by the use of compost, the increase being 11.0, 27.0 and 32.8% in the loamy soil as well as 5.4, 8.5, and 9.9% (P=0.05), in the clay soil for the 75, 150 and 300 m^3ha^{-1} compost rates.

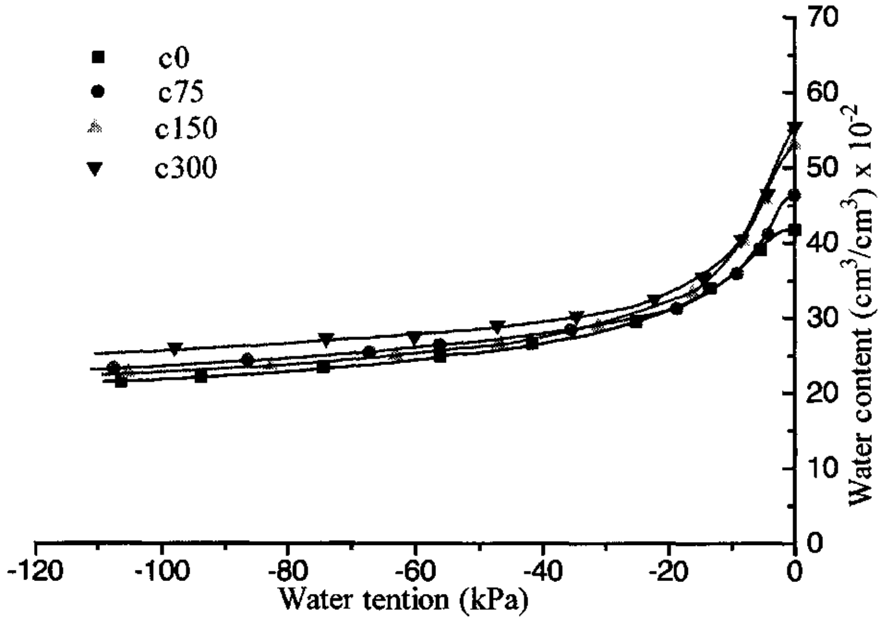

Fig.3. Soil water retention curves under the different treatments of loamy soil. Curves c0, c75, c150 and c300 corresponded to the loamy soil amended with the compost rates of 0, 75, 150 and $300m^3 ha^{-1}$.

The SWRC under the different treatments of the loamy and clay soils are presented in Figs. 3 and 4. The curve of each treatment represents the mean curve of four replicates. The addition of compost increased the retention ability of the soils in all treatments as any concrete soil moisture content retained in a higher negative soil water tension. The retention ability is higher in the soils amended with high compost rates than those are with low rates. Exception was the case of the retention curve belonging to the amended loamy soil with the rate of 75 m^3ha^{-1}, which for the moisture content between 0.30 and 0.36 overlapped the retention curve of the control treatment.

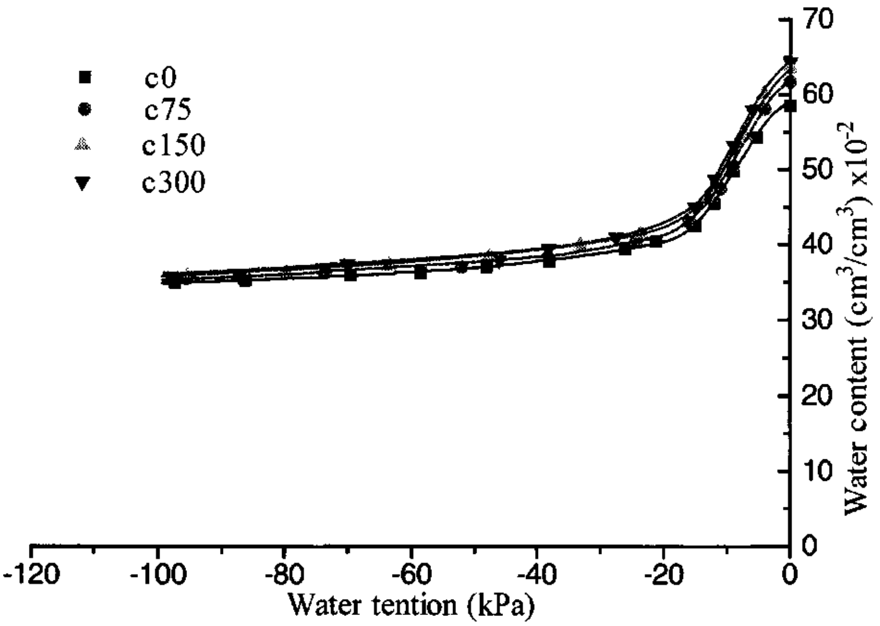

Fig.4. Soil water retention curves under the different treatments of loamy soil Curves c0, c75, c150 and c300 corresponded to the clay soil amended with the compost rates of 0, 75, 150 and 300m^{3}ha^{-1}.

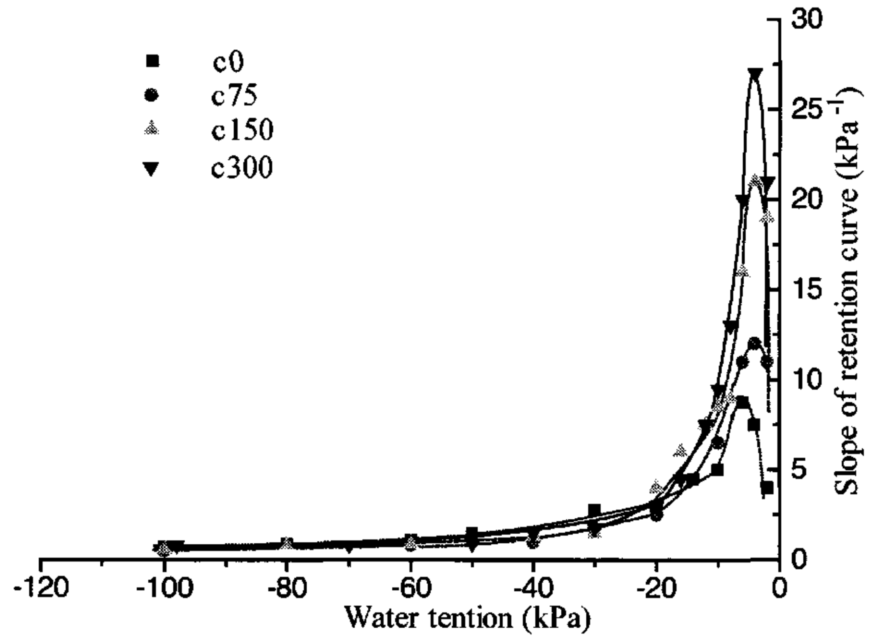

Fig.5. Differential curves of the retention curves in Fig. 3. Curves c0, c75, c150 and c300 corresponded to the loamy soil amended with the compost rates of 0. 75. 150 and 300m^{3}ha^{-1}

Differentiating the retention curves of Fig. 3 can reveal PSD (Childs, 1969; Aggelides, 1987) and it was presented in Fig. 5. From the above Fig. 3 concerning the loamy soil somebody can see that the addition of organic matter increased the large pores. Especially, the increase of large pores is higher in soils amended with high compost rates, than soils amended with low compost rates. Similar was the PSD of the clay soil.

The saturated hydraulic conductivity, Ks, was affected with the application of organic matter. There was a statistical significant treatment effect (P=0.05). Ks (0.083 and 0.38 mh^{-1} for the loamy and clay soil) was increased 32.5, 53.0 and 95.2% in the loamy soil and 55.3, 97.4 and 168.4% in the clay soil for the rates 75, 150 and 300 m^3ha^{-1} compost rates.

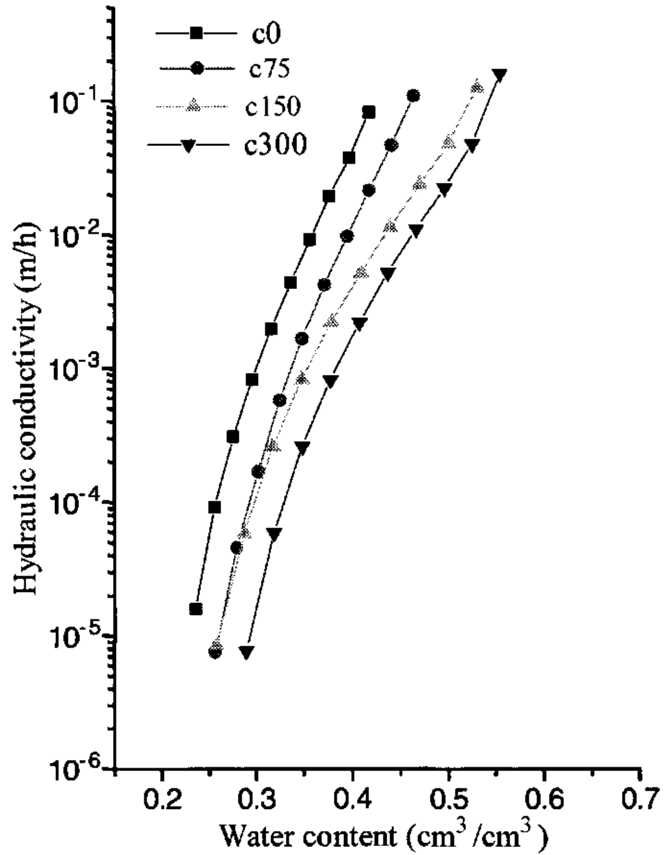

Fig.6. Hydraulic conductivity as a function of soil water under the different treatment of loamy soil.Curves c0, c75 c150 and c300 corresponded to the loamy soil amented with the compost rates of 0, 75, 150 and 300$m^3 ha^{-1}$.

The unsaturated hydraulic conductivity, K, was affected by the compost but in an opposite way. The K as a function of soil water content, θ, is presented in Fig. 6 for the loamy soil. The K(θ) was reduced more in the soils amended with high compost rates than those with low rates. The reduction was smaller in the clay soil than the loamy soil. From Fig. 6 one can see that for water content 0.40 the hydraulic conductivity value of 0.0406 mh^{-1} (control) was reduced to 0.0111, 0.0039 and 0.0016 for the rates of 75, 150 and 300 m^3ha^{-1}. Furthermore, for the hydraulic conductivity value of 0.01 mh^{-1} the soil water content was reduced from 0.359 (control) to 0.396, 0.435 and 0.464 for the rates 75, 150 and 300 m^3ha^{-1} respectively. The decrease in K(θ) of the amended soil was accompanied by an increase in moisture content with the relevant effects.

Aggregate stability was determined by using the concept of the instability index β (Valmis *et al.*, 1988) which is decreased as the stability of the soil is increased. The values of β were 0.46, 0.40, 0.37, 0.32 and 0.29, 0.27, 0.27, 0.24 in the loamy and clay soils respectively for the rates of 0, 75, 150 and 300 m^3ha^{-1}. The decrease of â in both soils indicated the increase of soil stability.

Conclusions

Changes in physical properties resulted from the application of organic matter (compost) to a loamy and a clay soil were determined. The organic matter affected all physical properties under consideration of the two soils. The improvement (changes) was proportional to the compost rate. The results support the following conclusions:

1. Penetration resistance was reduced. The reduction was greater to the loamy soil than the clay soil.
2. Total porosity and saturated hydraulic conductivity were increased. The increase of total porosity was greater in the loamy soil than the clay soil, and the saturated hydraulic conductivity was greater in the clay soil than the loamy soil. The unsaturated hydraulic conductivity was reduced.
3. Retention ability of two soils was increased as well as the corresponding soil pores.
4. Aggregate stability in both soils was increased.

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