Biological and mechanical subsoiling in potato production – a participatory research approach

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Cover: A collaborative research group visiting a farm trial
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Abstract

Soil compaction in agricultural fields has increased due to the use of heavy agricultural machinery and intensified vehicular traffic. Compaction reduces total porosity, permeability and water-holding capacity in soil, leading to poorer aeration and impeded root development and nutrient uptake. Soil compaction occurs in topsoil and subsoil, but subsoil compaction is considered more persistent, complex and costly to alleviate. Mechanical methods such as deep tillage and biological methods such as use of deep-rooting crops are available to deal with soil compaction, but combining these methods might tackle compaction more efficiently. This thesis investigates the effects of mechanical inter-row subsoiling, biological subsoiling and a combination of these on soil penetration resistance, potato root length density, nutrient uptake, tuber yield and quality. Part of the study involved interdisciplinary methodology and participatory research, in which farmers, advisors and researchers formed a collaborative research group to develop effective methods to reverse soil compaction and improve potato production. To test hypotheses field experiments at an experimental farm and on seven collaborating farms in southern Sweden (Skåne, Blekinge and Östergötland) following the principle for the so called mother and baby (farm) trial design were performed. Inter-row subsoiling alone and in combination with preceding crops greatly improved soil penetration resistance. Root length density (RDL) was higher in the combined treatment than in the separate inter-row and biological subsoiling treatments. Nitrogen uptake increased with inter-row subsoiling which in starch potato trials could be shown as an increase in total tuber yield. A positive effect of autumn-sown oilseed radish as preceding crop treatment was shown in farm trials. The incidence of external and internal quality defects was low in all treatments.

The results from the field trials led to many interesting debates with participating farmers with specific knowledge of their own farm conditions and to a new, deeper understanding of the potato cropping system and potential improvements. Over time, the unique combination of a collaborative research group in connection with regional participatory learning and development groups became a combined boundary organisation. Such structures can close the gap between science and practical farming and contribute to innovation and capacity building among farmers and all stakeholders, and thus need to be created and maintained.

Keywords: preceding crops, subsoiling, soil penetration resistance, radish, tuber yield and quality, RLD, boundary organisation, collaborative research

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Dedication

To my sons Lino and Noa, the most precious persons I have in my life

Education is the most powerful weapon which you can use to change the world

Nelson Mandela

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Ekelöf J, Guamán V, Jensen ES, Persson P (2014). Inter-row subsoiling and irrigation increase starch potato yield, phosphorus use efficiency and quality parameters. *Potato Research* 58, 15-27.

II Guamán V, Båth B, Hagman J, Gunnarsson A, Persson P. Optimising soil structure using biological and inter-row subsoiling to improve the root system, nitrogen uptake and yield in potato. *European Journal of Agronomy* (Accepted for publication)

III Guamán V, Gunnarsson A, Båth B, Hagman J, Persson P. Assessing effects on potato yield and quality of biological and inter-row subsoiling in field experiments - participatory collaboration (manuscript).

IV Ljung M, Helmfrid H, Guamán V, Gunnarsson A, Persson P. The potential of boundary organizations as platforms for experiential learning, participatory development and responsible scaling out in agriculture (manuscript).

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The contribution of Victor Guamán Sarango to the papers included in this thesis was as follows:

I Co-author. Contributed to writing the introduction, analysis and summary of results. Was responsible for correspondence with the journal.

II First author. Planned and performed the field work and laboratory analysis. Data management and statistical analysis. Wrote the paper in collaboration with the co-authors. Was responsible for correspondence with the journal.

III First author. Planned and performed the field work in cooperation with the co-authors. Analysed and interpreted the results. Wrote the paper in collaboration with the co-authors.

IV Co-author. Planned the experiment and formulated the hypothesis in collaboration with the co-authors. Gathered material from meetings and focus groups.

Abbreviations

CR group	Collaborative research group
N	Nitrogen
NUE	Nitrogen use efficiency
N_{min}	Mineralisable N in the soil
PLD group	Participatory learning and development group
RLD	Root length density

1 Introduction

Potato (*Solanum tuberosum* L.) is the fourth most important food crop in the world, after maize, rice and wheat, and because of its versatility and adaptability to many environmental conditions it is now grown in 149 countries (Birch *et al*., 2012). Potato is also used in the manufacturing industry, *e.g*. in production of high quality paper, due to its starch composition with some unique features compared with starch from other crops (Blennow *et al*., 2003). Sustainable potato production faces many threats to cultivation, one of which is soil degradation. Soil degradation as an effect of soil compaction has become an important global issue because of its adverse impact on agronomic productivity and food security. It is estimated that 68 million hectares of land worldwide are affected by compaction from vehicular traffic (Flowers & Lal, 1998) and almost half of this land is in Europe (Oldeman *et al*., 1991, *cit*. Batey, 2009).

Soil compaction occurs when soil particles are pressed together, reducing pore space and changing physical properties of the soil, *e.g*. increasing soil resistance and bulk density. It is caused by external contact pressure applied to soil, *e.g*. when using heavier agricultural machinery and tillage implements, and it may occur in all types of soils (Hamza & Andersson, 2005; van den Akker & Canarache, 2001; Flowers & Lal, 1998; Wolfe *et al*., 1995). Soil compaction effects on soil structure and crop development are well studied (Nawaz *et al*., 2013; Westermann & Sojka, 1996). Compaction reduces total porosity, permeability and water-holding capacity in soils and also leads to poorer aeration and impeded root development and nutrient uptake (Nawaz *et al*., 2013; Wolkowski & Lowery, 2008; Håkansson, 1994).

Soil compaction occurs in both the topsoil and subsoil and it is important to distinguish between these forms. Research has shown that the effects of topsoil compaction can be partly alleviated by *e.g*. mouldboard ploughing, whereas subsoil compaction is a more complex and costly problem to alleviate (Zink *et al*., 2010; Arvidsson & Håkansson, 1996; Håkansson & Reeder, 1994).

Berisson *et al*. (2012) suggested that subsoil compaction may persist for more than a decade and, depending on the compaction severity, Batey (2009) concluded that the problem may persist for up to 30 years.

Yearly vehicular traffic on potato fields is reported to be approximately 300 Mg km ha^{-1}, compared with a yearly total transport intensity of 150 Mg km ha^{-1} in cereal fields (Håkansson, 2000). Potato is quite sensitive to soil physical conditions and the ideal soil for potato production is deep, well drained and loose (Pierce & Burpee, 1995). Potato is a crop with a sparse, shallow root system, which makes it sensitive to drought and soil compaction (Stalhamn *et al*., 2005; Lynch *et al*., 1995). However, great variation in root length within the crop has been found (Wishart *et al*., 2013; Iwama, 2008) and under optimal soil conditions potato roots can reach a maximum root depth of 1.40 m (Stalham & Allen, 2001). Potato root growth is greatly reduced at soil penetration resistance above 1 Mpa, whereas the roots of most other plant species can penetrate compacted soils with soil resistance of up to 2-3 MPa (Stalham *et al*., 2007).

Agronomic practices aimed at alleviating subsoil compaction, such as deep cultivation, have been tested in many studies (Copas & Bussan, 2004; Canarache *et al.*, 2000; Holmstrom & Carter, 2000). Although soil resistance decreased in many studies (Copas *et al*., 2009; Roos, 1986), the results have been inconsistent and often of small actual impact (Henriksen *et al*., 2007; Haldersson *et al*., 1993).

Another method to improve soil structure is the use of cover crops (preceding crops) (Raper & Bergtold, 2006). Depending on the soil type, preceding crops may be able to reduce the surface soil strength by 24-41% (Folorunso *et al*., 1992). In laboratory experiments, Löfkvist (2005) found a positive effect on penetration of hard layers by different plant species and concluded that plant roots have the potential to act as tillage tools. A study in Norway showed that ryegrass undersown as a cover crop in spring wheat and left in the field until October influenced the water stability of soil aggregates, aggregate size distribution, bulk density and pore volume (Breland, 1995). Other studies suggest that annual preceding crops are unable to improve subsoiling structure by creating new pores if soil is too compacted, whereas perennial species might be more effective (Cresswell & Kirkegaard, 1995). However, the use of different preceding crops for potato has not been extensively studied (Griffin *et al*., 2009).

1.1 Aims

The overall aim of this thesis was to study possible methods to ameliorate soil structure and counteract the negative effects caused by subsoil compaction in potato production. To achieve this, a collaborative learning process involving the participation of stakeholders (farmers, advisors, representatives of the potato industry and scientists) in conventional research was established. Specific objectives of the work were to:

- Determine the effects of inter-row subsoiling and possible interactions with irrigation on potato yield and quality (Paper I).

- Study the effects of preceding crop and a combination of preceding crop and inter-row subsoiling on potato root length density, root distribution, nitrogen uptake and total tuber yield (Paper II).

- Evaluate the effects of preceding crop, inter-row subsoiling and a combination of preceding crop and inter-row subsoiling on potato tuber yield and tuber quality in potatoes (Paper III).

- Describe the development of a boundary organisation where farmers, advisors and researchers learn and do research together, and to identify what is needed for scaling out and up of new ideas (Paper IV).

2 Potato

2.1 Potato production and applications

Potato production has been increasing constantly over the past decade and this crop is now grown in 149 countries due to increased demand for potato-based foods, potato products and the expanding uses of potato as a food and an industrial raw material (Birch *et al*., 2012). World production of potato in 2013 was 376 million tons, on a potato growing area of 19.3 million hectares (FAO, 2015). World average yield in 2010 was around 17.4 Mg ha^{-1}, but there is great variation and many of the developed countries are producing above 40 Mg ha^{-1} (FAO, 2015). The top five potato producing countries in the world are China, India, Russia, Ukraine and United States (Table 1).

Table 1. *Top five potato producing countries in the world*
Source: FAO (2015)

Country	Potato Production 2013 (million tons)	% of World Total
China	95.9	25.4
India	45.3	12.0
Russia	30.2	8.0
Ukraine	22.3	5.9
United States	19.8	5.2

A potato tuber is composed of 20% dry matter and 80% water (Prokop & Albert, 2008). Potato is mainly consumed fresh and the remaining proportion is processed into food products. Potato is a very important source of starch, and is used as a thickener and stabiliser in food products such as soups, custards, sauces, salad dressings, *etc*. It is also used to make noodles and pastas. The composition of potato starch, consisting of high phosphate content and starch granules roughly twice as large as other starch granules, makes potato in addition interesting for industrial use, *e.g.* manufacture of high quality paper.

3 Soil compaction

3.1 Cause and effects of soil compaction

In agricultural fields, soil compaction is widespread and has become an important global issue because of its adverse impact on agronomic productivity and food security. Approximately 33 million hectares of land in Europe are affected by compaction from vehicular traffic (Oldeman *et al.*, 1991, *cit.* Batey, 2009).

Soil compaction occurs when soil aggregates and particles are compressed into a smaller volume, causing changes in soil physical properties. These changes often involve increased bulk density and increased soil strength or penetration resistance. Compaction reduces total pore volume, modifies pore size distribution and decreases the proportion of large pores, but also modifies the geometry, morphology and connectivity of soil pores (Servadio *et al.*, 2001). In addition, it has effects on soil hydraulic conductivity and on infiltration rate.

The main cause of soil compaction is intensive farming of crops and animals, including short crop rotations and use and intensification of heavy machinery under unfavourable soil conditions, in particular at high water content in the soil at the time the pressure is applied (Heesmans, 2007; Hamza & Anderson, 2005). Soil compaction may also be caused naturally by heavy rain and shrinking process in the soil due to drying, and thus compaction has always been present in agricultural fields, but with the mechanisation of agriculture the risk has been aggravated (Batey, 2009).

In comparison with other types of soil degradation, compaction is the most difficult to locate, especially if there are no visible signs on the soil surface. Soil compaction is influenced by the following factors: soil water content, pressure applied to the soil, intensity of traffic, and type of soil. According to Soane and Van Ouwerkerk (1994), soil water content influences most soil compaction processes. Soils are compacted more severely when soil moisture content is at or near field capacity and therefore is important to stay off the field until the soil moisture conditions are right, in order to minimise soil compaction. Farming practices in most crops demand a series of cultivation operations that contribute to deterioration of soil structure. In potatoes, the operations involve *e.g.* ploughing, bed creation, stone gathering, planting, crop spraying (pests and weeds) and harvesting. During harvesting, the soil is exposed to stress by compaction by tractors, harvesting machines and trailers used to carry off the tubers. Furthermore, the amount of yield that needs to be harvested and transported off the field is far larger than in the past (Batey, 1990). Sandy soils, unlike clay soils, experience major changes in bulk density when they are subjected to small increases in compressive force because of their larger air content and low water-holding capacity (Stalham et al, 2005).

Soil compaction can be identified by measuring soil bulk density, penetration resistance, degree of aggregation, porosity, relative density and shear strength (McKenzie & McBratney, 2001; da Silva *et al.*, 1997). Soil resistance is assessed with a penetrometer, which involves measuring the force required to push a steel cone into the soil, divided by the cross-sectional area of the cone. However, this method has some limitations and the results may vary between different soils, but also within a given soil at different water contents (Dexter, 2002). Directly in the field, soil resistance can be determined by a visual and tactile approach, observing dense soil formations from a trench. Other factors such as root distribution, water percolation and relative soil moisture may also be used to identify soil compaction, since these are affected by compaction (Batey & McKenzie, 2006).

Soil compaction can occur in any layer in the soil and is categorised as topsoil or subsoil compaction. Furthermore, in most fields a compacted soil layer, known as the plough pan, can be detected in the upper subsoil. The shape, strength and thickness of the plough pan are often related to the pressure applied to the topsoil (Spoor *et al.*, 2003; Barraclough & Weir, 1988; Håkansson & Reeder, 1994). Soil compaction in the topsoil may lead to limitations on emergence and initial growth, as well as large decreases in yield, but natural processes or tillage may eliminate the negative effects. Nevertheless, subsoil compaction is a more complex and costly problem to alleviate and may persist for long periods, depending on the compaction severity (Zink *et al.*, 2010; Arvidsson & Håkansson, 1996; Håkansson & Reeder, 1994).

Soil compaction influences soil properties and processes, leading to poor crop growth, yield and nutrient uptake. Soil compaction is one of the major causes of poor root growth and root system expansion, together with water stress and hypoxia or anoxia (oxygen limitations) (Bengough *et al.*, 2006). The correlation between soil resistance and water content in the soil is very strong; in fact soil strength increases when the soil dries out, leading to more negative matric potential due to capillary forces (Whitmore & Whalley, 2009; Whalley *et al.*, 2005). Soil compaction in field conditions may affect root growth by inducing clustering of roots, limiting uptake of water and nutrients (Passioura, 1991). Furthermore, soil compaction affects the mineralisation of soil organic carbon and nitrogen, and also the concentration of carbon dioxide in the soil (Neve & Hofman, 2000).

3.1.1 Hard pans

The plough pan or traffic pan is a dense soil formation located below plough or cultivation depth, but its location and scope may vary depending on the production system used (Raghavan *et al.*, 1990). Pan formation is caused by compressive forces under repeated cultivation to the same depth for many years. The plough pan displays a platy structure with a horizontal orientation, often with signs of smearing on the surface of the compacted layer (Needham *et al.*, 2004). Presence of a plough pan can reduce yield potential by restricting the amount of soil available for the plant roots to explore.

The plough pan can act as an elastic bridge, spreading the stress over a wider area by reducing the stress transmitted deeper into the subsoil.

3.2 Subsoil compaction

The increasing weight of farm machinery and their use in unfavourable soil conditions increases subsoil compaction, representing a serious long-term threat to soil and crop productivity (Alakukku *et al.*, 2003). The primary factor affecting subsoil compaction is total load and therefore subsoil compaction occurs mainly when heavy field equipment is used on wet soils. Subsoil compaction can be seen as a long-term threat to soil productivity because of its persistence (Håkansson, 1994).

The effects of subsoiling on crop growth include changes in the distribution of roots between soil layers and in some cases confinement of root development to the upper part of the soil profile, restricting water and nutrient uptake by roots to smaller volumes of soil (Zink *et al.*, 2010; Miransari *et al.*, 2009; Lipiec *et al.*, 2003; Unger & Kaspar, 1994).

Compaction can be avoided by assessing the strength of the soil and adjusting stress limits accordingly. General recommendations are to restrict axle loads and inflation pressures with respect to soil type and soil moisture conditions (van den Akker & Simota, 2008).

3.3 Effects of soil compaction on potato growth and development

Soil compaction is reported to have a negative effect on tuber yield (Westermann & Sojka, 1996; Saini & Grant, 1980) and quality (Van Loom & Bouma, 1978). It may also reduce plant root growth, resulting in negative effects on plant uptake of water and nutrients.

The effects on water flow and storage caused by soil compaction may have a more serious effect than restricted root growth. Water is essential for plants to carry out physiological processes such as transpiration, photosynthesis, cell enlargement and enzymatic activities. Many studies indicate that potato is very sensitive to water stress compared with other species, *e.g*. the stomata of potato leaves close at relative small water deficits, leading to reduced transpiration (Harris, 1978; Rijtema & Aboukhaled, 1973; Shepherd, 1972).

The potato plant has a very fine, branching root system that can be strongly restricted by soil compaction in terms of both total root mass and maximum root depth. Compaction may also affect tuber development and, additionally, cause tuber set in shallower parts of the ridge (Sojka *et al*., 1993).

3.3.1 Root growth

There are few studies about the effects of soil compaction on root growth in potatoes (Stalham *et al*., 2005), probably because it is a tedious and laborious process (Iwama, 2008). The different methods available for root research include monolith sampling, soil coring, in-growth coring and use of minirhizotrons (Heeraman & Juma, 1993; Weaver & Voigt, 1950). The accuracy may vary between methods, but studies have shown that the monolith and core methods give reliable data about root biomass and root length density (RLD) (Machado & Oliveira, 2003; Böhm, 1979).

The level of compaction considered critical for root growth is dependent on soil texture, macroporosity, root depth and crop type (Pabin *et al*., 1998; Glinski & Lipiec, 1990). Roots growing in compacted soils are shorter, thicker and more branched than roots growing in uncompacted soils. Root distribution may be altered, often resulting in reduced root length in compacted soil and increasing root length in the overlying soil (Shierlaw & Alston, 1984). There is also evidence that water stress can arise following changes in root system architecture as a result of soil compaction (Tardieu, 1994). Compaction even affects uptake and transportation of nutrients due to changes in aeration, soil hydraulic diffusive properties and root growth (Lipiec & Stepniewski, 1995).

Potato is a crop with a sparse, shallow root system and is sensitive to drought and soil compaction at all stages of growth, from emergence to harvest (Stalham *et al*., 2005; Lynch *et al*., 1995). However, there is great variation in root length within the crop (Wishart *et al.*, 2013; Iwama, 2008). Stalham and Allen (2001) report that between 40 and 73 % of the vertical distribution of root length density in different potato cultivars is located in the upper 0.30 m of the soil.

The principal effect of soil compaction observed on potato root growth has been a reduction in rooting depth and density (Boone *et al*., 1978). In optimal soil conditions, it has been observed that potato roots can produce large amounts of root mass, with a maximum root depth of 1.40 m (Stalham & Allen, 2001). One explanation for the shallow development of potato roots in practical field conditions may be the inability of the potato root system to penetrate the plough pan (Gregory & Simmonds, 1992). At soil resistance greater than 1 MPa, potato root growth is greatly reduced, whereas roots of other crops can penetrate soil with resistance values of between 2 and 3 MPa (Stalham *et al*., 2007). Another explanation may be the morphology of the potato root system, which consists of generous short branches where lateral and basal roots originate to root extent (Weaver, 1926). When growing, roots rearrange the closest soil particles by pushing particles aside or in front of the root apex. However, at unfavourable levels of soil resistance root elongation rate decreases and the diameter of roots increases markedly, leading to clustered root growth which restricts root extension (Bengough & Mullins, 1990; Taylor & Ratliff, 1969).

Large root systems enhance nitrogen uptake efficiency from deeper soil levels (White *et al*., 2005; Westermann & Sojka, 1996; Pierce & Burpee, 1995). By monitoring the pattern of nitrate depletion, Asfary *et al*. (1983) found that potato roots were substantially more active below 0.30 m than at shallower depth. High root density in the subsoil is therefore of great importance at later stages of growth, when nitrate in the topsoil is depleted (Strebel *et al*., 1983).

Root system distribution can be studied by measuring root length density (RLD, cm/cm^3), root dry weight (RDW, g/m^2), total root length (TRL, km/m^2) or maximum depth of rooting (D_{max}, cm) (Stalham & Allen, 2001).

4 Mechanical and biological subsoiling

4.1 Mechanical subsoiling

Mechanical subsoiling is defined as tillage below a depth of 0.35 m according to ASAE standards (1999). Subsoiling applied between potato ridges is known as inter-row subsoiling. It is a type of precision tillage and shows advantages such as minimised surface disturbance and reduced operating costs (*e.g.* labour, fuel costs, *etc.*) compared with subsoiling over the entire field. Furthermore, it can be applied after planting as one of the last heavy field operations in order to avoid re-compaction during crop growth. Subsoiling is designed to improve soil structure by loosening and fracturing the compacted subsoils and hard pans, which subsequently improves drainage and aeration and reduces root penetration resistance (Keller, 2004). In a fine-textured soil, Roos (1986) observed that subsoiling decreased soil strength and bulk density, whereas porosity below hard pans increased.

Subsoiling to alleviate compaction in potato production has been tested in many studies (Copas & Bussan, 2004; Canarache *et al*., 2000; Holmstrom & Carter, 2000). Although soil resistance has been found to decrease in most studies (Copas *et al*., 2009; Roos 1986), the results regarding tuber yield have been inconsistent (Henriksen *et al*., 2007; Haldersson *et al*., 1993). Subsoiling for crops other than potatoes has given different results in terms of yield response with different soil types (Mullins *et al*., 1997). On a sandy loam soil, cotton yield was highest for both years of a study by Touchton *et al*. (1986), while yield results on a silt loam soil were significantly higher only in one year of the study.

Subsoiling should be carried out only under certain conditions. Subsoiling also needs to be carried out at appropriate time, since if soil moisture is too high subsoiling will be ineffective. A soil examination should be carried out prior to subsoiling in order to determine the need for this operation, since otherwise the structure risks being damaged and the operation would represent an unnecessary cost for the farmer (Hatley *et al.*, 2005). Subsoiling applied in wet conditions on silty soils has been shown to have a negative effect on yield, probably as a response to accelerated disintegration of unstable structural units (Soane *et al.*, 1987). Subsoiling has also been proven to have limited longevity and it is a practice that needs to be used on an annual basis to loosen compacted soil profiles and also increase crop yield (Willis *et al.*, 2007; Raper *et al.*, 2005; Busscher *et al.*, 2002; Hamilton-Manns *et al.*, 2002). Busscher *et al.* (1986) found that on a loamy sand subsoiled to a depth of 0.5-0.6 m, although the effects of subsoiling were still visible, soil strength increased to levels of 1.5-2.5 MPa one year after subsoiling.

Significant results have been observed in deep rooting levels and water supply as an effect of subsoiling (Ibrahim, 1985). Early emergence and decreased levels of erosion and infiltration have also been reported (Sojka *et al.*, 1993). According to Miller and Martin (1986), subsoiling has positive effects on deep rooting, which may result in improved water uptake and less susceptibility to water stress.

A disadvantage with subsoiling, apart from the cost, is the possible lifting of stones to plough depth as these must then be collected (Holmstrom & Carter, 2000). After subsoiling, the proportion of large pores increases markedly, which in turn increases hydraulic conductivity (Löfkvist, 2005). However, in most cases the compaction within the soil aggregates remains, preventing roots from entering.

4.1.1 Equipment

Subsoilers can vary greatly in both shape and use. Variation in draught force requirements and both above- and belowground disruption may be affected by the shape of the shanks. A study by Raper (2002) on the effects of different types of shanks in a sandy loam soil and a clay loam soil showed that shanks of a bentleg design required a lower draught force than straight shanks. A saving of between 27% and 37% in draught force can be achieved with appropriate selection of subsoiler (Raper, 2005).

4.1.2 Subsoiling depth

The most effective subsoiling depth can be chosen only after examination of the soil to determine the location, depth and thickness of the compacted soil. The shanks should be set to a depth just below the compacted layer. Examination of soils in order to look for compact layers is best done in early summer when the soil is still moist (Batey, 1990). Additional tillage energy is required if subsoiling is carried out at depths greater than necessary.

4.2 Biological subsoiling

There are many benefits to using crops in order to improve soil health and profitability in agricultural fields (Table 2). The use of deep rooting crops as a method to improve soil physical properties may be a solution to soil compaction. Creswell and Kirkegaard (1995) use the term “biological drilling” referring to the use of crops as alternatives to deep tillage by the creation of bio-pores in the subsoil by plant roots.

Cover crops increase soil carbon and nitrogen levels, decrease bulk density, increase hydraulic conductivity and increase soil moisture and water holding capacity (Hubbard *et al*., 2013; Hoorman, 2009). Roots grow through compact soil layers by exerting a growth pressure that deforms the soil ahead of and around the roots (Clark *et al*., 2001). This growth pressure is generated by decreasing internal plant cell water potential as an effect of turgor pressure, but also as an induced stress on the cell wall due to response to soil resistance by the root tip (Atwell & Newsome, 1990).

In laboratory experiments, Löfkvist (2005) found a positive effect on penetration of hard layers by different plant species and concluded that plant roots have the potential to be used as tillage tools. There are differences in the capacity of roots from different species to penetrate compacted soil layers. According to Materechera *et al*. (1991), thicker roots penetrate hard soils layers more effectively and their root elongation is constant in very hard soils. Studies in Norway have shown that undersown ryegrass in spring wheat, left in the field until October, influences the water stability of soil aggregates, aggregate size distribution, bulk density and pore volume (Breland, 1995).

Crucifer crops have been found to be faster at developing deep roots, at an estimated 10 weeks after sowing, and also achieve much higher root frequency in the subsoil (layers deeper than 0.8 m) than rye and other monocots (Thorup-Kristensen, 2001). Species belonging to the Brassica family have been demonstrated to have great capability for penetrating compacted soils. Forage radish (*Raphanus sativus* var. *niger* cv. Daikon) and rapeseed (*Brassica napus,* cv. ‘Essex’) show greater penetration capability than rye on fine loamy soils (Chen & Weil, 2010). Using a computer-assisted tomography technique, Hamza *et al*. (2001) observed that radish plants were able to loosen compaction by temporary decreases and increases in root diameter after the commencement of transpiration. Legumes are known as scavengers of residual nitrogen and for their ability to fix substantial quantities of nitrogen (Hoorman, 2009). Legumes may also be effective in improving soil structure due to their strong root system and ability to produce substantial amounts of residues (Snapp *et al.*, 2005; Jones *et al.*, 1998). According to Cochrane and Aylmore (1994), legumes stabilise soil structure more effectively than non-legumes while growing and constitute a major source of organic matter when decomposed. Soil type and environmental factors also influence the effects of biological subsoiling (Monroe & Kladivko, 1987).

Table 2. *Advantages and disadvantages of using cover crops. Source: Dabney* et al. *(2001).*

Advantages	Disadvantages
Reduction soil erosion	Must be planted when time (labour) is limited
Increase residue cover	Additional cost (planting and killing)
Increase water infiltration into soil	Reduce soil moisture
Increase soil organic carbon	May increase pest populations
Improve soil physical properties	May increase risks of diseases
Improve field trafficability	Difficult to incorporate with tillage
Recycle nutrients	Allelopathy
Legumes fix nitrogen	
Weed control	
Increase populations of beneficial insects	
Reduce some diseases	
Increase mycorrhizal infection of crops	
Potential forage harvest	
Improve landscape aesthetics	

4.3 Combined inter-row subsoiling and biological subsoiling

Little information is available regarding the effects of combining a preceding crop (biological subsoiling) with inter-row subsoiling in potato production. In cotton production, Raper *et al*. (2000) found that in three of four years of an experiment, a combination of subsoiling and use of rye as a cover crop in a silt loam soil gave the highest yields.

Use of a preceding crop and inter-row subsoiling after potato planting may be a good combination of methods to enhance the positive effects on soil structure, resulting in a better potato crop performance.

5 Collaborative research approach

5.1 The need for social innovation for learning

The Swedish agricultural sector is embedded in a fast-changing global context of market, technology, policy and regulatory settings that present both challenges and opportunities.

The application of science or innovations has long been thought to follow a top-down transfer process involving research being carried out by scientists, diffused by the advisory services and applied by farmers (Carr & Wilkinson, 2004). Lately, however, it has been found that the linear model of research diffusion is more complex and its flow is limited by strong boundaries between the actors. Farmers and scientists have been seen in the past as culturally different, but their roles in agricultural research are intertwined and not as distinct as they once were. Although scientists are trained to apply scientific methods to test hypotheses in a precise, methodological and deliberate way, farmers also perform experimentation when they encounter problems and search for quick solutions. Advisors, as intermediaries, act as interpreters of scientists' language into farmers' language.

There is a need within the agricultural sector to develop new arenas for social learning among stakeholders. It is not only the most innovative farmers who should improve their production, but the whole collective of farmers in a sector. All have to make a similar shift in order to be competitive.

5.2 Responsible scaling up and out

A core question is how to generalise from individual experiences and locally adapted inventions and scale out these experiences in an efficient and responsible way. Evidence suggests that the process of scaling up and out of innovations is not simple and that there are many thresholds and frictions. In international research, these difficulties have been elaborated upon in recent years and 'responsible scaling up and out' has been launched as an alternative view (Wigboldus & Leeuwis, 2013). In this perspective, the implementation problem is not viewed merely as a question of attitudes and technical feasibility, but also includes a deeper discussion of the underlying changes that contribute to improvement and development on an individual and collective level.

5.3 Boundary organisations

The concept of boundary organisations originates from science studies and it aims to help describe the increased interaction between scientists and farmers: "*Boundary organizations provide an institutionalized space in which long term relationships can develop and evolve, two-way communication is fostered, tools for management (such as models) are developed and utilized, and the boundary of the issue itself is negotiated*" (Cash, 2001, p. 450).

It is the "boundary" between *e.g.* farmers, advisors, suppliers and scientists that becomes an important site for negotiation and contestation of competing knowledge claims when these actors interact in new ways (Carr & Wilkinson, 2005).

5.4 Participatory learning and development groups

There has been an historical tradition in Sweden of developing informal and local network structures of farmers' study groups or participatory learning and development (PLD) groups. Activities within these groups include information exchange; use of members' farms for field experiments; experienced farmers acting as coaches for less experienced farmers; best practice meetings discussing a theme of common interest, *etc*. The farmers' field experiments are normally at large scale with a strip design and without replications. These experiments are of core importance for a dialogue and also as a tool for empowerment. The farmers' groups are guided by an external facilitator, often together with an advisor. The advisors also have the role of innovation brokers, focusing on demand articulation, strengthening links between participants and with the wider set of agricultural innovation actors, and 'gatekeeping' by bringing relevant external information and contacts into the networks.

5.5 BoT-A collaborative research group

This thesis is based on work made within a project "Biology and technology for improved land use in potato production – Collaborative learning for sustainable knowledge development" with the Swedish acronym BoT-A. The BoT-A collaborative research group (CR group) was developed to enable collaborative and social learning among stakeholders and bridge between research and practice. The method used was inspired by participatory action research, which can be defined as an "*systemic inquiry, with the collaboration of those affected by the issue being studied, for purposes of education and taking action or effecting change*" (Green *et al*., 2003, p 419).

The BoT-A CR group consisted of seven farmers, 10 researchers including a PhD student, seven advisors, a project coordinator and a consultant on collaborative work. The selection of the farmers was based on interest and willingness to learn and share knowledge concerning inter-row subsoiling and preceding crops in potato production.

The first CR group meeting took place in the beginning of 2011. The collaboration process consisted of two meetings per year, one in summer and one in winter. The summer meetings focused on informal discussions in the field, while in the winter meetings the group received quantitative feedback from the field work. BoT-A project activities and outcomes are scheduled in the timeline in paper IV, Appendix 1.

The CR group focused on mechanical and biological subsoiling in potatoes. Therefore regular field experiments on an experimental farm were established to study the effects of preceding crops and the combination preceding crops and inter-row subsoiling on tuber yield, quality, root length density, root distribution, and nitrogen uptake (Papers II and III). In addition, the farmers in the CR group carried out trials on their own farms according to the so-called 'mother and baby trial' design (Snapp *et al*., 2002; Snapp 2002, 1999). The mother trials comprised regular field experiments on an experimental farm, while the 'baby' trials in this study were trials on collaborating farmers' fields (farm trials). The aim of this approach was to improve user relevance and anchor results from the mother and farm trials, and to facilitate communication across different approaches to experimentation and information flow among stakeholder. The members of the CR group had a strong influence in decisions about measures to be tested in the mother trial, although project finances set some limitations.

Five farmer participatory learning and development groups (PLD groups) together with the CR group constituted BoT-A platform.

The PLD groups were introduced to the overall concept of the new platform and to the CR group at an early stage. Activities within PLD groups included information exchange; use of members' farms for field experiments; experienced farmers acting as coaches for less experienced farmers; best practice meetings discussing a theme of common interest, *etc*.

For a better understanding of the BoT-A platform and in order to systematise findings in the process, a model for programme evaluation (Brulin *et al*., 2009) was used (Figure 1).The learning process in the CR group in connection with long-lasting regional PLD groups is analysed in Paper IV.

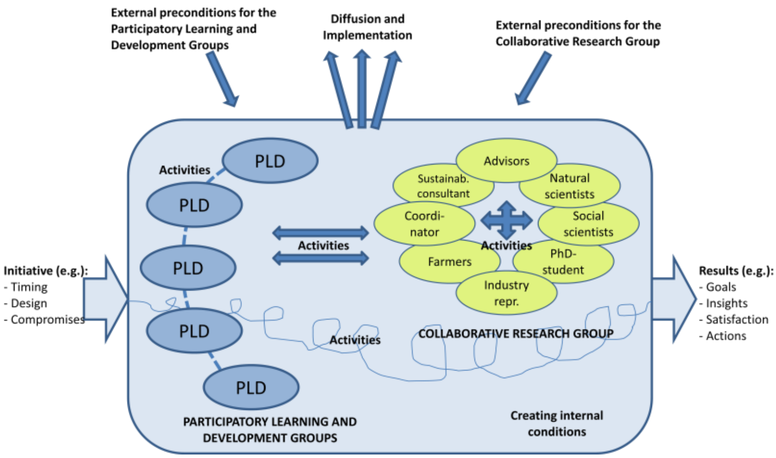

Figure 1. Model used for programme evaluation of the BoT-A platform. Source: Brulin et al. (2009).

6 Material and Methods

6.1 Experimental sites & design – field experiments

6.1.1 Paper I

Three plot experiments, arranged as a two-factorial completely randomised block design with the factors irrigation and inter-row subsoiling (four replicates), were conducted in 2008 and 2009 in Kristianstad, Sweden.

The potato cultivars used in the experiments were Kuras and Seresta, both commercial starch potato cultivars. The soil type consisted of a sandy loam with a plough pan located at 0.25-0.30 m depth.

6.1.2 Papers II & III

Two potato field experiments were carried out from 2011 to 2013 at Helgegården experimental farm, Kristianstad, Sweden; one using table potatoes and one using starch potatoes. The experimental design was a split-plot block with four replicates and the experiments were repeated from 2012-2014 on adjacent fields. The treatments consisted of a factorial combination of preceding crops as main plot and inter-row subsoiling as subplots. The field experiments with table potatoes were the same in Papers II and III, but the experimental field in Paper III included both table and starch potatoes. The potato cultivars used in the experiments were King Edward VII (table potatoes) and Kuras (starch potatoes). The soil type consisted of a sandy loam. In Paper III the two experiments were referred to as 'mother trials'.

6.1.3 Treatments – field experiments

6.1.3.1 Tillage system (Papers I, II & III)

The tillage system for the potato crop in the studies included in Papers I-III consisted of: a) normal tilling and b) normal tilling and inter-row subsoiling.

Normal tilling included mouldboard ploughing in the autumn (0.25 m depth) and harrowing in spring (1-3 passes, 0.12 m depth) prior to planting potatoes. Inter-row subsoiling was carried out to 0.55 m (Paper I) and 0.45 m (Paper II & III), measured from the levelled soil surface, one week after the potatoes were planted, using a subsoiler with four shanks (Agrisem International SAS, France) (Figure 2). The depth applied in the experiments in Paper III was decided after a series of pilot studies.

Figure 2. Agrisem cultiplow subsoiler with four shanks. a) Subsoiler shanks, b) subsoiler operating, and c) soil surface after subsoiling.

6.1.3.1 Irrigation regime

The experiment described in Paper I was supplied with drip irrigation in three different irrigation regimes: control (non-irrigated), moderate (30 kPa) and intensive irrigation (70 kPa). The amount of water applied at each irrigation was adjusted to the weather forecast and varied from 3 to 9 mm ha^{-1} day^{-1}.

In the experiments presented in Papers II & III, irrigation was not a treatment factor. The mother trial with table potatoes was irrigated on six occasions and the mother trial with starch potatoes on four occasions. On each irrigation occasion, the trials received approximately 20 mm of water.

6.1.3.2 Preceding crop (Papers II & III)

The preceding crops studied in Papers II & III were selected in consultation with the members of the CR group. To support the decision making on preceding crops, a demonstration trial with 20 possible ‘biological subsoiler’ crops was carried out in 2011 (data not shown). In addition to good loosening soil effects, other important factors taken into account prior to selection of the preceding crops were sanitisation effects on soil-borne pests and economic advantages, *e.g*. high production of biomass suitable for biogas production, fodder, *etc*.

The final selection of preceding crops to potatoes in the mother trials was as follows:

A Spring barley (*Hordeum vulgare* L., cv. Mercada)

B Spring barley and autumn-sown Chinese radish (*Raphanus sativus* L. ssp. *longipinnatus*, cv. Structurator)

C Spring barley and autumn-sown oilseed radish (*R. sativus* L. ssp. *oleiformis*, cv. Terranova)

D Summer-sown oilseed radish (cv. Terranova) – biomass harvested and removed

E Summer-sown oilseed radish (cv. Terranova) – biomass cut and left as green manure

F Blue lupin (*Lupinus angustifolius* L., cv. Probur) – harvested mature seed pods

G Second-year red clover (*Trifolium pratense* L., cv. Ares) – biomass harvested twice and removed

H Second-year red clover (cv. Ares) and summer-sown Chinese radish (cv. Structurator) – biomass of red clover harvested once and removed, biomass of Chinese radish cut and left as green manure.

In Paper II, the preceding crop treatments A, B, C, E and H with table potatoes were chosen to be included.

6.2 Farm trials (Paper III)

The farm trials were carried out from 2011 to 2013 in two adjacent fields located on farms belonging to the farmers involved in the CR group. The experimental design was a strip trial consisting of two blocks with preceding crops in main plots and tillage systems (no subsoiling or inter-row subsoiling) in subplots (Figure 3). Within each subplot, two cells were harvested. This design was chosen taking into consideration the need for large experimental units.

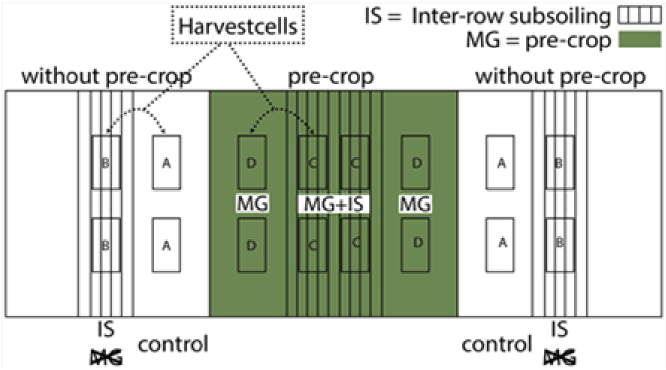

Figure 3. Experimental design (strip trial) used in farm trials

The farms were located in Skåne and Blekinge and Östergötland, southern Sweden (Figure 4).

Figure 4. Geographical location of the seven farms involved in farm trials 2011-2013 to study effects of preceding crop and inter-row subsoiling on tuber yield and potato quality. Each dot represents two field studies on the same farm.

6.2.1 Treatments

6.2.1.1 Preceding crop in farm trials

The preceding crop was either cereal (according to the farmer's normal practice) or one of the following possible biological subsoiling crops:

1) Chinese radish (cv. Structurator), autumn-sown
2) Oilseed radish (cv. Terranova), autumn-sown
3) Oilseed radish, biomass cut and left as green manure, summer-sown.

6.2.1.1 Tillage system

The tillage treatments were the same as for the mother trials and inter-row subsoiling was carried out with the same equipment and at the same depth and timing as in the mother trials (Paper III).

6.3 Potato management

6.3.1 Papers II & III

The nitrogen fertilisation rate was adjusted based on analyses of soil samples taken in spring, prior to potato planting, estimated potential N mineralisation from preceding crop residues, measurements of N status in plant sap of potato leaf petioles during the growing season, and yield and specific gravity (for table potatoes) estimates at the end of July.

6.4 Measurements and sampling

6.4.1 Field experiments

6.4.1.3 Soil penetration resistance (Papers I & II)

Soil penetration resistance in the experiments presented in Papers I & II was measured with a penetrometer (Penetrologger, Eijkelkamp, Netherlands). In the study presented in Paper I, the measurements were made in the subsoiled and in the normal tilling treatment plots on three occasions during the growing season: immediately after planting, three weeks after inter-row subsoiling and a few days prior to harvest. In the field experiments presented in Paper II, soil resistance was measured three weeks after the potatoes were planted.

6.4.1.4 Root growth (Paper II)

Sampling of roots was carried out in July 2013 and 2014 with soil cores (0.073 m inside diameter, height 0.05 m) at three horizontal spatial positions from four different depth layers measured from the soil surface after removal of the ridge (Figure 5). Roots were recovered by washing the soil cores under running tap water on a sieve with a mesh size of 1 mm. The clean roots were scanned and root length was determined by image analysis using the WIN-RHIZO software system (version 2007a, Regent Instruments) (Figure 6). The preceding crop treatments were grouped together in the statistical analysis in order to facilitate a more understandable presentation of the results and avoid confusion for the reader.

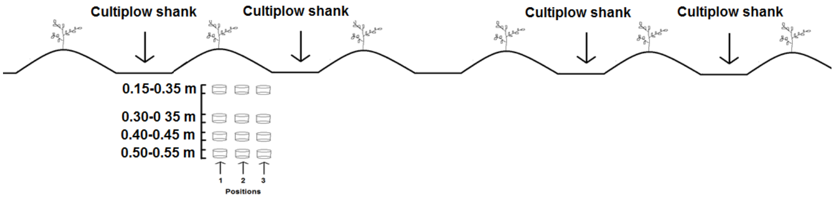

Figure 5. Sampling of roots at four depths: 0.15-0.20, 0.30-0.35, 0.40-0.45 and 0.50-0.55 m, and three horizontal spatial positions: (1) beneath the centre of the bed, (2) beneath the centre of the bed and the bottom of the furrow, and (3) beneath the bottom of the furrow.

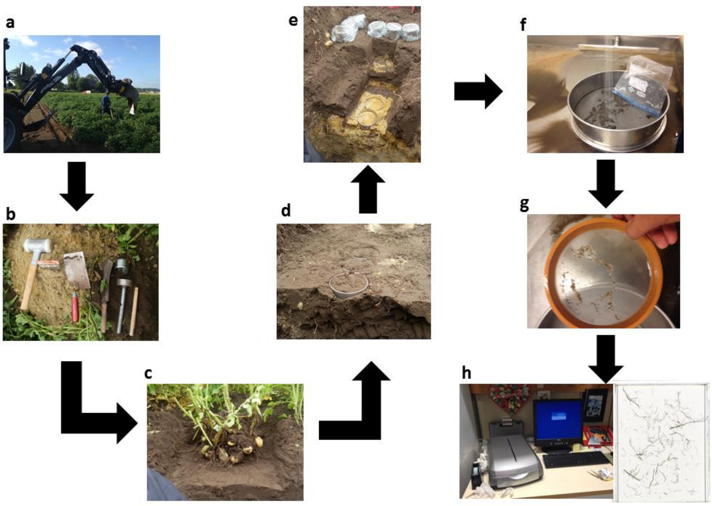

Figure 6. Sampling roots in the field with the core sampling method: a) excavation of hole, b) tools needed to start sampling, c) measuring depth beneath the potato plant, d) positioning the cores, e) sampling with cores in the subsoil, f) washing roots, g) clean roots, and h) scanning roots.

6.4.1.5 Yield & quality (Papers I & III)

Tuber yield, tuber size distribution and starch concentration were measured in the experiments. Starch content was calculated from specific gravity (weight in water divided by weight in air). In addition, tuber quality including external defects and cooking quality was evaluated.

6.4.1.6 Other measurements (Papers II & III)

Nitrogen uptake (Papers II and III) was determined on plant material sampled prior to haulm killing before leaf senescence and in tubers from material sampled at harvest. Yield-specific N use efficiency (NUE) was defined according to Moll et al. (1982) as: Fresh/dry matter production per unit crop N accumulation – N in tuber and haulm. Starch content was estimated from specific gravity calculations according to Maerker (von Schéele 1930).

6.4.2 Farm trials

6.4.2.1 Yield & quality (Paper III)

Tuber yield was measured by harvesting an area that ranged from 30 to 45 m^2 at two places within each plot (Figure 3). Tuber size distribution was also recorded. Starch content was calculated from specific gravity.

Due to differences in production type and cultivars on the different farms, analysis of external quality was carried out only on two farms located in Skåne and on two farms located in Östergötland. Cooking analysis was carried out only on tuber samples from the farms in Östergötland.

6.5 Statistical analysis

6.5.1 Papers I, II and III

In Paper I, the data were subjected to analysis of variance using the General Linear Model (GLM) procedure of IBM SPPS statistics 20.0 for Windows. Since cv. Seresta was grown only in 2009 and in a separate trial next to cv. Kuras, the year and cultivar factors were modelled as one factor called ‘cultivar year’. The main effects, two-way interactions and three-way interactions of irrigation, subsoiling and cultivar year were included in the model when average effects were evaluated. The block effect was also included in the model, but as a random factor. Blocks were nested within trials. When the effect of each individual trial (cultivar year) was evaluated, inter-row subsoiling, irrigation and inter-row subsoiling×irrigation were set as main factors, while block was kept as a random factor. Non-transformed data were used and the two yield estimates were evaluated separately. The Tukey *post hoc* test was used to test differences between the mean values when F tests were significant ($p<0.05$).

The data in Papers II and III were subjected to analysis of variance (ANOVA) using a linear mixed-effect model. In Paper II, the fixed effects when analysing RLD were year, depth, position and treatment, and the random effects of block, main plot, subplot and position. All random effects were assumed to be independent and normally distributed. The fixed effects when analysing N uptake, soil resistance and tuber yield were year, preceding crop and subsoiling, and the random effects block and main plot.

In order to facilitate presentation of the results in Paper II, they were subdivided into four groups: 1) control (*i.e.* barley as preceding crop without subsoiling), 2) inter-row subsoiling (*i.e.* barley and subsoiling post planting), 3) biological subsoiling (merging of preceding crops barley + Chinese radish, barley + oilseed radish, summer-sown oilseed radish, and red clover + Chinese radish without subsoiling), and 4) combination of inter-row subsoiling and the preceding crops in group (3). The results for RLD, soil resistance and N uptake are presented as the mean for two years.

The data in Paper III were subjected to ANOVA using a linear mixed-effects model with fixed effects of preceding crop, tillage system, year and their interactions, and random effects of block and main plot. The data from the farm trials were analysed using a liner mixed-effects model with fixed effects of site, year, preceding crop (cereal according to farmer's practice or "farmer's choice"), tillage system (no subsoiling or inter-row subsoiling) and their interactions. The random effects were block and main plot. As the preceding crop in farmer's choice was different on different farms, separate statistical analyses using this statistical model were performed for each crop type of farmer's choice.

Tuber yield, starch content, N yield, specific gravity and mineralisable N (N_{min}) were analysed using the mixed procedure of SAS, assuming normal distribution. The data on cooking quality from mother trials with table potatoes and from farm trials were subjected to the glimmix procedure of SAS assuming a binomial distribution. The Kenward and Roger method was used for computation of denominator degrees of freedom.

The models in Papers II and III were fitted using the SAS program (SAS Systems for Windows, release 9.1.3, SAS Institute).

6.6 Approach to analyse qualitative data

A multi-methodological approach (Mingers & Gill, 1997) was used to analyse and interpret the findings and to allow triangulation of data (Paper IV). The data within the BoT-A project were collected through different methods, such as focus groups, individual interviews, participant observations at platform meetings, evaluations, field testing and outcomes, as well as mimeos and documented reflections. At the end of the project, focus group methodology was used to evaluate the process and to test emerging hypotheses. The results presented in Paper IV are mainly based on the focus group discussions, but triangulated against other data sources collected over the whole project period. The choice was to have stakeholder-specific focus groups, so four groups were organised; a) farmers from PLD groups, b) farmers from the CR group, c) advisors and industry representatives, and d) researchers.

7 Results and Discussion

7.1 Evaluation of subsoiling effects on soil structure

Penetrometer measurements from the field experiments presented in Paper I showed decreased soil compaction in the subsoiled treatment in the entire soil profile. Inter-row subsoiling decreased soil compaction from approximately 5 to 1 MPa at 0.30 and 0.40 m depth. The effects were consistent during the whole growing period, although slight re-compaction in the subsoiled treatment was observed at the measurements carried out just before harvest.

Penetrometer data from the field experiments presented in Paper II showed that treatments with inter-row subsoiling differed from those without subsoiling regarding soil penetration resistance throughout the soil profile (Figure 7). In the control and biological subsoiling treatment, soil compaction increased at 0.20 m depth, reaching around 3 MPa at 0.30 m depth and remained at this value to 0.60 m depth. In the two treatments including inter-row subsoiling no such compaction boundary was evident and instead compaction began to increase at 0.35 m depth in the profile and reached the same compaction level as in the two other treatments at 0.60 m depth.

The loosening effects of inter-row subsoiling were verified in Papers I and II and are in line with earlier findings (Copas *et al.*, 2009; Roos, 1986). However, there was no difference in penetration resistance between the inter-row subsoiling and the combined treatments in Paper II. Moreover, there was no difference in soil penetration resistance between the control and the biological subsoiling treatment. It is likely that the full potential of the preceding crops was not reflected in our results, due to short growing periods. The decreased penetration resistance in the combination treatment is more likely to be an effect of inter-row subsoiling. The results from the biological subsoiling treatment are in accordance with earlier findings by Kautz *et al*. (2010), who studied effects of perennial alfalfa and grass/clover on soil resistance and found no general decrease in soil resistance in the subsoil and only slightly lower resistance in the topsoil. The benefit of using preceding crops to improve soil structure may thus be a long-term process that is difficult to study in short-term field experiments. According to Abdollahi and Munkholm (2014), autumn-established forage radish sown in five consecutive years on a sandy loam soil substantially decreased soil penetration resistance in the plough pan.

It was also remarkable that at 0.50 m depth, penetration resistance reached values close to 2 MPa a few weeks after operation with the subsoiler down to 0.55 and 0.45 m depth (Paper I and II). According to modelling studies by Stenitzer (1988), values of penetration resistance that restrict root growth vary from 1 MPa with low root strength to 1.7 MPa with high root strength, while penetration resistance values from 3 to 4 MPa are considered to stop root growth.

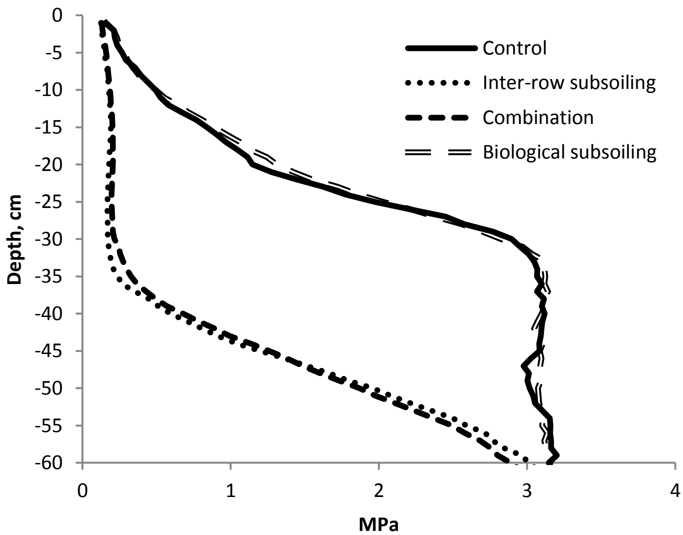

Figure 7. Soil compaction measured three weeks after planting of potatoes in the treatments: control, inter-row subsoiling, biological subsoiling and combination of inter-row subsoiling and biological subsoiling. Values presented are mean values from a two-year field experiment at Helgegården, Kristianstad, Sweden.

7.2 Root growth and root distribution

The highest root length density RLD value was recorded in the combined treatment including both biological and inter-row subsoiling (Figure 8), where

RLD was more than twice as high as in the barley control without subsoiling. RLD was higher in the inter-row subsoiling and biological subsoiling treatments than in the control, but lower than in the combined treatment. In the 0.15-0.20 and 0.30-0.35 m layers, RLD was lower in the barley control than in the other treatments. The RLD values in the 0.15-0.20 and 0.40-0.45 m layers were higher in the combined treatment than in the inter-row and biological subsoiling treatments as single treatments. In the 0.50-0.55 m layer no differences in RLD were observed between treatments. There were no differences at any depth between the inter-row and biological subsoiling treatments. Differences regarding RLD between years were found. In 2013, mean RLD was 25% higher than in 2014 but in 2014 RLD was higher in the 0.15-0.20 m soil layer than in 2013 (data not shown). At other depths, root development pattern was the opposite, with higher RLD values in 2013.

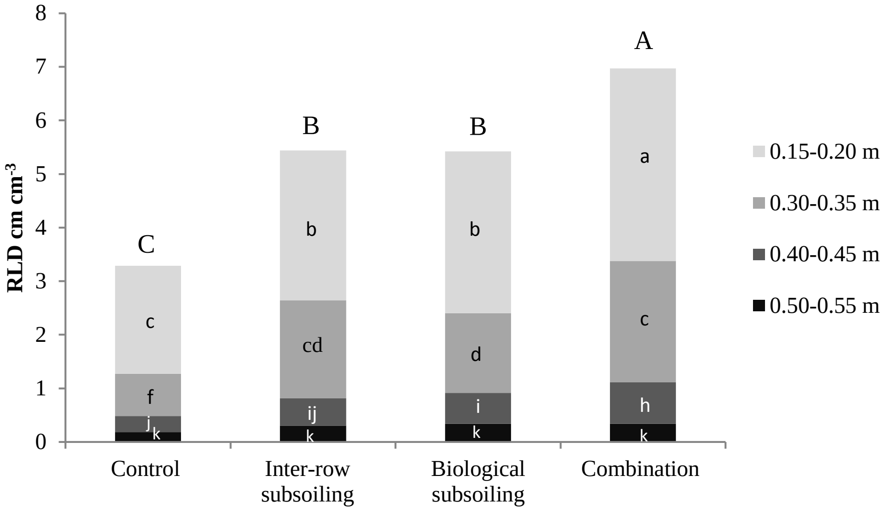

Figure 8. Root length density (RLD cm cm^{-3}) in four soil layers measured 58 days after emergence of potato. The values presented are mean values from a two-year field experiment at Helgegården, Kristianstad, Sweden. Different letter(s) indicate significant differences. Capital letters indicate differences between treatments, lower case letters differences between layers.

As in previous studies (Iwama, 1998, 2008), the results obtained for potato root distribution in this study demonstrated that most roots are located in the topsoil. Total RLD and RLD in soil layers down to 0.45 m were higher in the combined treatment than in the other treatments, which indicated that the combined treatment involving both inter-row and biological subsoiling encourages deeper rooting than applying these two treatments separately. It is also noteworthy that RLD was lower in the control treatment than in the other treatments, contradicting previous claims that total root length may not be affected by soil compaction due to growth compensation by unimpeded roots (Unger & Kaspar, 1994).

The higher soil penetration resistance in the treatment with biological subsoiling (Figure 7) did not result in lower mean RLD (Figure 8). Similarly, Seyed *et al.* (2011) found the highest values of RLD in soils with high penetration resistance. This may be because soil resistance is not the sole limiting factor determining rooting depth, which may also depend on soil texture, water availability, cultivar and changes in soil biological environment (Stalham & Allen, 2001).

RLD at the three different horizontal positions was lower in the barley control than in the other treatments in all cases (Figure 9). The highest values at all three positions were measured in the combined treatment. In the inter-row subsoiling treatment, the RLD value observed at position 3 (bottom of the furrow) was as high as in the combined treatment at this position and higher than the value observed at position 1 (beneath the centre of the bed) and position 2 (beneath the centre of the bed and at the bottom of the furrow). No differences in RLD between positions were observed in the other treatments.

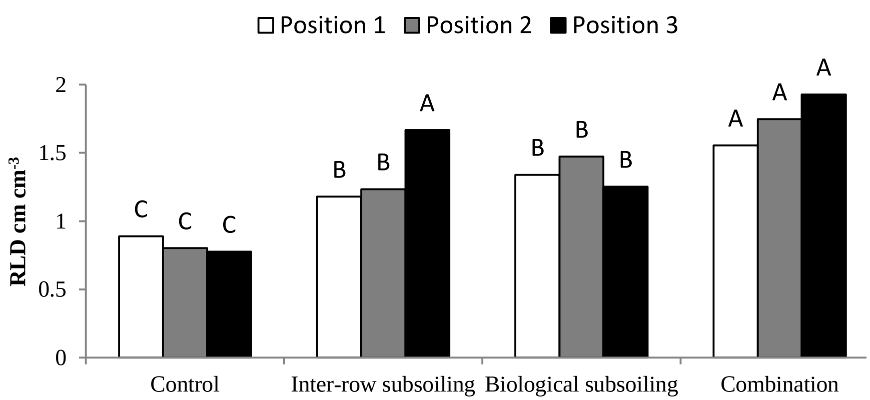

Figure 9. Root length density (RLD cm cm^{-3}) measured 58 days after emergence of potatoes at three different horizontal positions: 1 = beneath the centre of the bed, 2= beneath the centre of the bed and at the bottom of the furrow, and 3= beneath the bottom of the furrow. The values presented are mean values from a two-year field experiment at Helgegården, Kristianstad, Sweden. Different letter(s) for treatments and positions indicate significant differences.

Root distribution of potatoes has been reported to spread horizontally (Stalham & Allen, 2001), but the results in this thesis showed that for all treatments except the inter-row subsoiling treatment, root distribution was uniform beneath the ridge and the bottom of the furrow. In the treatment with inter-row subsoiling, RLD was higher beneath the bottom of the furrow than at the other horizontal positions, which according to Zhang and Davies (1989) may be due to improved aeration conditions in the furrow.

7.3 Yield & quality

7.3.1 Tuber, starch and nitrogen yields

The results obtained from the starch potato experiments presented in Paper I showed that inter-row subsoiling after potato planting, increased both total tuber yield (+7%) and starch yield (+7%). Inter-row subsoiling also significantly increased the proportion of tubers larger than 65 mm, by on average 20%, a positive quality for starch potato. Improved physical conditions of the soil allowing plants roots to growth deeper may be an important factor for the yield increases (Paper II; Roos, 1986).

Compared with the control, the intensive irrigation strategy increased average tuber yield by 14% and also the starch yield (+15%). However, since all irrigated plots responded positively to inter-row subsoiling, it is likely that other factors besides water availability, such as improved nutrient accumulation, contributed to the yield effects.

The results presented in Paper III showed that on loamy sand, inter-row subsoiling increased starch yield in mother trials with table potatoes by 2-4%, confirming findings in previous studies (Paper I; Pierce & Burpee 1995; Bishop & Grimes, 1978). The yield increase in starch potatoes in treatments with inter-row subsoiling was however lower than reported in Paper I.

Starch concentrations, but not always total tuber yield was affected by preceding crop. However, in starch potatoes, inter-row subsoiling showed positive effects on tuber and starch yields when barley was compared with the other preceding crops grouped together (Figure 10a, 10b). For starch potatoes in a cropping system where barley is the preceding crop, inter-row subsoiling may be a good strategy to increase tuber yield when a plough pan is confirmed. However, a ‘good’ preceding crop may match such positive effects (Figure 10a).

Specific gravity was affected by inter-row subsoiling, preceding crop and the interaction of these two factors. Inter-row subsoiling decreased specific gravity in potatoes, contradicting findings by Pierce and Burpee (1995) that subsoiling increases specific gravity in potatoes compared with conventional tillage with a mouldboard plough. However, tuber-specific gravity values suggest that all treatments yielded tubers of good quality.

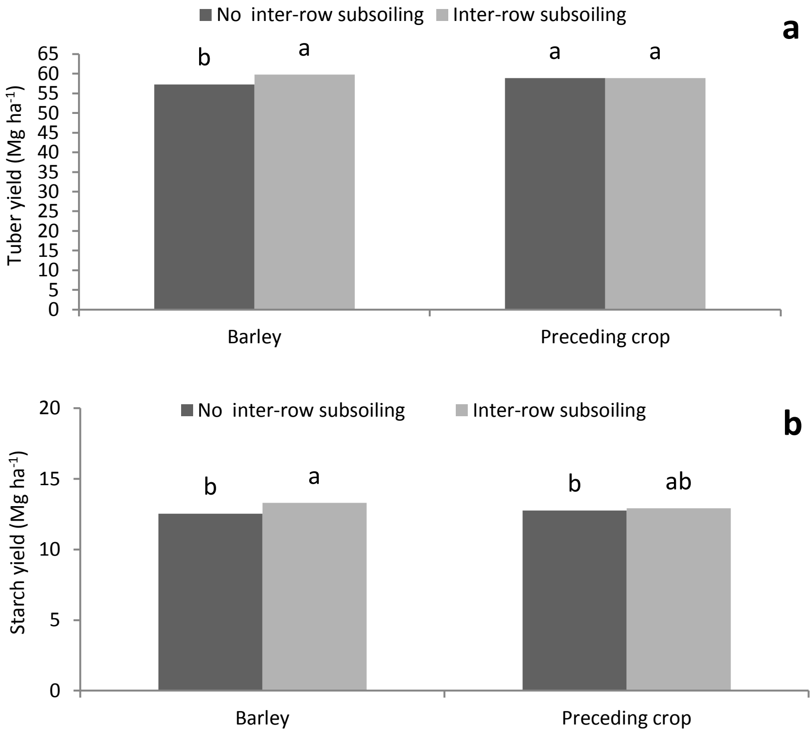

Figure 10. Starch potatoes: a) total tuber yield and b) starch yield. Mean of two field experiments (mother trials), Kristianstad, Sweden, 2013 and 2014. Bars marked with different letters are significantly different ($p<0.05$). Results of ANOVA using a linear proc mix model. Preceding crop = Chinese radish and autumn-sown oilseed radish, harvested summer-sown oilseed radish; summer-sown oilseed radish as green manure; lupin; red clover – harvested twice and red clover with Chinese radish as green manure. For tuber yield: main plot factor (i.e. preceding crop) $p=0.53$; subplot factor (i.e. tillage system) $p<0.05$; interaction $p=0.04$. For starch yield: main plot factor $p=0.57$; subplot factor $p<0.05$, interaction $p=0.04$.

In table potato trials, there was a significant interaction between inter-row subsoiling and preceding crop for tuber yield in the fractions <40 mm and >60 mm, but not in the marketable fraction 40-60 mm. In starch potatoes, tuber yield in the <40 mm fraction increased with inter-row subsoiling, while no differences was found in the largest fraction which was reported in Paper I where the amount of tubers in the larger fraction increased in the inter-row subsoiling treatment.

Yield of 40-60 mm tubers increased with inter-row subsoiling in farm trials in Östergötland (2.8 Mg ha^{-1}) and decreased in the mother trial with table potatoes (-0.7 Mg ha^{-1}) compared with no subsoiling. Yields of <40 mm tubers decreased and of >60 mm increased with inter-row subsoiling in table potato in the mother trials.

In table potato in the mother trials, N content in haulm and yield-specific NUE were higher with inter-row subsoiling than without. The N content in the haulm was higher when the preceding crop was harvested red clover than when the preceding crop was a non-legume crop. The effect of red clover on N yield in haulm was probably due to a high contribution of N, extending plant growth and delaying allocation of resources to the tubers. Likewise, the effects of inter-row subsoiling on N yield may be explained by better root growth and effective utilisation of nutrients and water (Paper II; Iwama, 1998).

7.3.2 Potato tuber quality

The incidence of external and internal quality defects was low for all treatments and differences were only shown for a few traits. In the mother trials with table potatoes, the incidence of common scab and greening increased for the inter-row subsoiling treatment compared with no subsoiling which could not be shown in the farm trials. In the farm trials in Skåne, the combination of inter-row subsoiling and oilseed radish decreased common scab, but increased growth cracks.

Wireworm injury was in the mother trial shown to be negatively connected with red clover as preceding crop. This was an expected result as red clover is known to be a good environment for wireworm multiplication (Shepl and Paffrath, 2005). In the farm trials with table potatoes in Östergötland, inter-row subsoiling decreased the incidence of wireworm damage. The incidence was low, but the wireworms seem to have been disturbed by the mechanical treatment.

For skinning, inter-row subsoiling clearly increased this defect compared with no subsoiling when the potato crop followed harvested red clover (G). The reason cannot be fully determined but a high N availability due to red clover may have prolonged the growing period, delaying the initiation of maturity and skin setting.

Cooking quality analyses showed that disintegration and sogginess in the mother trials and blackening in the farm trials in Östergötland were affected by the combination of preceding crop and inter-row subsoiling. In comparison with no subsoiling, inter-row subsoiling increased the probability of disintegration by 21% when tubers were grown after summer-sown oilseed radish used as green manure (E), but had no significant effect in tubers grown after any of the other preceding crops in the mother trials with table potatoes. In the farm trials in Östergötland, it was also found that the incidence of sogginess increased from 59 to 70 % in the following potato crop compared with cereal as preceding crop, whereas the incidence of after-cooking blackening increased by 7-8% in the treatment combination with oilseed radish as preceding crop + inter-row subsoiling compared with the other treatment combinations.

7.4 A new platform for learning

The results from focus groups discussions showed that some activities were more important than others in creating a sense of meaningfulness and commitment to the collaborative research group (CR group) among the participants. The group of researchers reported that the dialogue with the other participants had been of most value, especially when combined with farm and field visits. The advisors who had regular contact with researchers valued the field visits most, while for advisors who had a strong connection to practical farming it was the interaction with researchers that was most appreciated. The farmers participating in the CR group valued the deeper reflections on specific issues, the opportunity to gain an insight into the research process and the satisfaction of having their own hypotheses confirmed.

Farmers in the participatory learning groups (PLD groups) reported that the work in these groups resulted in new impulses, capacity building, more reliable knowledge, testing of new ideas adapted to their local contexts, a possibility to test their own ideas, creation of social openness and support among peers, making them feel safer and more confident overall. The informal character and size of these groups, the self-directed learning and the dialectic relationship between reflection and action all contributed to the view that such groups are valuable for both individual and farm development.

A feature shared by participants in the CR group and PLD groups was that their most important learning took place when interacting with other participants, learning from their experience, resulting in reflection upon their own limited horizon. However, learning also took place by listening to dissemination of research results or evaluations.

One important challenge in the CR group was that very few of the participants had previous experience of participatory learning and action research. This meant that only a few participants were able to grasp this complexity and envision the possible synergies between the different parts of the project, which affected their motivation and ability to contribute on a deeper level in the project. It was also found that for some individuals who had participated in other farmers' groups or participatory research projects, it was less difficult to navigate in the project and they also knew more about how to contribute. Furthermore, they had more trust in relation to the evolving character of the work, even if some of them also did not have an overview of all parts of the project. The sense of belonging to the project among participants was clear for those who had a clear role in the project, and they also felt more confident.

Farm experiments in combination with traditional research methods strengthened the possibility for scaling out of new findings. However, in the BoT-A platform connection between the PLD groups and the CR group was too weak, which limited scaling. Bridging individuals (too few in this project) are important for scaling out of emerging ideas. It is clear that this model is worthwhile developing further in the future.

A common view was that scaling out would not be possible if not supported by a skilled facilitator. A perhaps even more important component is that advisors take on the task of spreading findings and ideas between groups and also to other farmers not involved in groups. Advisors function as an intermediary and a knowledge broker.

In this study, a boundary organisation was defined as an organisational structure that provides an institutionalised space where long-term relationships can be developed, two-way communication is fostered, management tools are utilised and the boundary of the issue itself is negotiated between stakeholders. From this definition, it is clear that the PLD groups in BoT-A platform can be defined as boundary organisations, especially those involving farmers only and those involving farmers, advisors and industry representatives. However, the CR group also developed over time into a boundary organisation. Together, the two organisational structures created a strong platform for involving stakeholders and bridging the gap between research and practice. This combined boundary organisation is the BoT-A platform. While there is great room for further improvement, the evaluations and analysis show that this is a major step forward.

8 Conclusions

Potato farmers need to take action with the problem of soil compaction. Results from this thesis demonstrate that inter-row subsoiling alone and in combination with biological subsoiling can improve soil structure by decreasing penetration resistance. It also shows that potato roots can grow deeper into the subsoil as an effect of combining two subsoiling methods (mechanical, biological), thus showing that the combined treatment generated added value in root development compared with using the two treatments separately. This is especially important in supporting agronomic efforts to improve water and nutrient use efficiency in *e.g.* organic and integrated farming, agriculture in dry areas of the world and, in general, future scenarios of more restrictions concerning water and nutrient supply.

The results regarding tuber yield were variable in the field trials performed and it was difficult to generalise or to identify clear effects of preceding crop treatments and inter-row subsoiling on tuber yield. Inter-row subsoiling increased total tuber yield in some cases, whereas in others there was no response observed. The combination of biological subsoiling and inter-row subsoiling did not increase total tuber yield, so the hypothesis that combining these two subsoiling methods provides advantages concerning total tuber yield had to be rejected. Preceding crop treatments affected tuber marketable size, where harvested red clover as preceding crop gave significantly lower yield. However, the deviating results on the nature of this impact show the importance of performing studies at different sites under different conditions, *e.g.* using regular field experiments and farm trials in parallel, as in this thesis. Furthermore, preceding crops should be tested during longer periods of time to acquire consistent information about their effects on soil structure and potato crop performance.

Interdisciplinary methodology and a participatory research approach were employed in the work presented in this thesis. Farmers, advisors and researchers met to discuss specific research questions and, by participating in meetings, and performing regular field trials together with farm trials, developed more robust and applicable knowledge. Evaluation and analysis of the process showed that such work constellations offer the right structures providing an institutionalised space where long-term relationships can be developed, two-way communication is fostered, management tools are utilised and the boundary of the issue itself is negotiated between stakeholder participants. Funding bodies need to be aware that the success of projects developed by multi-actor participation rests on having the necessary resources to support an explorative initial stage and to develop an understanding of the process. The current funding system requires applications with a high level of specification, leaving no room for supporting upcoming ideas generated later on.

References

Abdollahi, L. & Munkholm, L.J., (2014). Tillage system and cover crop effects on soil quality: I. Chemical, mechanical, and biological properties. Soil Science Society of America Journal, 78, 262-270.

Alakukku, L., Weisskopf, P., Chamen, W.C.T., Tijink, F.G.J., van der Linden, J.P., Pires, S., Sommer, C., & Spoor, G., (2003). Prevention strategies for field traffic-induced subsoil compaction: a review Part1. Machine/soil interactions. Soil & Tillage Research, 73, 145-160.

Arvidsson, J. & Håkansson, I., (1996). Do effects of soil compaction persist after ploughing? Results from 21 long-term field experiments in Sweden. Soil & Tillage Research, 39, 175-198.

ASAE Standards, 45th Ed., (1999). EP291.2. Terminology and definitions for soil tillage and soil-tool relationships. St- Joseph, Mich.: ASAE.

Asfary, A.F., Wild. A. & Harris, P.M., (1983). Growth, mineral nutrition and water use by potato crops. Journal of Agricultural Science, 100, 87-101.

Atwell, B.J. & Newsome, J.C., (1990). Turgor pressure in mechanically impeded lupin roots. Australian Journal of Plant Physiology, 17, 49-56.

Barraclough, B. & Weir, A.H., (1988). Effects of a compacted subsoil layer on root and shoot growth, water-use and nutrient-uptake of winter-wheat. Journal of Agricultural Science, 110, 207-216.

Batey, T., (1990). Control of compaction on the farm. A personal view. Soil Technology, 3, 225-229.

Batey, T., (2009). Soil compaction and soil management—a review. Soil Use Manage, 25, 335–345.

Batey, T., & Mckenzie, D.C., (2006). Soil compaction: identification directly in the field. Soil Use and Management, 22, 123-131.

Bengough, A.G., Bransby, M.F., Hans, J., McKenna, S.J., Roberts, T.J. & Valentine, T.A., (2006). Root responses to soil physical conditions: growth dynamics from field to cell. Journal of Experimental Botany, 57, 437-447.

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.
Berisson, F.E., Schjønning, P., Keller, T,, Lamandé, M., Etana, A., De Jonge, L.W., Iversen, B.V., Arvidsson, J. & Forkman, J., (2012). Persistent effects of subsoil compaction on pore size distribution and gas transport in a loamy soil. Soil & Tillage Research, 122, 42-51.
Birch, P.R.J., Bryan, G., Fenton, B., Gilroy, E.M., Hein, I., Jones, J.T., Prashar, A., Taylor, M.A., Torrance, L., & Toth, I.K., (2012). Crops that feed the world 8: Potato: are the trends of increased global production sustainable? Food Security, 4, 477-508.
Bishop, J.C. & Grimes, D.W., (1978). Precision tillage effects on potato root and tuber production. American Potato Journal, 55, 65-71.
Blennow, A., Bay-Smidt, A., Leonhardt, P., Bandsholm, O. & Madsen, M.H., (2003). Starch paste stickiness is a relevant native starch selection criterion for wet-end paper manufacturing. Starch, 55, 381–389.
Boone, F.R., Bouma, J. & de Smet, L.A.H., (1978). A case study on the effect of soil compaction on potato growth in a loamy sand soil. I. Physical measurements and rooting patterns. Netherlands Journal of Agricultural Science 26, 405-420.
Breland, T.A., (1995). Green manuring with clover and ryegrass catch crops undersown in spring wheat: effects on soil structure. Soil Use and Management 11, 163-167.
Brulin, G., Svensson, L., Jansson, S. & Sjöberg, K., (2009). Lärande utvärdering genom följeforskning. Studentlitteratur, Lund.
Busscher, W.J., Bauer, P.J. & Frederick, J.R., (2002). Recompaction of a coastal loamy sand after deep tillage as a function of subsequent cumulative rainfall. Soil & Tillage Research, 68, 49-57.
Busscher, W.J., Sojka, R.E. & Doty, C.W., (1986). Residual effects of tillage on coastal plain soil strength. Soil Science, 141, 144-148.
Böhm, W., (1979). Methods of Studying Root Systems. Springer-Verlag, Berlin.
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.
Carr, A. & Wilkinson, R., (2005). Beyond participation: boundary organizations as a new space for farmers and scientists to interact, Society & Natural Resources, 19, 255-265.
Cash, D.W., (2001). ‘In order to aid in diffusing useful and practical information’: agricultural extension and boundary organizations, Science, Technology & Human Values, 26, 431-453.

Chen, G. and Weil, R.R., (2010). Penetrations of cover crops through compacted soils. Plant and Soil, 331, 31-43.

Clark, L.J., Whalley, W.R. & Barraclough, P.B., (2001). Partial mechanical impedance can increase the turgor of seedling pea roots. The Journal Experimental Botany, 52, 167-171.

Cochrane, H.R. & Aylmore, L.A.G., (1994). The effects of plant roots on soil structure. In: Proceedings of 3rd Triennial Conference "Soils 94", 207-212.

Copas, M. & Bussan, A.J., (2004). Influence of compaction and deep tillage on yield and quality of potato. Abstracts of 88th Meeting of the Potato Association of America, Scottsbluff, Nebraska USA, 8-12 August, 2004.

Copas, M.E., Bussan, A.J., Drilias, M.J. & Wolkowski, R.P., (2009). Potato yield and quality response to subsoil tillage and compaction. Agronomy Journal 101: 82–90.

Cresswell, H.P. & Kirkegaard, J.A., (1995). Subsoiling amelioration by plants roots – the process and the evidence. Australian Journal of Soil Research, 33, 221-239.

Dabney, S.M., Delgado, J.A., & Reeves, D.W., (2001). Using cover crops to improve soil and water quality. Communications in Soil Sciences and Plant Analysis, 32, 1221-1250.

da Silva, A.P., Kay, B.D. & Perfect, E., (1997). Management versus inherent soil properties effects on bulk density and relative compaction. Soil and Tillage Research, 44, 81-93.

Dexter, A.R., (2002). Soil mechanical notes. Course in agricultural soil mechanics, Swedish University of Soil Sciences, Uppsala, Sweden.

FAO (2012). *Food and Agriculture Organization*. *http://faostat.fao.org*.

Folorunso, O.A., Rolston, D.E., Prichard, T. & Louie, D.T., (1992). Soil surface strength and infiltration rate as affected by winter cover crops. Soil Technology 5, 189-197.

Flowers, M. & Lal, R., (1998). Axle load and tillage effects on soil physical properties and soybean grain yield on a mollic ochraqualf in northwest Ohio. Soil Tillage Research, 48, 21-35.

Glinski, J., & Lipiec, J., (1990). Soil physical conditions and plant ´ roots. CRC Press, Boca Raton, FL, 250.

Green, L.W., George M.A., Daniel, M., Frankish, C.J., Herbert, C.P., Bowie W.R., & O'Neill, M., (2003). "Appendix C: Guidelines for Participatory Research in Health Promotion," in Minkler, Meredith and Nina Wallerstein(eds), Community-Based Participatory Research for Health. San Francisco, CA: Jossey-Bass Inc.

Gregory, P.J. & Simmonds, L.P., (1992). Water relations and growth of potatoes. In: Harris PM (ed) The potato crop: the scientific basis for improvement. Chapman and Hall, London, 214-246.

Griffin, T.S., Honeycutt, C.W. & Larkin, R.L., (2009). Delayed tillage and cover crop effects in potato systems. American Journal of Potato Research, 86, 79-87.

Halderson, J.L., Mccann, I.R. & Stark, J.C., (1993). Zoned tillage for potato production. American Society of Agricultural Engineers 36, 1377-1380.

Hamza, M.A. & Anderson, S.H., (2005). Soil compaction in cropping systems. A review of the nature, causes and possible solutions. Soil & Tillage Research, 82, 121-145.

Hamza, M.A., Anderson, S.H. & Aylmore, L.A.G., (2001). Studies of water drawdowns by single radish roots at decreasing soil water content using computer assisted tomography. Australian Journal of Soil Research, 39, 1387-1396.

Hamilton-Manns, M., Ross, C.W., Horne, D.J. & Baker, C.J., (2002). Subsoil loosening does little to enhance the transition to no-tillage on a structurally degraded soil. Soil & Tillage Research, 68, 109-119.

Harris, P.M., (1978). Water. In: The potato crop. Ed. P.M. Harris. Chapman and Hall, London, 244-279.

Hatley, D., Wiltshire, J., Basford, B., Royale, S., Buckley, D. & Johnson, P. (2005). Soil compaction and potato crops. Research Review R260, British Potato Council, Oxford, UK.

Heeraman, D.A., & Juma, N.G., (1993). A comparison of minirhizotron, core and monolith methods for quantifying barley (Hordeum vulgare L.) and fababean (Vicia faba L.) root distribution. Plant & Soil, 148, 29-41.

Heesmans, H., (2007). Bibliography on current risk assessments in EU. PR1.1. Netherlands, Alterra, Wageningen UR. Report number: Specific Support Action SSPE0-CT-2006-044240.

Henriksen, C.B., Rasmussen, J. & Mølgaard, J.P., (2007). Potato tuber yield and quality and soil inorganic nitrogen as affected by timing of ridging with and without catch crops. Soil &Tillage Research, 94, 36-46.

Holmstrom, D.A., & Carter, M.R., (2000). Effects of subsoil tillage in the previous crop year on soil loosening and potato yield performance. Canadian Journal of Plant Science, 80,161-164.

Hoorman, J.J., (2009). Using Cover Crops to Improve Soil and Water Quality. Agriculture and Natural Resources. The Ohio State University.

Hubbard, R.K., Strickland, T.C. & Phatak, S., (2013). Effects of cover crop systems on soil physical properties and carbon/nitrogen relationships in the coastal plain of southeastern USA. Soil & Tillage Research, 126, 276-283.

Håkansson, I., (2000). Packning av åkermark vid maskindrift. Omfattning – effekter – motåtgärder. Rapport från jordbearbetningsavdelningen. Uppsala, 99.
Håkansson, I., (1994). Subsoil compaction by high axle load traffic. Soil & Tillage Research, 29, 105-306.
Håkansson, I. & Reeder, R., (1994). Subsoil compaction by vehicles with high axle load - extent, persistence and crop response. Soil & Tillage Research, 29, 277-304.
Ibrahim, B.A., (1985). Effect of subsoiling on corn and potatoes as affected by irrigation frequency. M.S. Thesis, Washington State University, Pullman.
Iwama, K., (1998). Development of nodal and lateral roots in potato under field conditions. Journal of the Faculty of Agriculture, Hokkaido University 68:33–44
Iwama, K., (2008). Physiology of the potato: New insights into root system and repercussions for crop management. Potato Research, 51, 333-353
Jones, M.E., Harwood, R.R., Dehne, N.C., Smeenk, J. & Parker, E., (1998). Enhancing soil nitrogen mineralization and corn yield with overseeded cover crops. Journal of Soil and Water Conservation, 53, 245-249.
Kautz, T., Stumm, C., Kösters, R. & Köpke, U., (2010). Effects of perennial fodder crops on soil structure in agricultural headlands. Journal of Plant Nutrition and Soil Science, 173, 490-501.
Keller, T., (2004). Soil compaction and soil tillage – studies in agricultural soil mechanics. Acta Universitatis Agriculturae Sueciae, 489, Swedish University of Agricultural Sciences, Uppsala, Sweden.
Lipiec, J., Arvidsson, J. & Murer, E., (2003). Review of modelling crop growth, movement of water and chemicals in relation to topsoil and subsoil compaction. Soil & Tillage Research, 73, 15-29.
Lipiec, J., & Stepniewski, W., (1995). Effects of soil compaction and tillage systems on uptake and losses of nutrients. Soil & Tillage Research, 35, 37-52.
Lynch, D.R., Foroud, N., Kozub, G.C. & Farries, B.C., (1995). The effect of moisture stress at three growth stages on the yield, components of yield and processing quality of eight potato cultivars. American Potato Journal, 72, 375-386.
Löfkvist, J., (2005). Modifying soil structure using plant roots. Doctoral Thesis. Acta Universitatis Agriculturae Sueciae, 60, Swedish University of Agricultural Sciences, Uppsala, Sweden.
Machado, R.M.A., & Oliveira, M.R.G. (2003). Comparison of tomato root distributions by minirhizotron and destructive sampling. Plant and Soil, 255, 375-385.

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.

McKenzie, D.C. & McBratney, A.B., (2001). Cotton root growth in a compacted Vertisol (Grey Vertosol). I. Prediction using strength measurements and 'limiting water ranges'. Australian Journal of Soil Research, 39, 1157-1168.

Miller, D.E. & Martin, M.W., (1986). The effect of irrigation regime and subsoiling on yield and quality of three potato cultivars. American Potato Journal, 64, 17-25.

Mingers, J. & Gill, A., (1997). Multimethodology. Wiley: Chichester, UK.

Miransari, M., Bahrami, H.A., Rejali, F. & Malakouti, M.J., (2009). Effects of arbuscular mycorrhiza, soil sterilization, and soil compaction on wheat (Triticum aestivum L.) nutrients uptake. Soil & Tillage Research, 104, 48-55.

Moll, R.H., Kamprath, E.J. & Jackson, W.A., (1982). Analysis and interpretation of factors which contribute to efficiency of nitrogen utilization. Agronomy Journal, 74, 562-564.

Monroe, C.D. & Kladivko, E.J., (1987). Aggregate stability of a silt loam soil as affected by roots of corn, soybeans and wheat. Communications in Soil Science and Plant Analysis, 18, 1077-1087.

Mullins, G.L., Burmester, C.H., & Reeves, D.W. (1997). Cotton response to in-row subsoiling and potassium fertilizer placement in Alabama. Soil & Tillage Research, 40, 145-154.

Nawaz, M.F., Bourrié, G. & Trolard, F., (2013). Soil compaction impact and modelling. A review. Agronomy for Sustainable Development, 33, 291–309.

Needham, P., Scholz, G. & Moore, G., (2004). Hard layers in soils. In: Soil guide: a handbook for understanding and managing agricultural soils (ed. G. Moore), Department of Agriculture, Western Australia, 4343, 111-115.

Neve, S., & Hofman, G., (2000). Influence of soil compaction on carbon and nitrogen mineralization of soil organic matter and crop residues. Biology and Fertility Soils, 30, 544-549.

Oldeman, R.,Kakkeling, R.T.A. & Sombroek, W. (1991). World Map on the status of human-induced soil degradation. An explanatory note. Global assessment of soil degradation. GLASOD. ISRIC – Winand Centre – ISSS – FAO – ITC, Wagening.

Pabin, J., Lipiec, J., Włodek, S., Biskupski, A. & Kaus, A., (1998). Critical soil bulk density and strength for pea seedling root growth as related to other soil factors. Soil &Tillage Research, 46, 203-208.

Passioura, J.B., (1991). Soil structure and plant-growth. Australian Journal of Soil Research, 29, 717-728.

Pierce, F.J. & Burpee, G.C., (1995). Zone tillage effects on soil properties and yield and quality of potatoes (Solanum tuberosum L.). Soil & Tillage Research 35, 135-146.

Prokop, S., & Albert, J., (2008). International Year of the Potato: Potatatoes, nutrition and diet. [online] Available from: *http://www.potato2008.org/*

Raghavan, G.S.V., Alvo, P. & McKyes, E., (1990). Soil Compaction in Agriculture: A View Towards Managing the Problem. In: Lal R. and B.A. Stewart (ed.) Soil Degradation, Advances in Soil Science, 11, 1-36.

Raper, R.L., (2002). Force requirements and soil disruption of straight and bentleg subsoilers for conservation tillage systems. ASAE Paper No. 021139. St. Joseph, Mich.: ASAE.

Raper, R.L., (2005). Subsoiler shapes for site-specific tillage. Applied Engineering in Agriculture 21, 25-30.

Raper, R.L. & Bergtold, J.S., (2006). Using In-row subsoiling and cover crops to increase use of conservation agriculture in the Southern U.S. Presented at an ASABE meeting, 061039.

Raper, R.L., Reeves, D.W., Burmester, C.H., & Schwab, E.B., (2000). Tillage depth, tillage timing, and cover crop effects on cotton yield, soil strength, and tillage energy requirements. Applied Engineering in Agriculture, 16, 379-385.

Raper, R.L., Schwab, E.B., Balkcom, K.S., Burmester, C.H. & Reeves, D.W. (2005). Effect of annual, biennial, and triennial in-row subsoiling on soil compaction and cotton yield in Southeastern U.S. silt loam soils. Applied Engineering in Agriculture, 21, 337-343.

Ross, C.W., (1986). The effect of subsoiling and irrigation on potato production. Soil & Tillage Research 7, 315-325.

Rijtema, P.E. & Aboukhaied, A., (1973). Crop water use in the Arab Republic of Egypt. FAO report. RNEA Cairo, 61.

Saini, G.R. & Grant, W.J., (1980). Long-term effects of intensive cultivation on soil quality in the potato-growing areas of New Brunswick (Canada) and Maine (U.S.A.). Canadian Journal of Soil Science, 60, 421-428.

Schepl, U. & Paffrath, A., (2005). Strategies to regulate the infestation of wireworms (Agriotes spp.) in organic potato farming: Results. Insect Pathogens and Insect Parasitic Nematodes: Melolontha IOBC wprs Bulletin, 28, 101-104.

Servadio, P., Marsili, A., Pagliai, M., Pellegrini, S. & Vignozzi, N., (2001). Effect on some clay soil qualities following the passage of rubber-tracked and wheeled tractors in central Italy. Soil & Tillage Research, 61, 143-155.

Seyed, H,A., Plauborg, F., Andersen, M.N. & Sepaskhah, A.R., (2011). Effects of irrigation strategies and soils on field grown potatoes: Root distribution. Agricultural Water Management, 98, 1280-1290.

Shierlaw, J., & Alston A.M., (1984). Effect of soil compaction on root growth and uptake of phosphorus. Plant and Soil, 77, 15-28.

Shepherd, W., (1972). Some evidence of stomatal restriction of evaporation from well-watered plant canopies. Water Resources Research, 8,1092-1095.

Snapp, S., (1999). Mother and baby trials: a novel trial design being tried out in Malawi Target newsletter of the Southern Africa Soil Fertility Network 17,8.

Snapp, S., (2002). Quantifying farmer evaluation technologies: the mother and baby trial design In: MR Bellon and J Reeves (eds), Quantitative analysis of data from participatory methods in plant breeding Mexico, DF: CIMMYT Publisher, 9-16.

Snapp, S., Kanyama-Phiri, G., Kamanga, B., Gilbert, R., Wellard, K., (2002). Farmer and researcher partnerships in Malawi: Developing soil fertility technologies for the near-term and far-term Experimental Agriculture, 38, 411-431.

Snapp, S.S., Swinton, S.M., Labarta, R., Mutch, D., Black, J.R., Leep, R., Nyiraneza, J. & O'Neil, K., (2005). Evaluating benefits and costs of cover crops for cropping system niches. Agronomy Journal, 97, 322-332.

Soane, G.C., Godwin, R.J., Marks, M.J. & Spoor, G. (1987). Crop and soil response to subsoil loosening, deep incorporation of phosphorus and potassium fertilizer and subsequent soil management on a range of soil types. Part 2: Soil structural conditions. Soil Use and Management, 3, 123-130.

Soane, B.D., Van Ouwerkerk, C. (Eds.), 1994. Soil Compaction in Crop Production. Developments in Agricultural Engineering Series, vol. 11. Elsevier Science, Amsterdam, Netherlands.

Sojka, R.E., Westermann, D.T., Kincaid, D.C., McCann, I.R., Halderson, J.L. & Thornton, M., (1993). Zone-subsoling effects on potato yield and grade. American Potato Journal, 70, 475-484

Spoor, G., Tijink, F.G.J. & Weisskopf, P., (2003). Subsoil compaction: risk, avoidance, identification and alleviation. Soil & Tillage Research, 73, 175-182.

Stalham, M.A. & Allen, E.J., (2001). Effect of variety, irrigation regime and planting date on depth, rate, duration and density of root growth in the potato (Solanum tuberosum). Journal of Agicultural Science, 137,251-270.

Stalham, M.A., Allen, E.J. & Herry, F.X., (2005). Effects of soil compaction on potato growth and its removal by cultivation. Research Review R261. British Potato Council, Oxford, UK

Stalham, M.A., Allen, E.J., Rosenfeld, A.B. & Herry FX., (2007). Effects of soil compaction in potato (Solanum tuberosum) crops. Journal of Agricultural Science, 145, 295-312.

Stenitzer, E., (1988) SIMWASER—A Numerical Model for Simulation of Soil Moisture Regimes and of Crop Yields, Mitteilung Nr. 32. Institute for Land Water Management Research, Petzenkirchen (in German, with English summary).

Strebel, O., Duynisveld, W.H.M., Grimme, H., Reuper, M. & Fleige, H., (1983). Wasserentziige durch Wurzeln und Nitratnachlieferung (MassenfluB und Diffusion) als Funktion von Bodentiefe und Zeit bei einem Zuckerriibenbestand. Dtsch. Bodenkundl. Ges. 38,153-158.

Taylor, H.M. & Ratliff, L.F., (1969). Root elongation rates of cotton and peanuts as a function of soil strength and soil water content. Soil Science, 108, 113-119.

Tardieu, F., (1994). Growth and functioning of roots and root systems subsjected to soil compaction. Towards a system with multiple signalling? Soil & Tillage Research, 30, 217-243.

Thorup-Kristensen, K., (2001) Are differences in root growth of nitrogen catch crops important for their ability to reduce soil nitrate-N content, and how can this be measured? Plant and Soil, 230, 185-195.

Touchton, J.T., Rickerl, D.H., Burmester, C.H., & Reeves, D.W., (1986). Starter fertilizer combinations and placement for conventional and no-tillage cotton. Journal of Fertilization Issues, 3, 91-98.

Unger, P.W., & Kaspar, T.C., (1994). Soil compaction and root growth: a review. Agronomy Journal, 86, 759-766.

Van den Akker, J.J.H. & Canarache, A., (2001). Two European concerted actions on subsoil compaction. Landnutzung und Landentwicklung / Land Use and Development, 42, 15-22.

Van den Akker, J.J.H. & Simota, C., (2008). Risk assessment methods of compaction. RAMSOIL report 2.3 accessible via www.ramsoil.eu dd October 2015.

van Loon, C.D. & Bouma, J., (1978). A case study on the effect of soil compaction on potato growth in a sandy loam soil. 2. Potato plant responses. Netherlands Journal of Agricultural Science, 26: 421-429.

Von Schéele, C., (1930). Om polarimetrisk bestämning av stärkelse i potatis samt sambandet mellan potatisens torrsubstans- och stärkelsehalt. Kungliga Lantbruksstyrelsen.

Weaver, J.E., (1926). Root development of field crops. McGraw-Hill, New York.
Weaver, J.E. & Voigt, J.W., (1950). Monolith method of root-sampling in studies on succession and degeneration. Botanical Gazette, 111, 286-299.
Westermann, D.T. & Sojka, R.E., (1996). Tillage and nitrogen placement effects on nutrient uptake by potato. Soil Science Society of America Journal, 60, 1448-1453.
Whalley, W.R., Leeds-Harrison, P.B., Clark, L.J. & Gowing, D.J.G., (2005). Use of effective stress to predict the penetrometer resistance of unsaturated agricultural soils. Soil & Tillage Research, 84, 18-27.
White, P.J., Broadley, M.R., Hammond, J.P. and Thompson, A.J., (2005). Optimising the potato root system for phosphorus and water acquisition in low-input growing systems. Aspects of Applied Biology, 73, 111-118.
Whitmore, A.P. & Whalley, W.R., (2009). Physical effects of soil drying on roots and crop growth. Journal of Experimental Botany, 60, 2845–2857.
Willis, T.M., Hall, D.J.M,, Mckenzie, D.C. & Barchia. I., (1997). Soybean yield as affected by crop rotations, deep tillage and irrigation layout on a hard setting Alfisol. Soil &Tillage Research, 44, 151-164.
Wigboldus, S. & Leeuwis, C., (2013). Towards responsible scaling up and out in agricultural development. An exploration of concepts and principles. Discussion paper. Centre for Development Innovation and Knowledge, Technology & Innovation Group, Wageningen UR (University & Research centre), the Netherlands.
Wishart, J., George, T.S., Brown, L.K., Ramway, G., Bradshaw J.E., White, P.J. & Gregory, P.J., (2013). Measuring variation in potato roots in both field and glasshouse: the search for useful yield predictors and a simple scree for root traits. Plant and Soil, 368, 231-249.
Wolfe, D.W., Topoleski, D.T., Gundersheim, N.A. & Ingall, B.A., (1995). Growth and yield sensitivity of 4 vegetable crops to soil compaction. Journal of the American Society for Horticulture Science, 120, 956-963.
Wolkowski, R. & Lowery, B., (2008). Soil compaction: causes, concerns, and cures. Cooperative Extension Learning Store, Madison.
Zhang, J. & Davies, W.J., (1989). Abscisic acid produced in dehydrating roots may enable the plant to measure water status of the soil. Plant, Cell & Environment, 12, 73-81.
Zink, A., Fleige, H. & Horn, R., (2010). Load risks of subsoil and depths of stress propagation in arable luvisols. Soil Science Society of America Journal, 74, 1733-1742.

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