

Modifying Soil Structure Using Plant Roots

John Löfkvist

*Faculty of Natural Resources and Agricultural Sciences
Department of Soil Sciences
Uppsala*

**Doctoral thesis
Swedish University of Agricultural Sciences
Uppsala 2005**

Acta Universitatis Agriculturae Sueciae

2005: 60

ISSN 1652-6880

ISBN 91-576-6959-7

© 2005 John Löfkvist, Uppsala

Tryck: SLU Service/Repro, Uppsala 2005

Abstract

Löfkvist, J. 2005. *Modifying Soil Structure Using Plant Roots*.
Doctoral dissertation. ISSN: 1652-6880, ISBN: 91-576-6959-7.

Compaction in the subsoil may lead to permanent yield losses. The main objectives of this thesis was to test the possibility of using plant roots to modify soil structure and to use laboratory screening methods to find plant species suitable for penetrating strong soil.

Two laboratory screening methods were tested. The first method used soft and hard wax layers installed in sand cores. The proportion of roots penetrating the hard relative to the soft layer was highest for lucerne, intermediate for chicory, lupin and red clover, and lowest for barley. The second method used natural soil compacted by different vertical stresses. Measurements of root length density showed that lucerne had a greater ability to establish a deep root system in compacted soil than barley and lupin.

A field experiment was carried out to test the possibility to use plant roots to modify subsoil structure. The complete area of all plots except the control plots were compacted by a dump truck (weight 30 Mg) prior to the start of the experiments. The plant species studied were lupin (*Lupinus luteus* L.), lucerne (*Medicago sativa* L.), red clover (*Trifolium pratense* L.), tall fescue (*Festuca arundinacea* L.), chicory (*Cichorium intybus* L.) and barley (*Hordeum vulgare* L.). Tall fescue had the highest root length density (RLD) at 30-35 cm depth, but RLD of chicory and lucerne were also fairly high. Chicory had the largest effect on subsoil structure, as estimated by saturated hydraulic conductivity (K_{sat}) at 30-35 cm depth, closely followed by lucerne. Abundance of earthworms was related to tillage intensity and was consistently higher in plots of perennial crops. The influence of earthworms on K_{sat} was lower than that of plant roots.

Two field experiments were carried out to study mechanical subsoiling in combination with: a) incorporation of slaked lime and b) the use of plant roots as reinforcement of the loosened soil. Incorporation of slaked lime increased stability of the modified soil structure. Growing crops of lucerne prolonged the effect of subsoiling on K_{sat} . Conventional mechanical subsoiling gave short-lived results.

Keywords: root growth, soil structure, subsoil compaction, subsoil loosening, saturated hydraulic conductivity

Author's address: John Löfkvist, Department of Soil Sciences, SLU, P.O. Box 7014, SE-750 07 Uppsala, Sweden. E-mail: John.Lofkvist@mv.slu.se

Contents

Introduction, 7

Objectives, 8

Background, 8

Soil structure and strength as affected by compaction, 8

Soil strength, 8

Soil compaction, 11

Root growth, 12

Root systems, 12

Responses to increased mechanical impedance, 15

Decreasing rate of elongation of roots, 16

Growth pressure (σ_r), 16

The swelling behaviour of roots, 17

The shrinking behaviour of roots, 18

Proliferation of laterals, 18

The role of plant hormones, 19

Root growth in strong and heterogeneous soil, 19

Plant roots, soil structure and compaction, 21

Thesis work, 22

Screening roots for effective penetration, 22

Experiment 1 (Paper I), 22

Experiment 2 (Paper II), 26

Conclusions, 31

Roots as biological subsoilers (Paper III), 32

Conclusions, 39

Saturated hydraulic conductivity as a measure of soil quality (Paper IV), 39

Biologically and chemically assisted mechanical subsoiling (Paper IV), 41

Experiment 1, 41

Experiment 2, 43

Conclusions, 45

Final Remarks, 45

References, 46

Acknowledgements, 50

Appendix

Paper I-V

This thesis is based on the following papers, which are referred to in the text by their Roman numerals:

- I. Löfkvist, J., Whalley, W.R., & Clark, L.J. 2005. A rapid screening method for good root-penetration ability: Comparison of species with very different root morphology. *Acta Agriculturae Scandinavica Section B-Soil and Plant. In press*
- II. Löfkvist, J. & Arvidsson, J. A method for screening the ability of different crops to penetrate compacted soil and increase hydraulic conductivity. *Manuscript*
- III. Löfkvist, J. Biological sub-soiling – field trials testing the ability of six different species to act as ‘biological subsoilers’. *Manuscript*
- IV. Löfkvist, J. Comparing two common methods of determining saturated hydraulic conductivity coefficient in soil. *Manuscript*
- V. Svantesson, U. & Löfkvist, J. Mechanical, biological and chemical improvement of subsoil structure. *Manuscript*

Paper I is reprinted by permission of the publisher.

Introduction

Soil compaction is a serious problem inflicted by the use of heavy field machinery and is estimated to be responsible for the degradation of an area of 33 million hectares in Europe (Van den Akker & Canarache, 2000). In Sweden, the avoidance of subsoil compaction is established as a national environmental target in a report by the Swedish Board of Agriculture (SJV, 1999). The Swedish Environmental Protection Agency has therefore commissioned the Swedish University of Agricultural Sciences to develop a programme for monitoring the physical properties of soil of arable land, with emphasis on subsoil compaction.

The risks associated with soil compaction are well documented and have been known for several decades. Soil compaction below plough depth is very persistent and may lead to permanent yield losses (Håkansson & Reeder, 1994; Etana & Håkansson, 1994). Methods for deciding maximum axle load and wheel pressure to avoid soil compaction and rules of thumb for approximating these parameters have been developed, but despite this, field machinery in modern agriculture continues to increase in terms of weight and axle load (Chamen *et al.*, 2000; Van den Akker & Canarache, 2000), increasing the risk for detrimental soil compaction.

However, as large areas of arable land are already affected by soil compaction, methods need to be developed to restore the physical fertility of compacted soil. Unless remedial measures are implemented, improvements in the physical fertility of the subsoil are not likely in the foreseeable future.

Various methods to improve subsoil structure have been tested and a few are in practical use. Call & Throckmorton (1915) used dynamite to improve a heavy clay soil. Mechanical subsoil loosening with different implements dragged through the soil has produced various results, often with poor longevity (Nilsson & Henriksson, 1968; Alblas, 1987; Canarache, Horn & Colibas, 2000; Chamen *et al.*, 2000). Most mechanical methods have in common the fact that the time span for effective subsoil loosening is narrow, as soil moisture content limits the effective depth of the implement. It has also been demonstrated that mechanical loosening of soil increases its susceptibility to compaction (Lebert, 1992; Chamen *et al.*, 2000). Draught force requirements for mechanical subsoiling are significant and increase with operating depth. Several researchers have suggested the use of plant roots as tillage tools, but results are scarce and inadequately reported (Goss, 1985; Elkins, 1985; Heinonen, 1986; Dexter, 1991; Cresswell & Kirkegaard, 1995).

This thesis presents the results from laboratory experiments on screening methods for finding plant species especially able to modify soil structure. It also describes field experiments on the effects of plant roots on soil structure. Comparisons are made between root subsoil effects and other methods of subsoil loosening. A literature review of related research is also included to put the results into context.

Objectives

The objectives of the work presented in this thesis were:

- To investigate the possibilities of using plant roots to improve the structure of soils damaged by compaction
- To use and evaluate laboratory screening methods to test the possibility of finding species more likely than others to increase soil physical fertility.

Background

Soil structure and strength as affected by compaction

Soil strength

The principal constituents of soil strength are the cohesion in the soil material and the friction between the soil particles (Marshall, Holmes & Rose, 1996). In addition to being dependent on textural and mineralogical properties, cohesion of soil is also strongly dependent on soil moisture content, increasing rapidly with decreasing soil water content. The level of friction between the soil particles is also dependent on soil water content and increases as surface tension builds up in the meniscus of water between the soil particles. Apart from water content, compactness of soil material also influences soil strength, since both cohesion and friction increase as soil particles get closer to each other.

The cohesion of soil is the shear stress that causes failure at zero normal load. The shear stresses needed to cause failure are generally accepted as being linearly proportional to the applied normal load. The relationship is expressed by the following formula:

$$\tau = c + \sigma \tan \phi, \quad (1)$$

where τ (kPa) is the shear stress needed to cause failure, c (kPa) is cohesion of the soil, σ (kPa) is the applied normal stress and ϕ is the angle of internal friction of the soil.

Stress-strain relationships describe the strength of materials. Stress is a vector quantity, determined by the force acting on a surface. Stress applied to a point can be divided into six components, three tangential (shear) stresses parallel to the surface they act on, and three normal stresses acting perpendicular to the surface. Each of the tangential and normal stresses is perpendicular to both other tangential and normal stresses, respectively. Strain is the amount of deformation upon stress application. Strain of solid bodies can be either fully elastic, plastic, or have a component of both behaviours. Elastic bodies retain their original shape immediately as the stress is relieved, while plastic bodies remain deformed.

Describing soil strength using models for idealized solid and fluid materials is difficult, since most assumptions of established models are not met for soil. Soil is structurally heterogeneous and anisotropic regarding strength, in comparison to solids such as metals and fluids such as water. Soil exhibits a combination of elastic and plastic behaviour, strongly dependent on water content and textural and mineralogical composition. Thus, failure of soil upon stress application can be of a different nature for a given soil depending on soil water content, and for specific water contents depending on soil composition. As a result, soil strength is often characterized by empirical non-comparable or interchangeable methods. Penetrometers, vane shear apparatus and oedometers are common tools for characterizing soil strength.

Measuring penetrometer resistance is perhaps the most widely used method in both field and laboratory assessments of soil strength. The method has been used to predict *e.g.* trafficability and root growth, to identify strong soil layers and to compare degrees of soil compaction due to different soil management strategies. The penetrometer consists of a rod fitted with a cone, usually somewhat larger in diameter than the rod, at one end. The cone is pushed into the ground while recording the force needed to maintain a constant rate of penetration (Fig. 1). Penetrometer resistance is then taken as the force recorded divided by the base area of the cone.

Penetrometer resistance is a complex variable depending on several soil mechanical processes and parameters of the soil. As the probe penetrates the soil, it deforms the soil creating a cavity. The failure of the soil ahead of the penetrometer cone may occur in different ways. In moist soil, plastic flow is common, while in dryer soil shear or tensile failure may occur. In addition to soil cohesion and soil internal friction, soil-to-metal friction also adds to the force needed to push the penetrometer into the soil at a constant rate. Bengough & Mullins (1988) found that much of the difference between penetrometer and root resistance to penetration was accounted for by the higher component of friction on the penetrometer. Rotating the probe while pushing it into the soil reduced soil-to-metal friction and resulted consistently in large drops in resistance, suggesting that at least half the resistance to a blunt penetrometer is frictional (Bengough & Mullins, 1988). That, however, does not account for all of the difference between penetrometer and root resistance to penetration. Experiments have shown that in homogeneous material, the resistance encountered by penetrometers is somewhere between 2 and 8 times higher than that encountered by roots (Whiteley, Utomo & Dexter, 1981). Differences in modes of deformation of soil by penetrometers compared to roots also contribute to the deviation. Deformation of soil by the blunt penetrometers commonly used is mainly spherical, while deformation by roots is cylindrical with a small spherical component.

Vane shear tests have the same field of application as the penetrometer. The apparatus consists of a rod to which blades are attached. The rod is inserted into the ground and the torque required to turn the rod and shear the soil is recorded (Fig. 1). The area on which shear failure has occurred is known and the force

needed for failure is calculated from the recorded torque (T). Torque (Nm) is related to soil cohesion and the size of the vane according to:

$$T = c\pi\left(\frac{1}{2}d^2h + \frac{1}{3}d^3\right) \quad (2)$$

where c (Pa) is cohesion of the soil, d is the diameter of the vane (m) and h (m) is the height of the vane. The height of the blades of a standard vane shear apparatus is 4 times their width, so that the cylinder of soil that it rotates has a height-radius ratio of 4:1. The above formula can then be simplified so that soil cohesion can be calculated as follows:

$$c = 3T / 28\pi r^3 \quad (3)$$

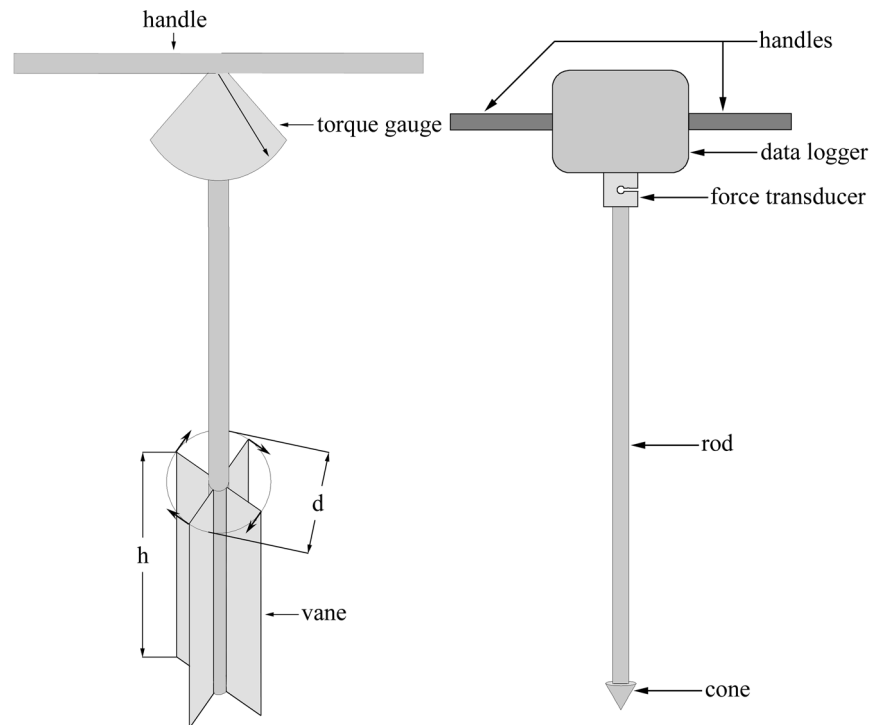


Figure 1. A vane shear apparatus to the left and a penetrometer to the right. Both devices are gripped by their handles, but while the penetrometer is pushed into the ground while measuring, the vane shear apparatus must first be driven into the ground to the depth of interest and then turned, as indicated by the arrows on the vane, while recording the maximum torque on the gauge.

The use of penetrometers and vane shears to assess the strength of the soil is not likely to find the planes of weakness established by shrinkage or the low-resistance pathways in empty root channels (Russel & Goss, 1974). The two mechanical devices work on a different scale compared to that of root channels and are

inflexible. Penetrometers are pushed straight into the ground following a straight line, whether this is the easiest way or not, away from the position of the probe apex. Vane shears create failure of the soil at a pre-determined surface regardless of the orientation, location and shape of planes likely to fail by natural stresses. Despite the weaknesses associated with the apparatus, the measurements produced by the penetrometer show good correlations to root growth and increased degree of soil compaction. However, it is important to note that the resistance to penetration of a penetrometer compared to that of roots is at best correlated and is definitely not identical (Russel & Goss, 1974).

Oedometers are used to determine the loading capacity of a soil without inducing further compaction, often called the pre-compression stress. A usual method is the uniaxial compression test, where a confined cylindrical soil core is loaded with vertical stress in increments while the vertical strain of the soil core is measured. Each level of stress is maintained for a certain period of time before the load is increased. The duration of loading is somewhat arbitrary, since to find the absolute pre-compression stress as defined it would have to be infinite. However, for different purposes different loading times are used. Typically, a 24 hours per load increment is used for construction engineering purposes and only 30 minutes for agricultural soil mechanics (Keller *et al.*, 2004). Plotting the logarithm of applied stress against measured strain gives a curve from which two linear parts can be detected. These two lines are called the re-compression line and the virgin compression line and the level of applied stress corresponding to the intersection of these lines is the pre-compression stress. Several methods to determine the pre-compression stress from uniaxial compression test data are in use, but the standard method is the graphical method developed by Casagrande (1936).

Pre-compression stress is a concept that is subject to some discussion. Its definition assumes a distinct stress value below a strain that is fully elastic and no remaining compression occurs. Determining that specific value is difficult with the methods currently available and the data suggest that instead of a distinct threshold value, a continuous change of soil behaviour occurs in a rather narrow interval. As for all measures of soil strength, pre-compression stress is also strongly dependent on soil water content, as well as mineral composition and compaction history.

Soil compaction

Traffic on arable land is typically associated with cultivation, *e.g.* tractors pulling implements for soil cultivation, sowing, spreading of fertilizers and pesticides, machinery for harvesting and transport of crops from the field. The draught force required for these operations has to be transferred to the soil either via air-filled rubber wheels or via rubber or steel tracks. All methods of transferring draught force to the ground inevitably mean that horizontal (shear) stresses are added to the soil. The weight of the machinery adds vertical stresses to the soil. If the stresses exceed soil strength, failure of the soil occurs and results in unsaturated soil being compacted. Compaction of unsaturated soil is by definition a decrease in the air-filled porosity, *i.e.* a bulk density increase due to a volume reduction at the

expense of air. In saturated soil, volume is reduced as water is expelled from the soil matrix, a process known as consolidation.

Root growth

Root systems

Angiosperms are the plant group of major importance for agricultural use. The angiosperms can be divided into two subclasses, monocotyledons and dicotyledons. Anatomical and physiological differences between these groups are found in most plant organs, in the shoot as well as the root system.

In dicotyledonous plant roots, a cylinder of meristematic cells, called the vascular cambium, develops between the phloem and xylem. By cell division and differentiation, it inwardly gives rise to secondary xylem and outwardly to secondary phloem. This provides the roots of dicotyledons with the capacity for large increases in girth and, thereby, in strength. Dicotyledons also form another zone of meristematic cells in the pericycle, the cork cambium, at about the same time. The cork tissue produced surrounds the mature root and protects it from damage. The monocotyledons have neither vascular nor cork cambia (Fig. 2). For this reason the roots of grasses are approximately uniform in size along their length, in each species, and are not protected by an outer bark (Elowson, 1994; Forbes & Watson, 1992).

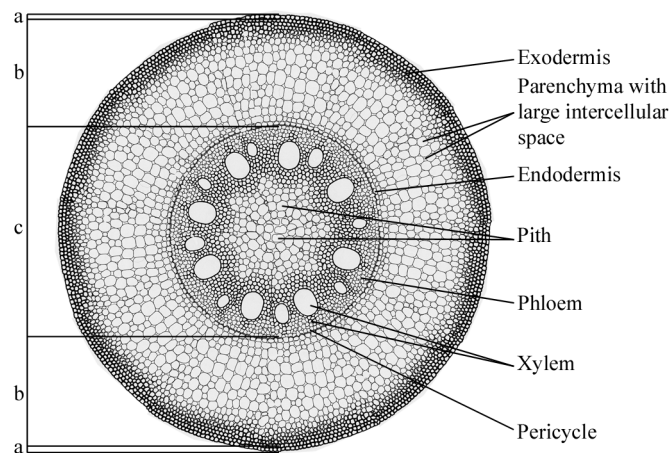


Figure 2. Cells of a monocotyledon root cut in transverse section. (a) epidermis, (b) cortex and (c) stele. After Elowson (1984).

The patterns of root growth differ among species, but some major groups can be detected. Again there is a big difference between monocotyledons and dicotyledons. Seminal roots, derived from the radicle in the seed, and adventitious roots, growing from the basal nodes of the shoot, build up the root system of a monocotyledonous plant (Elowson, 1994). In cereals, the seminal roots are usually those that explore the greatest depth of the soil profile, while the adventitious roots

proliferate in the upper parts of the soil (Forbes & Watson, 1992). The seminal roots are not very branched, while the adventitious roots usually are.

The dicotyledonous root system typically consists of a vertically growing main root, called the taproot, derived directly from the radicle, and lateral roots, of smaller diameter and much more branched than the taproot, growing semi-horizontally out from it (Forbes & Watson, 1992). These are the basic constituents of a dicotyledon root system, but the morphology of these components can differ substantially. Biennial and perennial species, for example, often have a thickened taproot, which besides serving as anchorage, an absorbing and transporting organ, and a producer of growth regulators, also serves as a storage organ for carbohydrates. Nonetheless, the taproot is the part of the root system that grows to the greatest depth, and is therefore of interest for the penetration of the subsoil. The fact that the taproot also has the largest diameter makes it even more important for the creation of large continuous biopores, effective in water transport and soil aeration (Mitchell, Ellsworth & Meek, 1995).

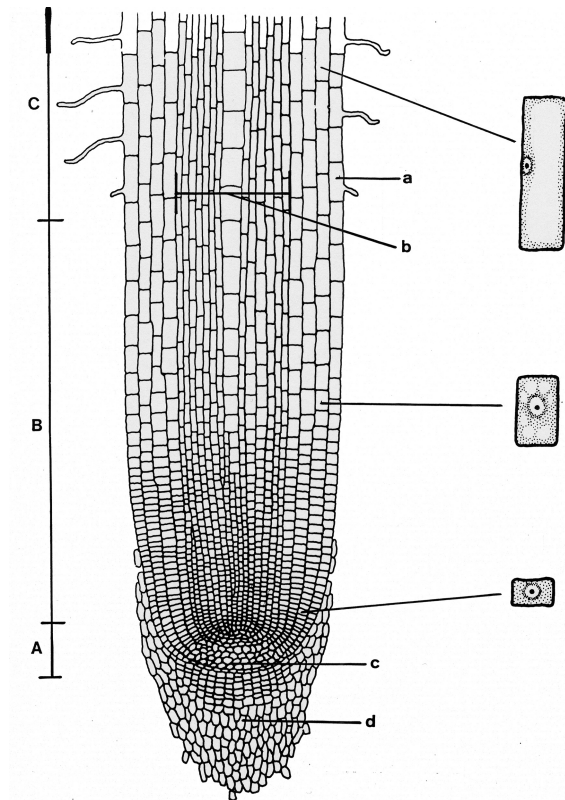


Figure 3. The zones of (A) cell division, (B) cell elongation and (C) cell differentiation in a longitudinal cut of a maize root. (a) epidermal cell with a root hair, (b) stele, (c) apical meristem and (d) root cap (calyptra). Notice the cell vacuolation process during cell elongation. From Elowson (1984).

The root elongates from its apical end (Fig. 3). A region of meristematic cells, found just a few cell layers from the extreme apical end, is the origin of all root cells contributing to its length. This meristem gives rise to the root cap (calyptra), epidermis, cortex and stele. The root cap is situated at the root's most apical end, and its cells are sloughed off as the root elongates through the abrasive soil. New cells are continuously produced in the meristem just behind the root cap and added to it. The main functions of the root cap in growing roots are usually regarded as being to protect the meristem, and to lubricate the surface of the root by exuding mucilage and sloughing of cells (Bengough & Mullins, 1988). Additional functions have been proposed, *e.g.* a role in the regulation of root growth rate as affected by mechanical impedance (Bengough & Mullins, 1990).

There is a small group of quiescent meristematic cells just beneath the root cap, the function of which is relatively unknown (Forbes & Watson, 1992). The cells occasionally divide and give rise to rapidly dividing meristematic cells, which build the main body of the meristem, and in this way seem to regulate the cell division in the meristem.

Following the zone of cell division, there is a zone of cell elongation. In that region the cells added to the columns of epidermal, cortex and stele cells undergo vacuolation, increasing their length and diameter. After elongating the cells differentiate into the typical cell type associated with the specific location. At this point cell elongation stops, and the cells have thereby reached their final length. Root elongation is therefore mainly confined to the root tips, since only the apical 10 mm or so of the root participates in elongation (Forbes & Watson, 1992).

Cell elongation is driven by turgor pressure in the cell vacuole, pressing the protoplast against the cell wall (Bengough, Croser & Pritchard, 1997). Turgor pressure (P , kPa) is determined by the osmotic potential (π_i , kPa) inside the cell vacuole and the osmotic (π_o , kPa) and matric potential (ψ , kPa) outside the cell:

$$P = \psi + \pi_o - \pi_i, \quad (4)$$

The magnitude of any potential drop needed to provide a flow of water into the root is thereby neglected (Greacen & Oh, 1972). In order for the cell to elongate, turgor pressure must exceed the resisting cell wall yield pressure (Y , kPa) beneath which no elongation can occur.

Lockhart (1965) describes the elongation rate (dl/dt , $m\ s^{-1}$) of cylindrical cells, assuming that water permeability of cells does not limit cell expansion, by the equation:

$$\frac{dl}{dt} = lm(P - Y), \quad (5)$$

where l (m) is the length of elongating tissue, m is the cell wall extensibility factor ($\text{m m}^{-1} \text{kPa}^{-1} \text{s}^{-1}$), t is time (s) and the other parameters as stated above. His equation has since been modified to include the resisting pressure offered by the confining soil (σ , kPa), so that:

$$\frac{dl}{dt} = lm(P - Y - \sigma) \quad (6)$$

(Greacen & Oh, 1972; Greacen, 1986).

In order to penetrate homogeneous soil, roots have to deform it. Time-lapse photography of soil movement near the root tip and X-ray studies of soil density patterns around cavities made by roots show that the type of deformation is almost cylindrical, with a small spherical component in the vicinity of the apex (Greacen, 1986; Fig. 4). The pressure required for cylindrical deformation of the soil is less than 50% of the pressure required for spherical deformation (Greacen, Farrel & Cockroft, 1968; Abdalla, Hettiaratchi & Reece, 1969). Abdalla, Hettiaratchi & Reece (1969), assuming only elastic strain, showed that radial enlargement of roots would create a stress relief in the axial direction.

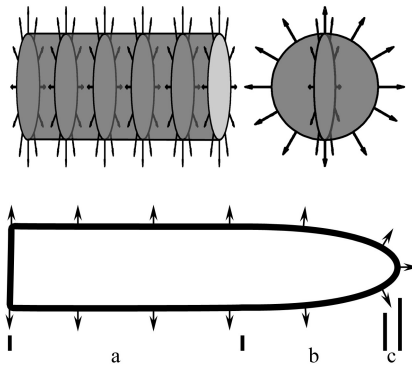


Figure 4. Roots deform soil both cylindrically and spherically as they penetrate the soil. As indicated by the arrows, growth forces are applied to the soil normally to the root surface. The soil around the root deforms in the different regions by (a) cylindrical expansion, (b) mostly by cylindrical expansion but with a small component of spherical expansion and (c) by spherical expansion.

Responses to increased mechanical impedance

Generally, mechanically impeded roots are shorter, thicker and more branched than unimpeded roots (Bennie, 1991). Therefore the total root volume of plants is usually less affected by mechanical impedance than total root length (Drew & Goss, 1973). Consequently, this results in a root system exploring a smaller volume of soil, to a shallower depth. However, as found for soybean by Bushamuka and Zobel (1998), individual root types within a root system may respond differently to compacted soil.

Decreasing rate of elongation of roots

Increased mechanical impedance reduces root elongation rate (Glinski & Liepiec, 1990). Both the length of the elongating zone and the final cell length decrease upon mechanical impedance. Total cell volume is usually less affected, however, since the reduction in cell length is almost totally accounted for by an increased cell diameter (Bengough, Croser & Pritchard, 1997). A major part of the reduction in root elongation rate is thereby accounted for by the increased cell diameter. Decreases in cell flux rate, *i.e.* the number of cells produced and added on to a cell column, have also been shown for several plant species and augment the reduction in root elongation rate (Bengough, Croser & Pritchard, 1997).

The influence of the root cap on root elongation rate in a compacted media has been investigated by Goss & Russel (1980). Root elongation rate was measured on roots grown in compacted sand and compared with the performance of normal roots and roots that had had their root caps removed. Measurements were also made on roots experiencing a minimum of mechanical impedance. The elongation rate of roots without caps did not decrease upon mechanical impedance, while that of the normal roots did, suggesting a role for the root cap in the response of roots to mechanical impedance.

Growth pressure (σ_r)

The ability of roots to increase the growth pressure when encountering increased mechanical impedance has been recognized by several researchers and different attempts to explain this phenomenon have been made (Greacen & Oh, 1972; Misra, Dexter & Alston, 1986; Clark *et al.*, 1996). Turgor pressure has been observed to be affected by soil water potential and mechanical impedance, and also to vary along the axis of roots (Atwell & Newsome, 1990; Spollen & Sharp, 1991). Greacen and Oh (1972) suggest that plant roots might 'osmoregulate', *i.e.* increase turgor pressure by decreasing internal cell water potential. They found an osmoregulating efficiency of 70% in peas. The term 'osmoregulation' infers that this is an active process triggered by increased mechanical impedance, but later studies indicate that the decreased water potential is merely a passive process. As root elongation is impeded while import and breakdown by metabolic processes continues, a passive build-up of solutes is likely, since volume enlargement is inhibited (Atwell, 1988).

Another explanation, not necessarily mutually exclusive, is that the cell wall yield stress and extensibility factors might be functions of the mechanical impedance experienced by the root tip. These factors are known to change with cell age, since cells recently divided from the apical meristem show lower resistance to elongation than cells in the end of the elongation zone, where the cell wall extensibility approaches zero. Experiments using probes to measure turgor pressure have shown increases in growth pressure while turgor has remained unchanged (Clark *et al.*, 1996). This has led to the conclusion that cell wall extension properties play a major role in root elongation in impeding media. Bengough, Croser & Pritchard (1997) present results strengthening that hypothesis from measurements of the cell osmotic potential of mechanically impeded roots.

They found that, after the pressure was removed, osmotic potential returned to that of unimpeded roots within hours. However, the elongation rate did not return to that of non-impeded roots for several days. Considering the Lockhart equation (5), this implies the influence of changes in m or Y .

Measurements of maximal root growth pressure (σ_{\max}) have shown that there is no significant difference between species in that variable. Some authors propose the possibility of differences between monocotyledonous and dicotyledonous plants in this ability, but experiments by Clark & Barraclough (1999) showed no such differences. Furthermore, σ_{\max} has been shown not to be dependent on root diameter. Differences in growth force can occur, however, since root diameter differs significantly between species. Large root diameter has been suggested as an indicator for species likely to have a superior ability to penetrate compact soil (Materechera *et al.*, 1993; Whalley & Dexter, 1993).

The swelling behaviour of roots

Plant roots commonly swell radially as a response to compressive forces (Bengough & Mullins, 1990). It has been observed that as root elongation rate decreases upon increased mechanical impedance, most of the reduction in root elongation rate can be accounted for by a reduction in final cell length, the cell production rate being practically unchanged. Measurements have shown that cell volume usually remains virtually the same, decreased cell length being compensated for by increased cell diameter. An induced production of additional cell columns has also been identified as being responsible for contributing to the increased diameter of mechanically impeded roots (Wilson, Robards & Goss, 1977), but others *e.g.* Atwell (1988) found little or no proliferation of new cell columns in lupin roots. The increased diameter was generated by increased cortical thickness; the tangential and radial cell walls yielded (Fig. 5). The diameter of the stele remained unaffected by degree of compaction. It is interesting to note that Atwell (1988) also measured up to 50% higher values of cell volume in impeded lupin roots.

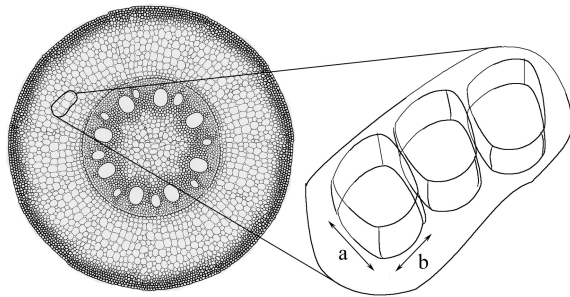


Figure 5. Root girth may increase by yielding of (a) radial and (b) tangential cell walls. After Elowson (1984).

For a single cell, the shape depends on the relative stiffness in different directions of the cell wall. If this stiffness were uniform in all directions, the cell would be spherical. This is not the case, however, since root cells even in roots grown in totally unconfined conditions are more or less cylindrical. This is because the cell walls are much stiffer in the direction perpendicular to the cell axis. The reason for this is not well understood, but the orientation of microfibrils and the rate of making and breaking of tethers between them are involved (Pritchard, Jones & Tomos, 1991; Passioura & Fry, 1992; McCann & Roberts, 1994). Adaptive responses of cell wall properties to mechanical impedance might favour radial thickening of roots. In mechanically impeded roots, Veen (1982) observed that microfibrils had been laid down longitudinally, thereby facilitating radial expansion.

Externally applied pressure also contributes to the shape of roots. A purely axial force applied to a root tip may for example result in a relatively large radial expansion (Bengough & McKenzie, 1994). In the soil, the distribution of pressure is normally more balanced, but rather large diversions from uniformity occur as the root tip encounters compacted layers and cracks, *etc.* In a very strong soil, given enough turgor pressure, the balance of cumulative forces of soil resistance and cell wall stiffness might shift more to the side of cylindrical deformation and radial enlargement.

The shrinking behaviour of roots

To penetrate soil, roots must either use existing pores larger than their nominal diameter or create their own pores by moving soil aside. Wiersum (1957) states that roots are unable to enter rigid pores smaller than their nominal diameter, but views on this issue have changed since experiments by Scholefeld and Hall (1985) showed that roots of *e.g.* perennial ryegrass were able to do just that. They found that when the ryegrass root entered a pore smaller than itself, the thickness of the cortex decreased while the diameter of the stele was unchanged. The smallest pore size possible to penetrate was decided by the diameter of the stele. Recent research has shown contradictions to these results, *e.g.* where stele diameter was also decreased (Bengough, Croser & Pritchard, 1997). However, the function of these roots with decreased stele diameter can be questioned since the conducting area of xylem vessels is thereby decreased.

Proliferation of laterals

Crosset, Campbell & Stewart (1975) showed that loss of apical dominance causes lateral roots of cereals to proliferate. Proliferation of laterals due to compaction has been observed in several species, *e.g.* in barley (Goss, 1977). On the other hand, Atwell (1988) found little or no proliferation of lateral roots due to compaction in lupin. This might indicate a differential response between monocotyledonous and dicotyledonous plants. Goss (1977) recognized a shift of the zone of lateral root growth further to the apex of the main axis upon compaction. That might simply be a consequence of the reduced cell length commonly observed in mechanically impeded roots and thus the age of the cells initiating lateral root growth may be the same as that of those in unimpeded roots.

The initiation of laterals is believed to be closely controlled by growth substances, and thus as mechanical impedance seems to affect the production of laterals, it is likely to influence the production or action of these substances (Russel and Goss, 1974). As root axes are forced to bend, initiation of lateral roots typically occurs on the convex side (Goss & Russel, 1980).

The role of plant hormones

The action of plant hormones has been proposed as a key to plant responses to mechanical stress. Grafting experiments have shown that sap from impeded plants reduces growth of unimpeded plants. When a root grows from compact soil into looser soil, it does not immediately regain the elongation rate of roots grown entirely in loose soil (Bengough & Young, 1993). This lag-time, which may extend for several days, implies an influence of growth regulators, since purely physical responses to decreased mechanical impedance would have been more or less instant.

No specific chemical substance has been identified as being responsible, although ABA (abscissic acid) has been mentioned as a possible messenger substance. Tardieu (1994) concluded that ABA may not play a significant role in this. Ethylene has also been mentioned in the discussion and possible evidence both for and against the role of ethylene has been presented. As yet, no convincing evidence regarding the substances and mechanisms involved has been presented.

Root growth in strong and heterogeneous soil

The growth of roots in a strong heterogeneous field soil is very different from the common situation in the laboratory, using homogenized soil compacted to a certain degree. Cracks, earthworm tunnels, root channels and compacted layers complicate the picture. Plant roots are flexible organs that follow the path of least resistance.

Experiments by Dexter (1986b,c) show no preferential growth of roots towards either cracks or round pores, except possibly for low oxygen availability conditions. Pure random direction of growth would, however, lead to roots encountering both cracks and holes. The likelihood of a root entering the cracks or pores is a function of crack width and pore diameter (Dexter, 1986b,c), respectively, while for cracks, the angle of approach is also of significance (Dexter, 1986b).

The effectiveness of roots penetrating largely unimpeded in existing pores and cracks is questionable, since the low root-soil contact decreases the ability to extract water and nutrients from the surrounding soil (Fig. 6). Furthermore, the possibility of roots exiting pores and cracks is limited since the angle of incidence usually favours deflection from the wall rather than penetration, at least for the tip of the main root axis (Whiteley, Hewett & Dexter, 1982). Laterals stand a better chance since they extend more or less at right angles to the main axis (Dexter,

1986a). On the other hand, they are usually thinner and therefore more prone to buckle.

Differences exist between species in their ability to penetrate strong soil. Bennie & Burger (1981) hypothesize that the ability to establish a root system in strong soil is directly proportional to the ability of the species to do so under non-constricted circumstances. Materechera *et al.* (1993), comparing faba bean, lupin, pea, safflower, barley oats, ryegrass and wheat, found evidence opposing that hypothesis. Materechera, Dexter & Alston (1991) and Materechera *et al.* (1992) found that dicotyledons penetrate strong soil better than do monocotyledons. They attributed the greater ability of the dicotyledons to their larger increase in diameter.



Figure 6. Lucerne roots growing down a vertical soil crack. A high concentration of roots in cracks from which they are not likely to exit, since they grow in the direction of least resistance, may be of limited use to the crop.

The above investigations have been carried out under laboratory conditions, but under field conditions other factors come into play. Soil water content varies during the growing season and, as a consequence of this, soil strength also varies. Roots able to use the periods of low soil strength for extensive growth have an advantage over roots lacking that ability. In Sweden, spring and autumn are the moist periods of the growing season and bearing this in mind, perennial species and winter annuals might be advantageous, as they start growing early and already have established a root system. Species with a long growing season and long total life span might also penetrate deeper into the soil.

Plant roots, soil structure and compaction

Plants have no need for soil structure *per se*. For their growth, plants need light, carbon dioxide, oxygen, water, a number of mineral nutrients and temperature within an acceptable range (Taylor & Brar, 1991). The roots govern the uptake of water, minerals and oxygen. Roots also contribute to the survival of plants by supplying anchorage, making it possible for the plant to maintain an upright position and preventing involuntary transfer to areas less favourable for plant growth. In essence, plants could be grown hanging on a clothesline as long as light, carbon dioxide, oxygen, water and mineral nutrients were provided in the right proportions. However, as most agricultural crops are grown in fields, favourable soil structure is essential for promoting root growth and uptake of water and nutrients.

When soil is compacted, its bulk density increases. It is mostly the larger pores present that are compressed (Hillel, 1980) and these are the pores most effective in draining the soil. Gas exchange between soil and atmosphere is much less dependent on the size of the individual pores and is instead directly proportional to the air-filled porosity and tortuosity, but as the volumetric proportion of water in the soil usually increases at the expense of air-filled porosity in compaction-damaged soil, gas exchange is strongly affected by soil compaction. Increasing the hydraulic conductivity of the soil, *i.e.* by increased drainage, best maintains sufficient gas exchange.

The effects of compaction of the topsoil can lead to large decreases in yield, but they are generally eliminated by natural processes and/or tillage within one or up to five years from the compaction event (Håkansson, 2000). Subsoil compaction is more persistent and may lead to permanent yield losses if left unremediated (Håkansson & Reeder, 1994).

To counteract the negative effects of subsoil compaction, changes must be made to soil structure. Loosening of the soil decreases bulk density, *i.e.* reduces compaction. Bulk density, however, does not give any information on how the soil has been loosened. In most cases when soil has been loosened mechanically, it yields in its weakest planes, while the resulting aggregates retain their initial degree of compaction or may even be further compacted (Arvidsson & Dexter, 2002). The proportion of large pores increases drastically during soil loosening, thereby increasing hydraulic conductivity. However, the ability of roots to enter aggregates does not increase to the same extent since the compaction of aggregates is not likely to be decreased. Thus, the aim should not be to return soil structure to its state prior to compaction, but to create a soil structure favourable for plant growth under as large a range of climatic conditions as possible.

Roots alter soil structure by pushing aside soil when they grow, creating new continuous pores that affect both hydraulic conductivity and gas flow. Different species are different in their response to increased resistance to penetration. Roots of more adaptable species can cause changes to soil structure by penetrating the soil and can thus increase the fertility of poorly structured soils.

Mitchell, Ellsworth & Meek (1995) found that channels left by decaying roots of lucerne increased hydraulic conductivity in swelling soils, but that the conductivity decreased as decay advanced beyond a point when the remaining root parts failed to keep the root channel from collapsing. Kuht & Reintam (2002) found that penetration resistance was lower in the subsoil of treatments with creeping thistle (*Cirsium arvense* L.) compared to treatments with grain crops. Alakukku (1998) found that saturated hydraulic conductivity and macroporosity increased in the upper part of the subsoil in a crop rotation with perennial crops.

Thesis work

This thesis is based mainly on the results of two series of laboratory experiments (I, II) and four field trials (III, IV and V) carried out during the period 1998 to 2004.

Screening roots for effective penetration

Two methods were tested to evaluate the possibility of finding species more likely than others to penetrate strong soil layers by means of rapid and simple laboratory experiments.

Experiment 1 (Paper I)

Barley (*Hordeum vulgare* L.), chicory (*Cichorium intybus* L.), lucerne (*Medicago sativa* L.), lupin (*Lupinus luteus* L.) and red clover (*Trifolium pratense* L.) were grown in sand contained in plastic tubes (152 mm inner diameter, 450 mm length) (Fig. 7). To simulate a hard pan, wax layers (145 mm diameter, 3 mm thick) were placed at 50 mm depth in the sand column. Two kinds of wax layers were prepared, hereafter referred to as 'hard' and 'soft', by melting together white soft paraffin and pastillated paraffin wax in proportions to give the desired strength.

Hard wax layers contained 80% paraffin wax and soft wax layers contained 3% paraffin wax, used as a control to the hard wax layers. The resistance to penetration of the soft wax layers was 0.06 MPa; the corresponding resistance of the hard wax layers was 1.78 MPa, as measured by a 30° semi-angle stainless steel penetrometer with a cone base diameter of 2 mm and a relieved shaft. The penetrometer resistance was taken as the maximum force recorded while pushing the penetrometer through the wax disc at a constant rate, divided by the cross-sectional area of the base of the cone.

The tubes were placed in plastic water tanks to enable an approximately constant watertable to be maintained. The watertable was set to 300 mm below the top of the sand columns by pouring nutrient solution into the tanks. The plants were grown in a controlled environment with day and night temperatures of 25 and 18 °C, respectively, with a day length of 16 hours. Day and night-time relative humidity was 60 and 65%, respectively.

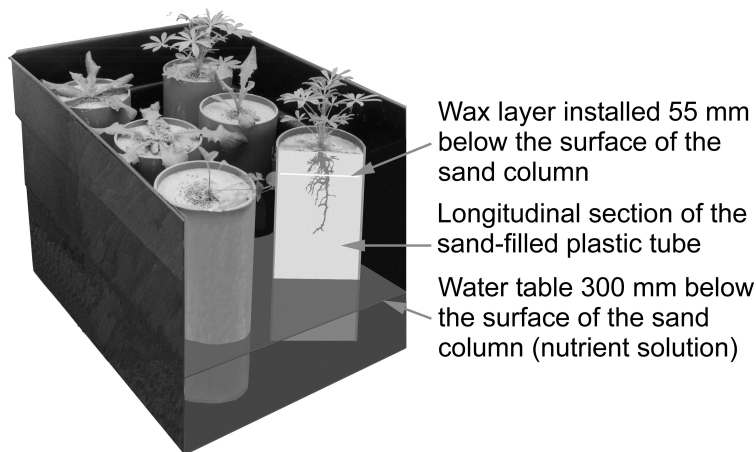


Figure 7. Schematic diagram showing the root growth environment.

Five weeks after planting the seedlings, each experiment was harvested. The number of root axes that had penetrated each wax layer was counted, as was the total number of root axes. In barley, the only monocotyledon in the experiment, both seminal and nodal root axes were counted. In the dicotyledonous species, separate counts were made of the number of taproot axes, adventitious and lateral roots that had penetrated the wax layers.

In Paper I, moist quartz sand was used instead of natural soil and the wax layer was inserted to simulate a hardpan. The cohesiveness and heterogeneity of natural soil are the main differences between quartz sand and natural soil. Using sand and wax instead of soil made the experiment easier to replicate and enabled rapid and straightforward measurements. Sand lacking the strength of cohesive soil facilitates the rinsing of roots, but it might put the anchorage of roots at risk, leading to plants lifting when encountering a strong layer in the growth medium. In our experience, however, a 50 mm layer of moist sand was sufficient to anchor the plant. No lifting of plants was observed in our experiment and earlier observations were that seedling roots only a few centimetres long tended to break rather than emerge when plants were pulled up too fast. Experiments by Clark, Aphale & Barraclough (2000) using this method featured some rice varieties having a penetration of 70%, so anchorage was clearly sufficient to withstand penetration of the wax layer.

Buckling or deflection was probably the most common reason why roots failed to penetrate the wax layer in Paper I, rather than impeded root elongation. As rooting is determined by many characteristics of the roots and the growth medium, it seems appropriate to assume that several of these characteristics influenced the results of the test. Increased knowledge of the main reasons why roots fail to penetrate hard pans in real soil may require changes in the method. If *e.g.* resistance to elongation is the main reason why roots fail to penetrate, weights might be put on top of the sand to increase the strength of the growth medium.

Barley had the greatest number of root axes that penetrated the hard wax layer (Fig. 8A), but this was simply due to the large number of root axes produced by barley. An individual barley root axis actually had a low chance of penetrating a hard wax layer: the fraction of the total barley root axes that did penetrate the hard wax layer was the smallest of the species tested (Figure 8B). The strength of the wax layer affected the penetration of root axes of lucerne the least, although there was no significant interaction between the dicot species and wax strength.

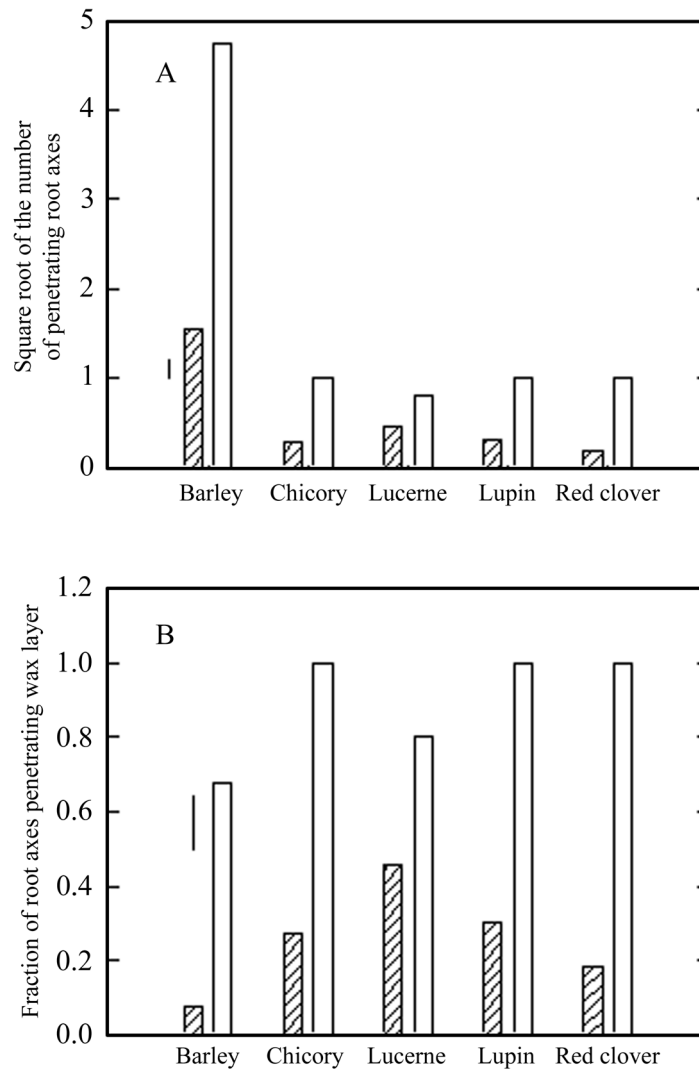


Figure 8. (A) The square root of the number of root axes (data were square-root transformed before analysis to stabilize the variance) and (B) the fraction of root axes that penetrated the hard wax layers (hatched bars) and soft wax layers (plain bars) for five crop species. The standard error of differences is shown (95 d.f.).

Similar results were obtained when all penetrating roots, including laterals, were considered (Fig. 9). The ANOVA of these data revealed a significant interaction between wax layer strength and the dicot species, which reflected lateral root penetration of soft wax layers by lupin and red clover roots.

Expressing root penetration as a fraction of the total number of roots under consideration as in Figure 8B has the possible disadvantages that it may not take into account whether these roots actually reach the wax layer (in the case of barley) or whether the roots react adversely to the hydrophobic wax layers. This can be addressed by expressing root penetration of hard layers as a fraction of root penetration of soft layers. This was done using the overall means for the different treatment combinations, both for root axes and all roots (Fig. 10). This shows that the penetration ability of lucerne roots was superior to that of the other species.

As found previously in different rice cultivars (Clark, Alphale & Barraclough, 2000) the assessment of 'good' performance in the wax layer screen depended upon the screening criterion used. For example, although barley had the greatest number of roots penetrating the hard wax layer, this was because it produced far more roots than the other species. Although the number of root axes of chicory, lucerne, lupin and red clover penetrating the hard wax layer was less than for barley (Fig. 8A), their success at penetrating hard layers relative to the soft controls was much higher (Fig. 10).

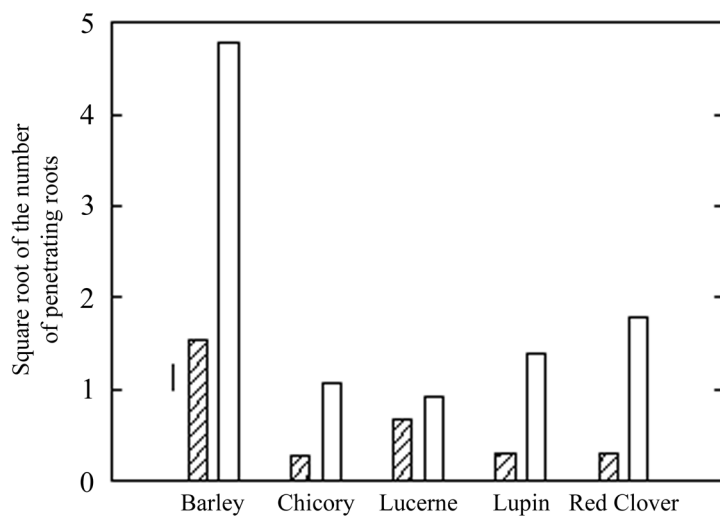


Figure 9. The square root of the number of roots (including laterals) that penetrated the hard wax layers (hatched bars) and soft wax layers (plain bars) for five crop species. Data on number of penetrated roots were square-root transformed before analysis to stabilize the variance. The standard error of differences is shown (95 d.f.).

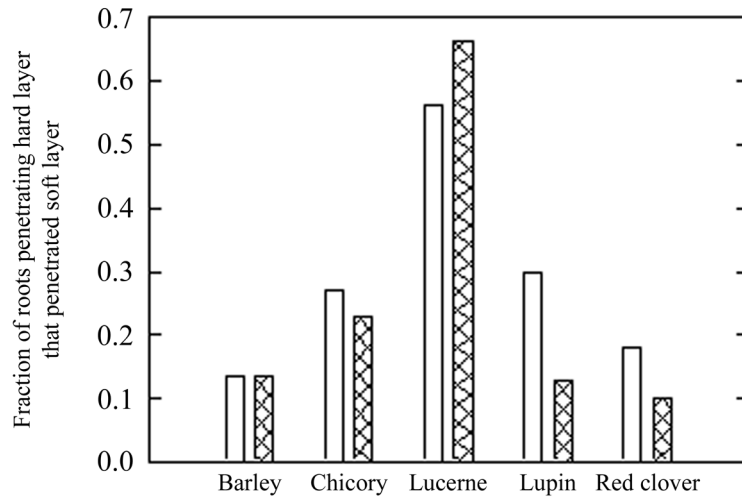


Figure 10. The fraction of the number of root axes (plain bars) and roots (including laterals, hatched bars) that penetrated the hard wax layers for five crop species. Fractions were calculated by dividing the mean number of axes or roots that penetrated the hard layer by the corresponding number that penetrated the soft layer.

Experiment 2 (Paper II)

A series of sub-experiments (Paper II) was carried out to develop and evaluate the method presented in Paper I. The first experiment (2.1) aimed at identifying the compaction levels that would best serve as a control level and a high compaction level. The second experiment (2.2) was carried out to test and confirm the results of the first experiment on a few different plant species and to study the effect of length of the growth period. The third experiment (2.3) was carried out to test the method for supplying water.

In Paper II, all sub-experiments included, plants were grown in soil contained in plastic tubes (400 mm long, 67 mm inner diameter). Each tube was split down the middle into two longitudinal sections to facilitate extraction of roots, and sand (0.1-0.45 mm mesh size) was glued to form a thin layer on the walls to reduce root growth along the casing walls (Löfkvist, Rydberg & Svantesson, 2000). Homogenized soil, at a water content of 20% by weight, was added to the tubes and compacted by a pneumatic cylinder successively in layers 1.5 cm thick. In experiments 2.1 and 2.2, the soil was a silty clay and plants were cultivated in a controlled environment with day/night temperature of 24 and 22°C, respectively, and a 16 h day length. The relative humidity was kept at 80%. Every second day, water was added to restore the initial weight of the lysimeter, to ensure that water availability did not restrict growth.

Experiment 2.1

Barley (*Hordeum vulgare* L.) was used as test crop for determining the vertical stresses to apply in order to get levels of compaction suitable for serving as control

and high compaction treatments. Four levels of compaction were used, produced by applying either 25, 100, 200 or 800 kPa stress to the soil. After a growth period of 8 weeks, leaf length, rooting depth and shoot and root dry weight were measured.

Leaf length of barley decreased with increasing levels of soil compaction. Both root and shoot dry weight decreased with increasing soil compaction above 200 kPa, as seen in Table 1. Rooting depth decreased with increasing levels of compaction above 100 kPa. In soil compacted by 25 and 100 kPa, there were no differences in rooting depth. However, low soil strength in the 25 kPa treatment resulted in poor anchorage so that plants could not maintain an upright position without help. Thus, compaction by a vertical stress of 100 kPa seemed more suitable for the reference compaction treatment.

Table 1. Leaf length, rooting depth, root and shoot dry weight of barley grown in lysimeters containing soil compacted by vertical stresses of 25, 100, 200 and 800 kPa, respectively. Means in each column followed by the same letter are not significantly different ($p < 0.05$)

Compaction (kPa)	Leaf length (cm)	Rooting depth (cm)	Root dry weight (g)	Shoot dry weight (g)
25	38.8 a	37.7 a	0.71 a	1.06 a
100	35.8 a b	37.8 a	0.69 a	1.11 a
200	31.8 b	30.8 b	0.63 a	0.89 a b
800	29.3 b	8.2 c	0.43 b	0.67 b

Large differences between levels of soil compaction facilitate the detection of effects of the treatment. However, too great a degree of soil compaction may impede growth too much. In the 800 kPa treatment, no root managed to grow even below 0.1 m depth, and this treatment was considered too compacted to allow a proper assessment of the comparative penetrating ability of roots of different crops. The effects of the 200 kPa treatment were more similar to that of 25 and 100 kPa than that of 800 kPa, and therefore 400 kPa was chosen as an intermediate level of vertical stress to apply as the compaction-limited treatment in further experiments.

Experiment 2.2

Two levels of applied stress (100 and 400 kPa), based on the results of experiment 2.1, were tested on tubes with barley (*Hordeum vulgare* L.), lucerne (*Medicago sativa* L.), lupin (*Lupinus luteus* L.) and unsown control tubes. However, since most of the earlier studies on the penetrative ability of roots have used growth periods of only a few weeks or less (e.g. Materechera, Dexter & Alston, 1991; Cook *et al.*, 1996), the age dependency of the capability to penetrate compacted soil within the species was also tested. Half the tubes were harvested after 5 weeks and the rest were allowed to grow for another 7 weeks. The same measurements were made on tubes of each growth period. Evapotranspiration was monitored during cultivation by weighing the growth tubes. Fresh and dry weights of the aboveground parts of all plants were recorded. Root length density was measured at four depth intervals.

Evapotranspiration decreased with increasing level of compaction for all treatments (Table 2). ANOVA indicated interactions between species and duration of growth period ($p \leq 0.0001$) on evapotranspiration. That is, the effect of duration of growth period on evapotranspiration was species-dependent. This, if caused by transpiration rather than evaporation, indicates differences in growth pattern between the species. Hence, comparisons of growth-dependent properties between seedlings of different species might not be valid for older plants.

Table 2. Evapotranspiration and the reduction of evapotranspiration due to compaction regime in the lysimeters containing the different species and in the unsown control tubes, for the five and twelve week growth period, respectively. Means in each row followed by the same letter are not significantly different ($p < 0.05$)

Applied stress (kPa)	Evapotranspiration (mm)							
	Barley		Lucerne		Lupin		Control	
	100	400	100	400	100	400	100	400
5-week treatment	91 abc	81 bcd	56 cd	46 d	124 a	94 ab	76 abcd	76 abcd
Reduction (%)	11		17		24		0	
12-week treatment	392 a	299 c	190 e	167 e	343 b	256 d	156 e	146 e
Reduction (%)	24		12		25		7	

Growth rate differed notably between the species used in Paper II (Tables 3 and 4). ANOVA showed interactions between species and level of compaction ($p \leq 0.001$) and species and duration of growth period ($p \leq 0.0001$) on shoot dry weight. Interactions were also found between species and duration of growth period ($p \leq 0.0001$) on root dry weight.

Table 3. Mean shoot dry weight, as affected by plant age and soil compaction regime for three plant species. Means in each row followed by the same letter are not significantly different ($p < 0.05$)

Shoot dry weight (g)	Barley		Lucerne		Lupin	
	100	400	100	400	100	400
5-weeks treatment	0.29 bc	0.26 bc	0.03 c	0.03 c	1.00 a	0.58 ab
12-week treatment	3.58 b	2.65 c	0.43 d	0.29 d	5.20 a	3.49 b

Table 4. Mean root dry weight, as affected by plant age and soil compaction regime for three plant species. Means in each row followed by the same letter are not significantly different ($p < 0.05$)

Root dry weight (g)	Barley		Lucerne		Lupin	
	100	400	100	400	100	400
5-week treatment	0.14 ab	0.09 ab	0.03 b	0.01 b	0.20 a	0.10 ab
12-week treatment	0.56 bc	0.28 d	0.51 c	0.24 d	1.16 a	0.70 b

Duration of the growth period should not be longer than necessary to minimize costs. On the other hand, as shown by the interactions between species and duration of growth period on evapotranspiration, dry shoot weight and dry root weight, plants have significantly different growth and development rates. Shortening the growth period would thus favour certain species at the expense of others. In the tubes with a growth period of five weeks, roots of lucerne had not penetrated the deepest soil layer even in the low impedance treatment, as

compared to the twelve-week growth period, where all species, though clearly impeded, could penetrate the compacted soil of the 400 kPa treatment. This indicates that the longer growth period may be needed to evaluate the ability of potential 'subsoiling' plants to establish a root system in compacted soil.

Adding water to the top of the growth tube was not compatible with the low infiltration rate in the compacted soil, and resulted in the upper part of the growth tube being much wetter than the rest of the soil column for a period of time following watering. Hence, soil strength probably varied with depth, the shallow soil layers being weakened by increased soil water content and the deeper part of the soil column strengthened by the water uptake of plant roots. Faster growing and highly transpiring species would be more strongly affected by that adversity. Thus, for the ability to use natural soil instead of washed and sieved sand as a growth medium, the watering procedure was considered to be an important problem to address.

Table 5 shows the root length density (RLD) for barley, lucerne and lupin at different depth intervals after 12 weeks of cultivation. ANOVA indicated interactions between species and level of compaction on average RLD below 10 cm depth ($p \leq 0.001$). There were no interactions when average RLD was considered over the complete growth tubes.

Table 5. Root length density (cm cm^{-3}) at different depth intervals for barley, lucerne and lupin grown in soil compacted by 100 and 400 kPa for twelve weeks. Means in each row followed by the same letter are not significantly different ($p < 0.05$)

Species Applied stress (kPa)	Barley		Lucerne		Lupin	
	100	400	100	400	100	400
Depth (cm)						
0-36	10.37 a	5.15 b	2.66 bc	0.80 c	3.18 bc	1.10 c
Reduction (%)	50 a		68 a		65 a	
10-36	2.09 a	0.04 c	1.36 b	0.28 c	1.21 b	0.04 c
Reduction (%)	98 a		79 b		97 a	

Barley had the highest RLD for both levels of compaction ($p < 0.05$) when the complete growth tube was considered. However, when the RLD depth distribution was analysed, roots of barley were observed to be concentrated to the upper part of the lysimeters. Higher levels of compaction exaggerated this feature; almost no roots were then able to penetrate below 10 cm depth. Lucerne had the lowest RLD for both levels of compaction. The depth distribution of lucerne roots, however, was more uniform, so that from 10 cm depth and downwards average RLD was significantly less reduced by increasing levels of compaction, 79% compared to 98% and 97% for barley and lupin, respectively.

This contradicts the suggestion by Bennie and Burger (1981) that a plant's ability to produce a root system in compacted soil is only a function of its ability to produce roots in non-stressed conditions. There are species-dependent differences in the ability to penetrate strong soil that might be used to improve the accessibility of the subsoil to weaker species.

Experiment 2.3

A new watering method was adopted and tested. The idea was to maintain a continuous supply of water that would prevent the occurrence of limiting variations in soil water tension and would also minimize variations in soil strength. Barley was grown in tubes containing sandy loam compacted by vertical stresses of either 100 or 400 kPa depending on treatment. During the growth period of 8 weeks, the lysimeters were placed on a sand table hydraulically connected to a constant-head water reservoir. The top of the soil columns was 1 m above the surface of the water reservoir. Soil water tension was monitored by tensiometers, connected to a logging device, installed at 0.06, 0.18 and 0.30 m depth in each soil column.

Soil water tension at 6, 18 and 30 cm depth is shown in Figure 11. Soil water tension was relatively constant during the growth period of two months, but tended to increase somewhat during the growth period. The largest deviation from the drainage equilibrium, set by the constant watertable depth of 1m below soil surface, did not exceed 7 kPa at any time during the experiment. That can be compared to the permanent wilting point, which is at -1500 kPa, and thus the plants should not have suffered from water deficiency during any part of the growth period. The watering procedure was considered to function well and minimized effects of differing water contents between the treatments. Liepec *et al.* (1988) used a similar watering system, but instead of controlling negative water pressure by drainage level, they used vacuum chamber connected to a pressure gauge, a vacuum switch and a magnetic valve. The difference in matric potential between start and termination of the experiments varied from 20 up to 170 kPa. Their experiments lasted from 8 up to 14 days.

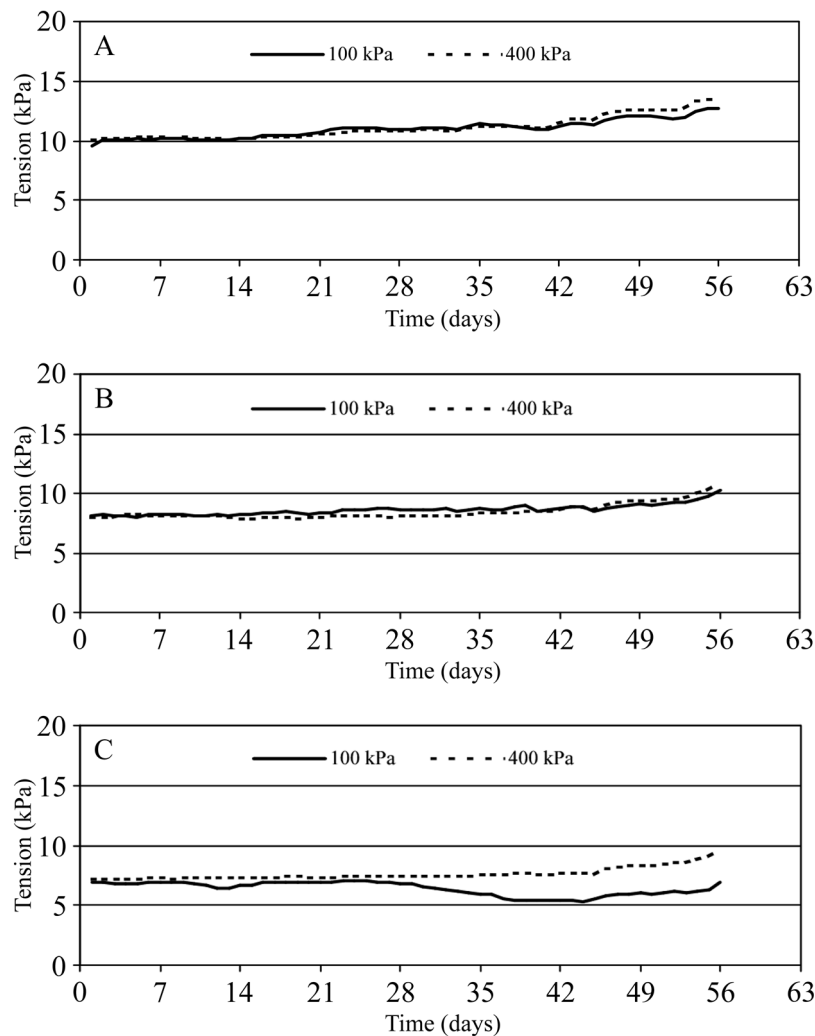


Figure 11. Soil water tension during cultivation of barley at (A) 0.94, (B) 0.82 and (C) 0.70 m above drainage depth, for treatments compacted by vertical stresses of 100 and 400 kPa.

Conclusions

Though constructed for similar purposes, the experimental setups of the screening methods used in experiments 1 and 2 are very different (I, II). The method used in experiment 1 was constructed with the simplicity and rapidity of laboratory procedures as the focus of attention, while experiment 2 was constructed to mimic field conditions as closely as possible. Thus different problems arose depending on the method used.

The simple and rapid laboratory procedures in Paper I enabled a high number of replicates to be investigated at a relatively moderate cost. However, assessments made on seedling roots might not be valid for older plants, as indicated in Paper II.

Replacing natural soil by sand and wax layers is not without significance for the process of penetration. Sand lacks the cohesiveness of soil and has a higher degree of internal friction, as well as sand-to-root friction. Earlier studies have pointed out the negative effects of abrasion of the root cap on root elongation (Goss & Russel, 1980). While it is possible to create realistic resistance to penetration using wax, it is from other standpoints not very similar to soil, it is *e.g.* highly hydrophobic and lacks macropores. Thus, using natural soil compacted to various degrees is more similar to the conditions of a compacted soil in field. Care should therefore be taken before drawing conclusions, especially from the rapid and simplified method for screening without field experiments to verify its results.

There were differences in the ability of the roots of different species to penetrate the hard wax layers in Paper I and the high compaction treatment in Paper II. Both laboratory screening methods (I, II) and the field experiment (III) were in agreement that lucerne is better at penetrating strong soil than barley. This shows that both laboratory methods may indicate how root systems will respond to strong soil and is important since it demonstrates that laboratory screening has a value in providing a rapid assessment of the root-penetration ability of different plant species. For tap-rooted species, the important issue is likely to be penetration by the taproot. If the taproot penetrates a strong layer, then the root system below the strong layer would then be able to explore the soil.

Roots as biological subsoilers

To evaluate the use of plant roots as 'biological subsoilers', a field trial was set up Eastern Baltic glacial till soil at Lönnstorp research station in Skåne in the south of Sweden in 1998. This trial is described in detail in Paper III. It consisted of nine treatments, A-I, repeated in four blocks as follows:

- A. Lupin (*Lupinus luteus* L.) sown on pre-compacted soil
- B. Lucerne (*Medicago sativa* L. v.) sown on pre-compacted soil
- C. Lucerne sown on pre-compacted soil subsoiled to 40 cm depth by a chisel plough
- D. Red clover (*Trifolium pratense* L. v.) sown on pre-compacted soil
- E. Tall fescue (*Festuca arundinacea* L. v.) sown on pre-compacted soil
- F. Chicory (*Cichorium intybus* L. v.) sown on pre-compacted soil
- G. Barley (*Hordeum vulgare* L.) sown on pre-compacted soil
- H. Barley sown on pre-compacted soil subsoiled to 40 cm depth by a chisel plough
- I. Barley sown on non-compacted soil

Soil texture, determined by the pipette method (Robinson, 1922), was 18% clay, 32% silt and 50% sand. Organic matter content by loss on ignition and correction for clay content (Ekström, 1927) was 2.5%.

Pre-compaction of the soil was performed in April 1998. All plots except the control plots (treatment I) were compacted by driving a 30 Mg dump truck track-by-track covering the complete area of each plot (Fig. 12). In September 1998, treatments C and H were subsoiled to 40 cm depth using a fixed-tine chisel plough.

The perennial species in treatments B-F were sown in May 1998, and the soil was not tilled again until it was ploughed in November 2001. Treatments A, G, H and I with annual species were ploughed each autumn and re-sown every year from 1999-2001. In autumn 2001, growth of all 'subsoiling species' was terminated, above ground biomass was removed and all plots were ploughed. Oats were sown in all treatments in May 2002 to test the benefits of biological subsoiling to a subsequent crop. Effects on subsequent crops continued to be tested in 2003, when sugarbeet was grown in all plots.

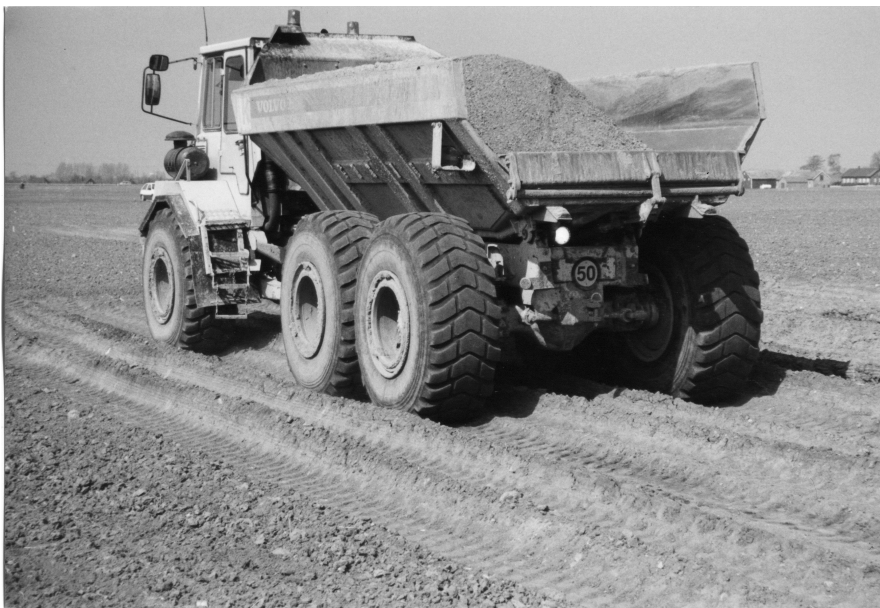


Figure 12. All plots except those of the control treatment I were compacted by a 30-Mg dump truck before the start of the trial. The dump truck wheeled the surface of each plot track-by-track.

In autumn 1998, saturated hydraulic conductivity (K_{sat}) and dry bulk density were measured on samples taken at 30-40 and 50-60 cm depth in the soil profile of treatments G, H and I to verify that compaction had occurred and taken effect (Table 6). K_{sat} was measured by a constant head method (Andersson, 1955) and dry bulk density by dividing the weight each sample, dried at 105 °C for 72 h, by its volume. Bulk density data showed significant differences only between treatments H and I ($p < 0.05$) at 30-40 cm depth, and no differences between treatment means at 50-60 cm depth. K_{sat} measurements showed no significant differences between means at either depth. However, mean values of bulk density were consistently higher and mean values of K_{sat} consistently lower in the compacted treatments G and H than in the non-compacted treatment I, and

additional measurements of K_{sat} at 30-35 cm depth (Table 10) made in 2000 showed significant differences between compacted treatments A-H compared to the non-compacted treatment I.

Although the measurements in 1998 could not prove any difference between compacted and non-compacted plots *per se*, the destruction of soil structure by the 35-Mg dump truck was considered successful when the total data of 1998 and 1999 were taken into account.

Table 6. Bulk density and K_{sat} of treatments G, H and I at 30-40 and 50-60 cm depth in 1998. Means in each row with the same letter are not significantly different ($p < 0.05$)

Parameter	Depth (cm)	G ¹	H ²	I ³
Bulk density (Mg m ⁻³)	30-40	1.74 ab	1.82 a	1.69 b
	50-60	1.67 a	1.73 a	1.66 a
K_{sat} (cm h ⁻¹)	30-40	0.41 a	0.01 a	1.64 a
	50-60	0.25 a	1.06 a	3.58 a

¹ Pre-compacted. ² Pre-compacted and mechanically subsoiled. ³ Non-compacted control.

Effects of soil compaction on yield are highly dependent on *e.g.* climatic factors, and although high yields are the obvious goal for maintaining high fertility of soils, yield is not a very precise indicator of the state of soil structure. Thus, while yields of barley in treatments G, H and I in 1999 further strengthened the assumption that the soil structure had been damaged, yields in 2000 and 2001 showed no effect of soil compaction on yield. Yields of treatments G, H and I in 1999-2001 are shown in Table 7. In 1999, yields of the compacted treatments G and H were significantly lower than the yield of the non-compacted control I. This was probably an effect of compaction of the topsoil. While subsoil compaction is very persistent, compaction of the topsoil is not. Depending on clay content and winter temperatures, compaction damage to annually ploughed topsoil in Sweden usually disappears within one to five years following compaction (Håkansson, 2000). Yields in 2000 were not significantly different. In 2001, only yields of treatments H and I were significantly different ($p < 0.05$). When yields of each plot over the three-year period were averaged, a mean treatment yield of 5200, 5190 and 5480 kg ha⁻¹ was obtained for treatments G, H and I respectively. Mean yield of treatment I over that period was significantly higher than that of treatments G and H ($p < 0.05$).

Table 7. Yields of treatments G, H and I, 1999-2003. Yields are expressed as kg ha⁻¹ at 15% water content. Means in each row with the same letter are not significantly different ($p < 0.05$)

Year	Crop	G ¹	H ²	I ³
1999	Barley	4010 b	4080 b	4840 a
2000	Barley	5180 a	5300 a	5120 a
2001	Barley	6400 a b	6190 b	6500 a
2002	Oats	5980 bc	5820 c	6320 ab
2003	Sugarbeet	84560 b	85390 b	88020 b

¹ Pre-compacted. ² Pre-compacted and mechanically subsoiled. ³ Non-compacted control.

Root growth is impeded as the size and continuity of air-filled pores decreases and roots are increasingly forced to penetrate compacted soil. The resistance to penetration of soil with pores smaller than the cross-section of roots increases, since compaction not only deteriorates soil structure but also increases soil strength and thereby the force needed for deformation. In Paper III, the performance of the presumptive subsoiling species was monitored by measurements of root length density in 1999 and 2001. Roots from soil cores taken at 30-35 and 50-55 cm depth were rinsed of soil and analysed for root length using the WinRhizo image analysis programme (Bauhus & Messier, 1999).

Root length density (RLD) of treatments B, C and E was highest at 30-35 cm depth in 1999. At 50-55 cm depth, RLD of treatment E was highest, while there were no significant differences between the other treatments. In 2001, RLD of treatment E was highest at both depths, while that of treatments B, C and F was intermediate. RLD in treatments A-I at 30-35 and 50-55 cm depth in all treatments are shown in Table 8.

Table 8. Root length density (cm cm^{-3}) at 30-35 and 50-55 cm depth of treatments A-I in 1999 and 2001. Means in each row with the same letter are not significantly different ($p < 0.05$)

Year	A	B	C	D	E	F	G	H	I
1999									
30-35	-	2.69 a	1.83 ab	1.30 bc	2.74 a	1.36 bc	0.84 c	1.29 bc	1.45 bc
50-55	-	0.86 b	0.84 b	1.03 b	2.32 a	0.96 b	0.33 b	0.45 b	0.97 b
2001									
30-35	0.92 d	1.72 bc	1.76 bc	1.07 d	3.42 a	1.78 b	1.18 cd	1.34 bd	1.47 bd
50-55	0.73 d	1.92 b	1.93 b	0.73 d	3.33 a	1.57 bc	0.89 d	0.99 cd	1.22 cd

¹ Pre-compacted treatments: A lupin, B lucerne, D red clover, E tall fescue, F chicory and G barley.

² Pre-compacted and mechanically subsoiled treatments: C lucerne and H barley.

³ Non-compacted control treatment: I barley

Earthworms are often regarded as the most important agent when it comes to improving soil structure (Edwards & Lofty, 1980; Heinonen, 1986). In Paper III, the presence of earthworms was studied each year 1999-2002, by counting and species identification of all worms surfacing within 30 minutes from initiation of infiltration of formaldehyde into cylinders (radius 20 cm) inserted to the ground (Table 9). The total numbers of earthworms increased throughout the trial but there was no specific treatment that attracted worms more than the others. However, there was a clear relationship between tillage intensity and size of earthworm population, with earthworms preferring the treatments without annual ploughing. Interestingly, the influence of amount of earthworms on K_{sat} was inferior to that of plant roots. Treatment D with red clover housed the most earthworms, but their influence on K_{sat} was not significantly different from that of treatment G, with the monocotyledonous barley crop and annual ploughing.

Table 9. Number of earthworms per m² in each treatment measured in 1999-2001. The amount and fresh weight of earthworms of the species *Lumbricus terrestris* L. (*L. t.*) are specified separately. Means in each row with the same letter are not significantly different (p<0.05)

Year	Species	A	B	C	D	E	F	G	H	I
1999	All	12 b	6 b	2 b	32 a	20 ab	18 ab	6 b	12 b	18 ab
	<i>L. t.</i>	0 a	0 a	0 a	2 a	4 a	0 a	0 a	0 a	0 a
2000	All	66 bcd	142 ab	128 abc	186 a	78 bcd	142 ab	36 cd	18 d	28 d
	<i>L. t.</i>	0 a	6 a	12 a	26 a	14 a	8 a	0 a	0 a	0 a
2001	All	138 abc	198 a	86 cd	196 a	164 ab	208 a	96 bcd	58 d	82 cd
	<i>L. t.</i>	18 bc	62 a	30 abc	46 ab	24 bc	40 abc	8 c	6 c	6 c

¹ Pre-compacted treatments: A lupin, B lucerne, D red clover, E tall fescue, F chicory and G barley.

² Pre-compacted and mechanically subsoiled treatments: C lucerne and H barley.

³ Non-compacted control treatment: I barley

Increasing the physical fertility of soils requires a change in one or more soil physical parameters to make the soil a more suitable environment for roots to fulfil the needs of plants. Heavy traffic on the soil surface adds both vertical and horizontal stresses to the soil, which may compact and consolidate it. The deteriorated soil structure of a compacted soil decreases drainage and gas flow by disrupting pores and decreasing total porosity. Root growth is impeded as the size and continuity of air-filled pores decreases. The use of plant roots as ‘biological subsoilers’ is intended to change soil structure by creating new persistent biopores that increase drainage, and thereby also gas flow. Cresswell & Kirkegaard (1995) stress the importance of specific measurements of soil pores and of pore size, number and continuity to establish soil structural changes induced by biological subsoiling. They suggest direct measurements of hydraulic conductivity in the subsoil and characterization of pores either by direct counting or image analysis.

In the present study, structural changes were monitored by measurements of K_{sat} at 30-35 cm depth, estimated by a field infiltration method in early summer of 2000-2002 (Table 10). K_{sat} of the compacted treatments A-H increased in years following compaction. In 2002, four years after compaction of the soil, treatment F was the only treatment that could not be statistically separated from the non-compacted treatment I as regards K_{sat} . All other treatments had significantly lower hydraulic conductivity.

Table 10. K_{sat} (cm h⁻¹) at 30-35 cm depth in all treatments measured in 2000-2002. Means in each row with the same letter are not significantly different (p<0.05)

Year	A	B	C	D	E	F	G	H	I
2000	0.43 b	0.11 b	0.20 b	0.20 b	0.00 b	0.10 b	0.15 b	0.33 b	1.97 a
2001	1.82 ab	2.97 a	3.27 a	1.25 b	1.10 b	2.34 ab	2.14 ab	2.14 ab	3.35 a
2002	1.83 cd	1.92 cd	2.44 bc	1.93 cd	1.68 cd	3.09 ab	1.35 d	1.34 d	3.63 a

¹ Pre-compacted treatments: A lupin, B lucerne, D red clover, E tall fescue, F chicory and G barley.

² Pre-compacted and mechanically subsoiled treatments: C lucerne and H barley.

³ Non-compacted control treatment: I barley

In addition to increased drainage and soil aeration, the benefits of 'biological subsoilers' include increased access to the subsoil for roots of species not able to penetrate the compacted soil themselves. Ehlers *et al.* (1983) found that root growth in a rigid soil matrix of apparent high mechanical impedance, as measured by penetrometer, benefited from the presence of continuous biopores. A suitable 'biological subsoiler' should therefore penetrate the soil extensively, increase drainage and result in high root density of succeeding crops. Viewing the results of our measurements in that context makes the comparison of the results of the measurements of K_{sat} and RLD important.

Treatments B, C and F all had both high RLD and K_{sat} . This shows that the roots of these species were able to grow in the compacted soil and indicates that they also have a rather large effect on soil structure by increasing drainage. This was particularly apparent in treatment F, with chicory as the subsoiling species. In 2002, K_{sat} of treatment F equalled that of the non-compacted control treatment I.

The potential of lucerne as a 'biological subsoiler' has been reported by Mitchell, Ellsworth & Meek (1995), who found that crops of lucerne were superior to wheat crops in increasing water infiltration rates on a silty clay in California, USA. However, no comparison was made to other dicotyledonous plants. In the present field experiment, the lucerne in treatments B and C penetrated the compacted soil well and the increase in K_{sat} suggests that lucerne might be a species suitable as a 'biological subsoiler'.

Materechera, Dexter & Alston (1991) and Materechera *et al.* (1993) reported that dicotyledonous plants were generally better than graminaceous plants at penetrating dense soil layers. In particular, lupin has been reported as being superior to many other dicots (Atwell, 1988; Materechera *et al.*, 1992). In the present study, the lupin in treatment A was not better than the other species tested in establishing an extended root system in the subsoil. In addition, the effect on K_{sat} did not indicate that any improvement in soil structure greater than that produced by other species had occurred. This is in agreement with the findings of Dracup, Belford & Gregory (1992) in Western Australia, where lupin was reported to be unable to penetrate the dense B-horizon of some duplex soils.

Among the monocotyledonous plants, some cultivars of tall fescue have been reported to be extra efficient in penetrating dense soil layers (Elkins, Haaland & Hoveland, 1977). This is supported by data in the present experiment, as treatment E with tall fescue as the presumptive subsoiler was superior in RLD, even compared to the barley crop of the non-compacted control treatment. However, the lack of a significant increase in saturated hydraulic conductivity in the subsoil following the growth of tall fescue indicates that the effect of tall fescue on soil structure is limited, and suggests that the relatively small diameter of monocot roots makes them generally inferior to roots of dicotyledonous plants, which are capable of large increases in girth, in altering soil structure. The roots of tall fescue were possibly small enough to use the existing pores of the soil matrix to a large extent.

Plant roots in combination with a tillage implement have been reported to stabilise and augment the tillage effect of subsoiling implements (Elkins, Thurlow & Hendrick (1983). That is not supported by the results presented here. The mechanical sub-soil loosening of treatments C and H, compared to their non-mechanically loosened counterparts B and G, respectively, had had no positive effect on K_{sat} .

The benefit of the ‘subsoilers’ in creating root pathways for subsequent crops was supported by RLD measurements in 2002 (Table 11). Measurement was complicated by residues of roots of the preceding crop, which were hard to distinguish from the roots of the present oat crop, especially in treatments E, G, H and I. RLD of the oat crop was highest in treatments B, C and E at 30-35 cm depth and in treatments B and E at 50-55 cm depth, with a risk that the value of treatment E is overestimated.

Effects on yields of the oat crop in the first year and sugarbeet in the second year following cultivation of the subsoiling species were only indicated in treatment F (Tables 12 and 13). The high yields in treatments A-D of the oat crop in 2002 are likely to be an effect of nitrogen mineralization from the preceding nitrogen-fixing species and should be interpreted with caution.

Table 11. Root length density (cm cm^{-3}) at 30-35 and 50-55 cm depth of the oat crop in treatments A-I in 2002. Means in each row with the same letter are not significantly different ($p < 0.05$)

Depth	A ¹	B ¹	C ²	D ¹	E ¹	F ¹	G ¹	H ²	I ³
30-35	1.32 be	1.98 ab	1.78 abc	1.30 be	2.60 a	1.10 cde	0.91 de	0.67 e	1.62 bd
50-55	1.09 d	2.55 ab	2.32 bc	1.37 d	3.29 a	1.01 d	0.95 d	0.72 d	1.55 cd

¹ Pre-compacted treatments: A lupin, B lucerne, D red clover, E tall fescue, F chicory and G barley.

² Pre-compacted and mechanically subsoiled treatments: C lucerne and H barley.

³ Non-compacted control treatment: I barley

Table 12. Yield of oats in treatments A-I in 2002. Yields are expressed as kg ha^{-1} at 15% water content. Means in each row with the same letter are not significantly different ($p < 0.05$)

	A ¹	B ¹	C ²	D ¹	E ¹	F ¹	G ¹	H ²	I ³
Yield	6400 a	6560 a	6560 a	6430 a	5800 c	6310 ab	5980 bc	5820 c	6320 ab

¹ Pre-compacted treatments: A lupin, B lucerne, D red clover, E tall fescue, F chicory and G barley.

² Pre-compacted and mechanically subsoiled treatments: C lucerne and H barley.

³ Non-compacted control treatment: I barley

Table 13. Yield of sugarbeet (SB) and sugar (S) in treatments A-I in 2003. Yields are expressed as Mg ha^{-1} . Means in each row with the same letter are not significantly different ($p < 0.05$)

	A ¹	B ¹	C ²	D ¹	E ¹	F ¹	G ¹	H ²	I ³
SB	87.92 b	89.40 ab	87.37 b	87.94 b	88.10 b	98.18 a	84.56 b	85.39 b	88.02 b
S	12.81 ab	12.27 b	12.32 b	12.30 b	13.07 ab	14.11 a	12.65 ab	12.59 ab	13.03 ab

¹ Pre-compacted treatments: A lupin, B lucerne, D red clover, E tall fescue, F chicory and G barley.

² Pre-compacted and mechanically subsoiled treatments: C lucerne and H barley.

³ Non-compacted control treatment: I barley

Conclusions

Modifying soil structure with plant roots as tillage tools is certainly possible. Data presented here show significant differences in K_{sat} between treatments, and measurement of RLD at different depths of the subsoil also show differences between treatments. Chicory in particular, but also lucerne, had a large effect on K_{sat} . Interestingly, K_{sat} was more affected by subsoiling species than by abundance of earthworms.

Direct benefits for subsequent crops are difficult to prove. However, there were differences in root length densities between treatments in the oat crop following subsoiling by plant roots and the oat yield of treatment F (chicory) was as high as that of the non-compacted control. Oat yields following legumes were also at the same level as that of the control treatment, but this was probably only a nitrogen effect. Yields of sugarbeet in treatment B (lucerne) and F (chicory) surpassed that of the non-compacted control.

Saturated hydraulic conductivity as a measure of soil quality

Paper IV describes a field trial carried out on farms in different sugarbeet growing regions in Skåne in the south of Sweden. Field measurements were made and soil cores extracted from 7 fields. In each field, 3 core samples were taken at 15-20, 25-30 45-50 cm depth in 4 plots in two blocks, separated by different management history. The samples consisted of cylindrical soil cores 50 mm high with a diameter of 72 mm. Each sample was then saturated with water and water content was measured after 1 and 24 hours of infiltration under a constant water head of 100 mm (Andersson, 1955).

In the field, vertical hydraulic conductivity was estimated by measuring the rate of a falling water head. One measurement was made in each of the 8 plots from which the core samples were taken, in all of the 7 fields. The measurements were performed by inserting a 400 mm diameter steel cylinder to a depth of 15 cm into a horizontal soil surface prepared at 20 cm depth in the soil. The soil inside the cylinder was submerged by a water head of 100 mm, which was kept constant between measurements of falling water head rate, which were carried out 5, 15, 30 and 60 minutes after ponding.

K_{sat} was calculated by applying Darcy's law to the vertical flow rate of water. To allow K_{sat} to be compared between methods, K_{sat} for each depth by the laboratory method (using small cylinders) was transformed to an estimate of K_{sat} for the entire profile down to 50 cm depth (K_{satL}). The model calculated the harmonic mean of the K_{sat} of each depth, weighted according to its thickness:

$$K_{satL} = \frac{\sum_{n=1}^3 z_n}{\left(\frac{z_1}{K_{sat1}} + \frac{z_2}{K_{sat2}} + \frac{z_3}{K_{sat3}} \right)} \quad (7)$$

where z = thickness of soil layer (cm), K_{sat} = coefficient of saturated hydraulic conductivity of soil layer (cm h^{-1}) and K_{satL} = estimated coefficient of saturated hydraulic conductivity (cm h^{-1}) of the soil profile.

K_{satL} was then plotted against K_{satF} (Fig. 13). No linear relationship was found between K_{sat} measured by the different methods. A paired Student's t-test showed significant differences ($p < 0.001$) between means obtained by the two measurement methods.

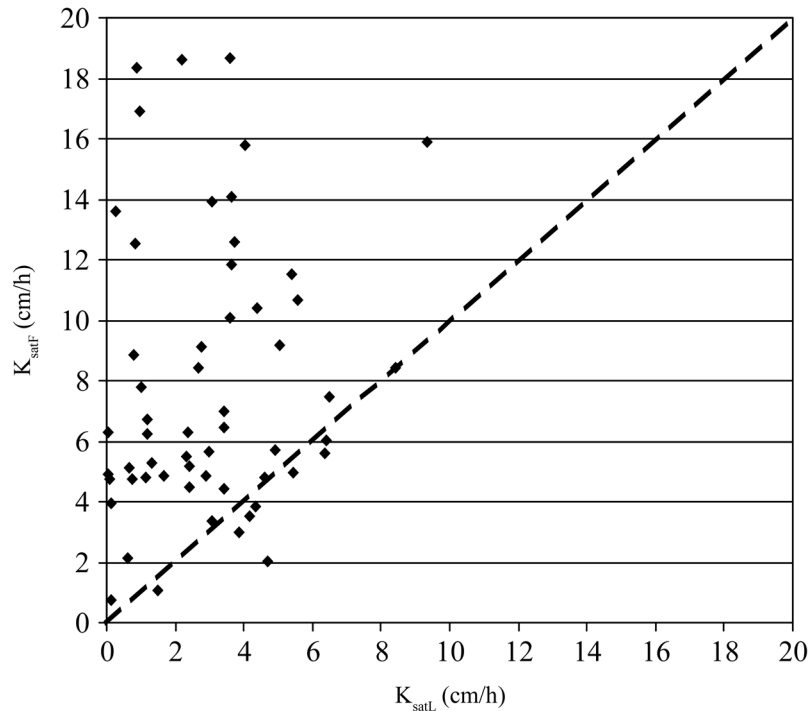


Figure 13. Dots in the chart show the saturated vertical hydraulic conductivity coefficient (K_{satF}) of a soil profile measured by the field infiltration method plotted against K_{satL} , the same parameter calculated from laboratory measurements on soil cores taken from 15-20, 30-35 and 45-50 cm depth in the vicinity of the field infiltration spot. The dashed line shows the 1:1 line of the chart.

Paper IV clearly showed that comparisons between estimates of K_{sat} measured by the two methods compared should be avoided. The results did not indicate any systematic correlations between the parameters. This was in agreement with the results of Reynolds et al. (2000) from measurements on various soil types. However, in contrast to the results of Reynolds et al. (2000) the data presented here indicates that K_{satF} always can be expected to be higher than K_{satL} .

Biologically and chemically assisted mechanical subsoiling

Two field trials, dealt with in detail in Paper V, were carried out in Uppsala, Sweden, to study different methods of modifying subsoil structure. The experimental site had been under long-term conventional tillage with annual mouldboard ploughing before the start of the experiments. The experiments were carried out on a clay soil classified as a Eutric Cambisol (FAO-UNESCO, 1994).

Experiment 1

The experiment was of a randomised block design with three blocks and was started in October 2000. Treatments were as follows:

- A. Control
- B. Subsoiling year 1
- C. Subsoiling year 1 & 2
- D. Subsoiling year 1, 2 & 3
- E. Subsoiling + slaked lime year 1
- F. Control + slaked lime year 1

All plots were ploughed in autumn each year to a depth of 22 cm. Spring cereal was sown each year after seedbed preparation. Fertilizers were applied in amounts normal for the area ($80 \text{ kg N ha}^{-1} \text{ year}^{-1}$). In subsoiled treatments, a share mounted underneath each plough body of a conventional mouldboard plough loosened the soil to 10 cm below ploughing depth. In treated plots 55% of the area was subsoiled; the width of each furrow and subsoiling share was 40 and 22 cm, respectively. In treatments E and F, slaked lime (Ca(OH)_2 , 4.4 Mg ha^{-1}) was applied at the start of the experiment in October 2000. Slaked lime mixed with water was sprayed directly into the loosened layer during subsoiling in treatment E, and sprayed on the base of each furrow during ploughing in treatment F.

Soil texture, determined by the pipette method (Robinson, 1922), was 70% clay, 18% silt and 12% sand in the topsoil, and 76% clay, 13% silt and 11% sand in the subsoil. Organic matter content by loss on ignition and correction for clay content (Ekström, 1927) was 3.5% and 0.4% in the topsoil and subsoil, respectively.

Saturated hydraulic conductivity (K_{sat}) was measured in May 2001-2003 (Table 14). In 2001, K_{sat} at 23-28 cm depth was determined on detached soil cores, and in 2002 and 2003 at 24-34 cm depth by a field infiltration method. No significant difference between treatments was found in any year, but mean values of K_{sat} were consistently highest in the treatment with lime incorporated during subsoiling.

Penetration resistance was measured in May 2001-2003 using handheld penetrometers (Table 15). In 2001 and 2002, penetration resistance was significantly lower in the subsoiled treatments than in the controls. In 2003, all subsoiled treatments except that with lime incorporated had significantly lower penetration resistance than the controls. This indicates a stabilizing effect of the slaked lime. Addition of lime to soil has previously been reported to enhance water

stability of soil aggregates (Peterson, 1947; Berglund, 1971; Chan & Heenan, 1998). Subsoiling more than once had no significant effect on penetration resistance.

Table 14. Saturated hydraulic conductivity (cm h⁻¹) in May 2001-2003. Means in each row followed by the same letter are not significantly different (p<0.05)

Year	Depth (cm)	A ¹	B ¹	C ¹	D ¹	E ¹	F ¹
2001 ²	23-28	0.037a	0.036a	-	-	0.094a	0.047a
2002 ³	24-34	1.20a	1.60a	3.40a	-	6.80a	3.00a
2003 ³	24-34	4.41a	7.24a	8.13a	8.19a	9.93a	6.49a

¹ A Control; B subsoiling year 1; C subsoiling year 1 & 2; D subsoiling year 1, 2 & 3; E subsoiling + lime year 1; F control + lime year 1. ² K_{sat} was measured on detached soil cores by a constant head method (Andersson, 1955) ³ K_{sat} was measured *in situ* by a field infiltration method.

Table 15. Penetrometer resistance (MPa) at 26-32 cm depth in May 2001-2003. Means in each row followed by the same letter are not significantly different (p<0.05)

Year	Depth (cm)	A ¹	B ¹	C ¹	D ¹	E ¹	F ¹
2001	26	1.71a	1.28b	-	-	1.41b	1.66a
	28	2.01a	1.40b	-	-	1.52b	1.97a
	30	2.29a	1.60b	-	-	1.69b	2.24a
	32	2.50a	1.85b	-	-	1.91b	2.47a
2002	26	1.17a	1.10ab	0.87c	-	1.01b	1.14ab
	28	1.38a	1.23ab	0.98c	-	1.17b	1.30ab
	30	1.58a	1.29b	1.05c	-	1.29b	1.49a
	32	1.74a	1.41c	1.24c	-	1.44bc	1.69ab
2003	26	1.13a	0.98abc	0.92bc	0.83c	1.04ab	1.09a
	28	1.35a	1.01bc	0.99c	0.92c	1.18ab	1.20ab
	30	1.44a	1.05b	1.03b	1.04b	1.27ab	1.44a
	32	1.54a	1.11c	1.06c	1.16bc	1.43ab	1.58a

¹ A Control; B subsoiling year 1; C subsoiling year 1 & 2; D subsoiling year 1, 2 & 3; E subsoiling + lime year 1; F control + lime year 1.

Table 16. Cereal yield (15% moisture content), 2001–2004. Means in each row followed by the same letter are not significantly different (p<0.05)

Year	Crop	A ¹	B ¹	C ¹	D ¹	E ¹	F ¹
2001	Barley	5100a	5060a	-	-	5370a	5300a
2002	Oats	5330a	5450a	5660a	-	5630a	5520a
2003	Oats	6380a	6170a	6180a	6000a	6280a	6250a
2004	Barley	5490b	5370b	5510b	5300b	5860a	5550ab

¹ A Control; B subsoiling year 1; C subsoiling year 1 & 2; D subsoiling year 1, 2 & 3; E subsoiling + lime year 1; F control + lime year 1.

In 2004, yield (Table 16) in the treatment with lime incorporated during subsoiling was significantly higher than in all other treatments except for the limed control. Higher values for K_{sat} and penetration resistance, and a trend for an increase in relative yield over time compared to all the other subsoiled treatments

may indicate an effect of the incorporation of slaked lime on the stability of the loosened layer.

Experiment 2

The experiment was of a randomized block design with four blocks and was started in spring 1998. The treatments were as follows:

- A. Lucerne (*Medicago sativa* L.), compacted soil
- B. Lucerne (*Medicago sativa* L.), compacted soil + subsoiling
- C. Spring cereal, compacted soil
- D. Spring cereal, compacted soil + subsoiling
- E. Spring cereal, non-compacted control

All plots except those of the control were pre-compacted in May 1998 by a 30 Mg dump truck track-by-track covering the complete area of each plot. In October 1999, treatments B and D were subsoiled to a depth of 45 cm by a rigid-tine chisel plough. The lucerne in treatments A and B sown in May 1999 was not cultivated until ploughed in October 2002, except for subsoiling in treatment B in 1999. Treatments C-E, with cereal crops, were ploughed and re-sown each year, 1999-2004. In 2003 and 2004 spring cereal was grown in all treatments.

In 1999, saturated hydraulic conductivity (K_{sat}) was measured in the compacted treatment with cereal crops and the non-compacted control to evaluate the pre-compaction of the soil (Table 17). Measurements were made on detached undisturbed soil cores taken at 30-40, 40-50 and 50-60 cm depth. Comparison between treatments showed no significant differences. However, consistently lower mean values of K_{sat} in the compacted treatment compared to the control indicated that the compaction had been successful. This conclusion was further enforced by vane shear strength and K_{sat} measured in 2002 (Tables 18 and 19).

Table 17. Saturated hydraulic conductivity (cm h^{-1}) in 1999. Means in each row followed by the same letter are not significantly different ($p < 0.05$)

Depth (cm)	C ¹			E ¹		
	30-40	40-50	50-60	30-40	40-50	50-60
K_{sat} (cm h^{-1})	0.06a	3.20a	3.04a	0.05a	7.91a	10.41a

¹ C Spring cereal on compacted soil; E Spring cereal, non-compacted control.

Soil strength at 30-40 and 50-60 cm depth was measured in treatments with cereal crops in June 2000 by a vane shear apparatus (Table 18). Significant differences were found between all treatments at 30-40 cm depth, soil strength being greatest in the compacted treatment and lowest in the subsoiled treatment. No significant differences were found at 50-60 cm depth.

In May 2002, K_{sat} at 30-35 cm depth was measured by a field infiltration method (Table 19). K_{sat} in the subsoiled treatment with lucerne was five times higher than in any other compacted treatment. Subsoiling in the cereal crop did not increase

K_{sat} significantly compared to any other compacted treatment. This is important and suggests that roots of certain species may stabilize mechanically loosened structure, in agreement with the findings of Elkins, Thurlow & Hendrick (1983).

Table 18. Vane shear strength (kPa) at 30-40 and 50-60 cm depth in June 2000. Means in each row followed by the same letter are not significantly different ($p < 0.05$)

Depth (cm)	C ¹	D ¹	E ¹
30-40	148a	85b	120c
50-60	143a	146a	137a

¹ C Spring cereal on compacted soil; D Spring cereal on compacted & subsoiled soil; E Spring cereal, non-compacted control.

Table 19. Saturated hydraulic conductivity (K_{sat}) measured by a field infiltration method at 30-35 cm depth. Means followed by the same letter are not significantly different ($p < 0.05$)

	A ¹	B ¹	C ¹	D ¹	E ¹
K_{sat} (cm h ⁻¹)	6.84a	35.39b	3.52a	4.85a	13.89a

¹ A Lucerne on compacted soil; B Lucerne on compacted & subsoiled soil; C Spring cereal on compacted soil; D Spring cereal on compacted & subsoiled soil; E Spring cereal, non-compacted control.

Yields (Table 20) showed no negative effects of compaction when the non-compacted control was compared with the compacted annual crop. On the contrary, in most years values of yields were higher in the compacted cereal crop. The effect of subsoiling on the cereal crop was significant in the first year after subsoiling, with a yield higher than in either the compacted spring-sown treatment or the control. However, yield declined rapidly relative to that of the control in the following years, consistent with earlier findings of relatively short-lived effects of mechanical subsoiling (Nilsson & Henriksson, 1968; Canarache, Horn & Colibas, 2000). In 2004, yields of barley were significant higher in the treatments with previous lucerne crops and while improved subsoil structure may be one explanation, residual nitrogen delivered by the previous lucerne crop is another (not mutually exclusive).

Table 20. Cereal yield (kg ha⁻¹, 15% moisture content), 1999–2004. Means in each row followed by the same letter are not significantly different ($p < 0.05$)

Year	Crop	A ¹	B ¹	C ¹	D ¹	E ¹
1999	Barley	-	-	3520a	-	3460a
2000	Barley	-	-	3540a	3780a	3480a
2001	Barley	-	-	5410a	5380a	5200a
2002	Barley	-	-	4190a	4250a	4130a
2003	Oats	6790a	6930a	6860a	6830a	6890a
2004	Barley	6820a	6900a	5920b	5790b	5930b

¹ A Lucerne on compacted soil; B Lucerne on compacted & subsoiled soil; C Spring cereal on compacted soil; D Spring cereal on compacted & subsoiled soil; E Spring cereal, non-compacted control.

Conclusions

The use of mechanical subsoiling without any additional measures being taken is questionable, as seen in experiment 2 in the subsoiled treatment with cereal crops. Incorporation of slaked lime into the loosened soil layer during subsoiling indicated increased stability of the modified soil structure, but further investigations are needed to verify these effects. Mechanical subsoiling in growing crops of lucerne prolonged the effect of subsoiling compared to subsoiling in spring cereals.

Final Remarks

Avoiding soil compaction is of high priority in preserving the fertility of arable land and decreasing the environmental risks associated with modern farming practices (Chamen *et al.*, 2000). Regeneration of the soil structure is possible, but is a long and expensive process that would be impractical for the vast areas already affected by detrimental soil compaction.

Plant roots have the ability to modify soil structure and may have beneficial effects on subsequent crops. The field trial in this thesis (III) showed significant differences between the effects of different 'subsoiling' species on K_{sat} . However, no predictions on the durability of these effects could be made from the measurements. Further measurements of hydraulic conductivity and crop yield in combination with notes on traffic intensity in the field trial would be of great interest to evaluate the stability of the soil structure created.

Chicory and lucerne were the two most successful modifiers of subsoil and are recommended for use in further investigations and for farmers willing to test new methods for maintaining and safeguarding the fertility of their soils. Introducing these species as perennial crops into crop rotations on compaction-damaged soil would be especially beneficial, as cultivation without annual tillage also promotes the abundance of earthworms.

The laboratory screenings in this thesis work (I, II) showed a good correlation to field results (III). Screening species for effective penetration in laboratory experiments before conducting large-scale field trials is recommended. The species tested in this thesis are just a few examples of species commonly known for their sturdy root systems. Further screenings and accompanying field trials with promising species are of interest to increase the potential to identify plant species that fit into current agricultural production.

References

- Abdalla, A.M., Hettiaratchi, D.R.P. & Reece, A.R. 1969. The mechanics of root growth in granular media. *Journal of Agricultural Engineering Research* 14(3), 236-248.
- Alakukku, L. 1998. Properties of compacted fine-textured soils as affected by crop rotation and reduced tillage. *Soil Tillage Research* 47, 83-89.
- Alblas, J. 1985. Some effects of deep cultivation of sandy loam soils. In: Soil Compaction and Regeneration. Eds. Monnier, G. & Goss, M.J. *Proceedings of the Workshop on soil compaction: Consequences and Structural Regeneration Processes / Avignon*, 17-18 Sept. 1985, 125-129.
- Andersson, S. 1955. Markfysikaliska undersökningar i odlad jord. VIII. En experimentell metod. (Soil physical measurements on arable land. VIII. An experimental method.) *Grundförbättring* 8, 35-44.
- Arvidsson, J. & Dexter, A.R. 2002. *Tillage*. Course in Agricultural Soil Mechanics, Swedish University of Agricultural Sciences, Uppsala, Sweden.
- Atwell, B.J. & Newsome, J.C. 1990. Turgor pressure in mechanically impeded lupin roots. *Australian Journal of Plant Physiology* 17, 49-6.
- Atwell, B.J. 1988. Physiological responses of lupin roots to soil compaction. *Plant and Soil* 111, 277-281.
- Bauhus, J. & Messier, C. 1999. Image analysis. Evaluation of fine root length and diameter measurements obtained using RHIZO image analysis. *Agronomy Journal* 91, 142-147.
- Bengough, A.G., Croser, C. & Pritchard, J. 1997. A biophysical analysis of root growth under mechanical stress. *Plant and Soil* 189, 155-164.
- Bengough, A.G. & McKenzie, C.J. 1994. Simultaneous measurements of root force and elongation for seedling pea roots. *Journal of Experimental Botany* 45, 95-102.
- Bengough, A.G. & Mullins, C.E. 1990. The resistance experienced by roots growing in a pressurised cell. A reappraisal. *Plant and Soil* 123, 73-82.
- Bengough, A.G. & Mullins, C.E. 1988. Use of a low-friction penetrometer to estimate soil resistance to root growth. *Proceedings of the 11th Conference of the International Soil Tillage Research Organisation* 1, 1-6.
- Bengough, A.G. & Young, I.M. 1993. Root elongation of seedling peas through layered soil of different penetration resistances. *Plant and Soil* 149, 129-139.
- Bennie, A.T.P. 1991. Growth and mechanical impedance. In *Plant Roots: The Hidden Half*. Eds. Y. Waisel, A. Eshel & U. Kafkafi. Pp. 393-414. Marcel Dekker Inc., NY.
- Bennie, A.T.P. & Burger, R. du T. 1981. Root characteristics of different crops as affected by mechanical resistance in fine sandy soils. *Proceedings of the 10th Congress of the Soil Science Society of Southern Africa*, East London, 29-32.
- Berglund, G. 1971. Kalkens inverkan på jordens struktur. (The influence of lime on soil structure). *Grundförbättring* 24, pp. 81-93.
- Bushamuka, V.N. & Zobel, R.W. 1998. Differential genotypic and root type penetration of compacted soil layers. *Crop Science* 38, 776-781.
- Call, L.E. & Throckmorton, R.I. 1915. The use of dynamite in the improvement of heavy clay soils. *Bulletin/Experimental Station Kansas State Agricultural College*, No. 209. 34pp.
- Canarache, A., Horn, R. & Colibas, I. 2000. Compressibility of soils in a long term field experiment with intensive deep ripping in Romania. *Soil Tillage Research* 56, 185-196.
- Casagrande, A. 1936. The determination of pre-consolidation load and its practical significance. *Proceedings of the International Conference of Soil Mechanics and Foundation Engineering*, 22-26 June. Harvard University. Cambridge. USA. Vol. 3, pp. 60-64.
- Chamen, W.C.T., Alakukku, L., Weisskopf, P. & Spoor, G. 2000. Equipment and field practices to avoid subsoil compaction. In: *Proceedings of the 3rd Workshop of the Concerted Action "Experiences with the impact of subsoil compaction on soil, crop growth and environment and ways to prevent subsoil compaction"*, 14-16 June 2000, Uppsala, Sweden. Eds. Arvidsson, J., Van den Akker, J.J.H., Horn, R., pp. 194-206.

- Chan, K.Y. & Heenan, D.P. 1998. Effect of lime (CaCO₃) application on soil structural stability of a red earth. *Australian Journal of Soil Research* 36, 73-86.
- Clark, L.J., Aphale, S.L. & Barraclough, P.B. 2000. Screening the ability of rice roots to overcome the mechanical impedance of wax layers: importance of test conditions and measurement criteria. *Plant and Soil* 219, 187-196.
- Clark, L.J. & Barraclough, P.B., 1999. Do dicotyledons generate greater maximum axial root growth pressures than monocotyledons? *Journal of Experimental Botany* 50: 336, pp. 1263-1266.
- Clark, L.J., Whalley, W.R., Dexter, A.R., Barraclough, P.B. & Leigh, R.A. 1996. Complete mechanical impedance increases the turgor of cells in the apex of pea roots. *Plant, Cell and Environment* 19, 1099-1102.
- Cook, A., Marriott, C.A., Seel, W. & Mullins, C.E. 1996. Effects of soil mechanical impedance on root and shoot growth of *Lolium perenne* L., *Agrostis capillaris* and *Trifolium repens* L. *Journal of Experimental Botany* 47, 1075-1084.
- Cresswell, H.P. & Kirkegaard, J.A. 1995. Subsoil amelioration by plant roots - the process and the evidence. Soil physics and hydrology. *Australian Journal of Soil Research* 33, 221-239.
- Crosset, R.N., Campbell, D.J. & Stewart, H.E. 1975. Compensatory growth in cereal root systems. *Plant and Soil* 42, 673-683.
- Dexter, A.R. 1986a. Model experiments on the behaviour of roots at the interface between a tilled seed-bed and a compacted sub-soil. I. Effects of seed-bed aggregate size and sub-soil strength on wheat roots. *Plant and Soil* 95, 123-133.
- Dexter, A.R. 1986b. Model experiments on the behaviour of roots at the interface between a tilled seed-bed and a compacted sub-soil. II. Entry of pea and wheat roots into sub-soil cracks. *Plant and Soil* 95, 135-147.
- Dexter, A.R. 1986c. Model experiments on the behaviour of roots at the interface between a tilled seed-bed and a compacted sub-soil. III. Entry of pea and wheat roots into cylindrical biopores. *Plant and Soil* 95, 149-161.
- Dexter, A.R. 1991. Amelioration of soil by natural processes. *Soil Tillage Research* 20, 87-100.
- Dracup, M., Belford, R.K. & Gregory, P.J. 1992. Constraints to root growth of wheat and lupin crops in duplex soils. *Australian Journal of Experimental Agriculture* 32, 947-961.
- Drew, M.C. & Goss, M.J. 1973. Effect of soil physical factors on root growth. *Chemistry and Industry* 21, 679-684.
- Edwards, C.A. & Lofty, J.R. 1980. Effects of earthworm inoculation upon root growth of direct drilled cereals. *Journal of Applied Ecology* 17, 533-543.
- Ehlers, W., Köpke, U., Hesse, F. & Böhm, W. 1983. Penetration resistance and root growth of oats in tilled and untilled loess soil. *Soil Tillage Research* 3, 261-275.
- Ekström, G. 1927. Klassifikation av svenska åkerjordar. (Classification of Swedish arable soils.) *Årsbok* 20, No 6. *Sveriges Geologiska Undersökning*, Stockholm, Sweden, 139 pp.
- Elkins, C.B., 1985. Plant roots as tillage tools. *Proceedings of an International Conference on Soil Dynamics. Volume 3: Tillage Machinery Systems as Related to Cropping Systems*. Auburn, AL. 519-23.
- Elkins, C.B., Haaland, R.L. & Hoveland, C.S. 1977. Grass roots as a tool for penetrating hardpans and increasing crop yields. *Proc. 34th Southern Pasture and Forage Improvement Conference*, Auburn, AL. 21-26.
- Elkins, C.B., Thurlow, D.L., Hendrick, J.G., 1983. Conservation tillage for long-term amelioration of plow pan soils. *Journal of Soil Water Conservation* 38, 305-307.
- Elowson, S. 1984. Växtanatomi. *Kurskompendium för Jägmästarlinjen*, 2:a omarbetade upplagan. Uppsala.
- Etana, A. & Håkansson, I. 1994. Swedish experiments on the persistence of subsoil compaction caused by vehicles with high axle load. *Soil Tillage Research* 29, 167-172.
- Forbes, J.C. & Watson, R.D. 1992. *Plants in Agriculture*. Cambridge University Press, Cambridge.
- Glinski, J. & Lipiec, J. 1990. *Soil Physical Conditions and Plant Roots*. CRC Press, Inc., Boca Raton, Florida.

- Goss, M.J. 1985. The specific effects of roots on the regeneration of soil structure. In: Soil Compaction and Regeneration. Eds. Monnier, G. & Goss, M. J. *Proceedings of the workshop on soil compaction: Consequences and Structural Regeneration Processes / Avignon*, 17-18 Sept. 1985, 145-155.
- Goss, M.J. 1977. Effects of mechanical impedance on root growth in barley (*Hordeum vulgare* L.). I Effects on the elongation and branching of seminal root axes. *Journal of Experimental Botany* 28, 96-111.
- Goss, M.J. & Russel, R.S. 1980. Effects of mechanical impedance on root growth in barley (*Hordeum vulgare* L.). III: Observations on the mechanism of response. *Journal of Experimental Botany* 31, 577-588.
- Greacen, E.L. 1986. Root response to mechanical properties. *Transactions of the 13th Congress of the I.S.S.S.*, Hamburg, Vol. 5, 20-47.
- Greacen, E.L., Farrel, D.A. & Cockroft, B. 1968. Soil resistance to metal probes and plant roots. *Transactions of the 9th Congress of the International Society of Soil Scientists* 1, 769-779.
- Greacen, E.L. & Oh, J.S. 1972. Physics of root growth. *Nature New Biology* 235, January 5, 24-25.
- Heinonen, R. 1986a. Alleviation of soil compaction by natural forces and cultural practices. In: *Land Clearing and Development in the Tropics*. Eds. Lal, R., Sanchez, P. A., Cummings, R. W. A & Balkema, Boston, 285-297.
- Heinonen, R. 1986b. Självvläkning i marken. In: *Jordpackning: Skördepåverkan – Motåtgärder – Ekonomi*. Eds. Håkansson, I., Polgar, J. von, Rask, K., Swedish University of Agricultural Sciences, *Reports from the Division of Soil Management* 71, 165-171.
- Hillel, D. 1980. 14 Soil compaction and consolidation. In: *Fundamentals of soil physics*. Academic Press, pp 355-385.
- Håkansson, I. 2000. Packningens omfattning och varaktighet i våra åkerjordar. In: *Packning av åkermark vid maskindrift – omfattning – effekter – motåtgärder*. Swedish University of Agricultural Sciences, Uppsala, *Reports from the Division of Soil Management* 99, 23-40.
- Håkansson, I. & Medvedev, V.W. 1995. Protection of soils from mechanical overloading by establishing limits for stresses caused by heavy vehicles. *Soil Tillage Research* 35, 85-97.
- Håkansson I. & Reeder, R.C. 1994. Subsoil compaction by vehicles with high axle load – extent, persistence and crop response. *Soil Tillage Research* 29, 277-304.
- Keller, T., Arvidsson, J., Dawidowski, J.B. & Koolen, A.J. 2004. Soil precompression stress II. A comparison of different compaction tests and stress-displacement behaviour of the soil during wheeling. *Soil Tillage Research* 77, 97-108.
- Kuht, J. & Reintam, E. 2002. The impact of deep rooted plants on the qualities of compacted soils. *ISTRO workshop in Tallin*.
- Lockhart, J.A. 1965. An analysis of irreversible cell elongation. *Journal of Theoretical Biology* 8, 264-275.
- Lebert, M. 1992. Mechanical strength properties of dry restored loess soils for agricultural use in western German brown coal mines. *Proc. Of Int. Conf. On Soil Compaction and Soil Management*, 8-12 June, Estonian Res. Inst. Of Agriculture and Land Improvement, Tallin, 95-104.
- Liepiec, J., Kubota, T., Iwama, H. & Hirose, J. 1988. Measurement of plant water use under controlled soil moisture conditions by the negative pressure water circulation technique. *Soil Science and Plant Nutrition* 34 (3), 417-428.
- Löfkvist, J., Rydberg, T. & Svantesson, U. 2000. A method for screening the ability of plant roots to penetrate soil and increase hydraulic conductivity. *Proceedings of the 15th Conference of the International Soil Tillage Research Organization*, 2-7 July 2000, Fort Worth, Texas, USA.
- Marshall, T.J., Holmes, J.W. & Rose, C.W. 1996. *Soil Physics* 3rd Ed. Cambridge University Press, New York, USA.
- Materechera, S.A., Alston, A.M., Kirby, J.M. & Dexter, A.R. 1993. Field evaluation of laboratory techniques for predicting the ability of roots to penetrate strong soil and of the influence of roots on water sorptivity. *Plant and Soil* 149, 149-158.

- Materechera, S.A., Alston, A.M., Kirby, J.M. & Dexter, A.R. 1992. Influence of root diameter on the penetration of seminal roots into a compacted subsoil. *Plant and Soil* 144, 297-303.
- Materechera, S.A., Dexter, A.R. & Alston, A.M. 1991. Penetration of very strong soils by seedling roots of different plant species. *Plant and Soil* 135, 31-41.
- McCann, M.C. & Roberts, K. 1994. Changes in cell wall architecture during cell elongation. *Journal of Experimental Botany* 45, 1683-1691.
- Misra, R.K., Dexter, A.R. & Alston, A.M. 1986. Maximum axial and radial growth pressures of plant roots. *Plant and Soil* 95, 315-326.
- Mitchell, A.R., Ellsworth, T.R. & Meek, B.D. 1995. Effect of root systems on preferential flow in swelling soil. *Communications in Soil Science and Plant Analysis* 26(15&16), 2655-2666.
- Nilsson, N.M. & Henriksson, L. 1968. Alvluckringsförsök 1937-1963 (Experiments on subsoil loosening 1937-1963). Agricultural College of Sweden, Uppsala, *Reports from the Division of Soil Management* 12, 32 pp.
- Passioura, J.B. & Fry, S.C. 1992. Turgor and cell expansion: Beyond the Lockhart equation. *Australian Journal of Plant Physiology* 19, 565-576.
- Peterson, J.B. 1947. Calcium linkage, a mechanism in soil granulation. *Soil Science Society of America. Proc* 12, 29-34.
- Pritchard, J., Jones, R.G.W. & Tomos, A.D. 1991. Turgor, growth and rheological gradients of wheat roots following osmotic-stress. *Journal of Experimental Botany* 42, 1043-1049.
- Reynolds, W.D., Bowman, B.T., Brunke, R.R., Drury, C.F. & Tan, C.S. 2000. Comparison of tension infiltrometer, pressure infiltrometer, and soil core estimates of saturated hydraulic conductivity. *Soil Science Society of America Journal* 64, 478-484.
- Robinson, G.W. 1922. A new method for the mechanical analyses of soil and other dispersions. *Journal of Agricultural Sciences* 12, 306-321.
- Russel, R.S. & Goss, M. J. 1974. Physical aspects of soil fertility – The response of roots to mechanical impedance. *Netherlands Journal of Agricultural Science* 22, 303-317.
- Scholefield, D. & Hall, D.M. 1985. Constricted growth of grass roots through rigid pores. *Plant and Soil* 85, 153-162.
- SJV, 1999. Report 18. Swedish Board of Agriculture.
- Spollen G.W. & Sharp, R.E. 1991. Spatial distribution of turgor and root growth at low water potentials. *Plant Physiology* 96, 438-443.
- Spoor, G. 1976. Effective subsoiling. *British Sugar Beet Review* 44 (2).
- Tardieu, F. 1994. Growth and functioning of roots and root systems subjected to soil compaction. Towards a system with multiple signalling? *Soil and Tillage Research* 30, 217-243.
- Taylor, H.M. & Brar, G.S. 1991. Effects of soil compaction on root development. *Soil and Tillage Research* 19, 111-119.
- Van den Akker, J.J.H. & Canarache, A. 2000. Concerted actions on subsoil compaction in Western European countries and on subsoil compaction in central and eastern European countries. In: *Proceedings of the 3rd workshop of the Concerted Action* "Experiences with the impact of subsoil compaction on soil, crop growth and environment and ways to prevent subsoil compaction", 14-16 June 2000, Uppsala, Sweden. Eds. Arvidsson, J., Van den Akker, J.J.H., Horn, R., pp. 7-19.
- Veen, B.W. 1982. The influence of mechanical impedance on the growth of maize roots. *Plant and Soil* 66, 101-109.
- Whalley, W.R. & Dexter, A.R. 1993. The maximum axial growth pressure of roots of spring and autumn cultivars of lupin. *Plant and Soil* 157, 313-318.
- Whiteley, G.M., Utomo, W.H. & Dexter, A.R. 1981 A comparison of penetrometer pressures and the pressures exerted by roots. *Plant and Soil* 61, 351-364.
- Whiteley, G.M., Hewitt, J.S. & Dexter, A.R. 1982. The buckling of plant roots. *Physiologia Plantarum* 54, 33-342.
- Wiersum, L.K. 1957. The relationship of the size and structural rigidity of pores to their penetration by roots. *Plant and Soil* 9: 75-85.

Wilson, A.J., Robards, A.W. & Goss, M.J. 1977. Effects of mechanical impedance on root growth in barley, *Hordeum vulgare* L. II. Effects on cell development in seminal roots. *Journal of Experimental Botany* 28, 1216-1227.

Acknowledgements

This thesis could not have been written without all the help I have received during my time as graduate student.

I would especially like to thank Tomas Rydberg for being a considerate boss, for taking care of all bureaucratic and financial matters, letting me dig into the world of roots leaving worldly matters behind.

Special thanks also to:

Johan Arvidsson for good advices, encouragement, maintained pressure and for teaching me the virtue of not to squander with words.

Richard Whalley, Lawrence Clark and co-workers at Silsoe Research Institute for the three great months I worked with them at the Institute.

Urban Svantesson for practical help, valuable discussions and for always being able to define the worst-case scenario of every situation.

All other friends and co-workers not already mentioned at the department of Soil Sciences that have enriched my time as a graduate student.

Mary McAfee for correcting my English with incredible precision and speed.

Camilla for endless support.

Financial support provided by FORMAS.