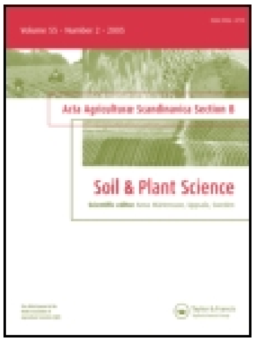

Acta Agriculturae Scandinavica, Section B — Soil & Plant Science

ISSN: 0906-4710 (Print) 1651-1913 (Online) Journal homepage: https://www.tandfonline.com/loi/sagb20

Root development in potato and carrot crops – influences of soil compaction

Tor J. Johansen, Mette G. Thomsen, Anne-Kristin Løes & Hugh Riley

To cite this article: Tor J. Johansen, Mette G. Thomsen, Anne-Kristin Løes & Hugh Riley (2015) Root development in potato and carrot crops – influences of soil compaction, Acta Agriculturae Scandinavica, Section B — Soil & Plant Science, 65:2, 182-192, DOI: 10.1080/09064710.2014.977942

To link to this article: https://doi.org/10.1080/09064710.2014.977942

Published online: 14 Nov 2014.

Acta Agriculturae Scandinavica, Section B — Soil & Plant Science, 2015
Vol. 65, No. 2, 182–192, http://dx.doi.org/10.1080/09064710.2014.977942

REVIEW ARTICLE

Root development in potato and carrot crops – influences of soil compaction

Tor J. Johansen[a*], Mette G. Thomsen[b], Anne-Kristin Løes[c] and Hugh Riley[b]

[a]*Arctic Agriculture and Land Use Division, Bioforsk – Norwegian Institute for Agricultural and Environmental Research, Holt, P.O. Box 2284, 9269 Tromsø, Norway;* [b]*Arable Crops Division, Bioforsk – Norwegian Institute for Agricultural and Environmental Research, Apelsvoll, Nylinna 226, 2849 Kapp, Norway;* [c]*Organic Food and Farming Division, Bioforsk – Norwegian Institute for Agricultural and Environmental Research, 6630 Tingvoll, Norway*

(*Received 11 August 2014; accepted 13 October 2014*)

Row crops such as potatoes (*Solanum tuberosum* L.) and carrots (*Daucus carota* L.) are of high economic value in the Nordic countries. Their production is becoming more and more specialized, including continuous arable cropping and heavier farm machinery, with increased risk of soil compaction. The result may be restricted root development and economic losses. Potatoes have widely branched adventitious roots, whereas carrots have taproots with fibrous roots extending from them. Under optimal soil conditions, total root length per surface area may reach more than 10 km m^{-2} for both species. Maximal root depth is about 140 cm for potato and more than 200 cm in carrots. Most of the root mass is usually distributed within the upper 100 cm, whereof more than 50% may be deeper than 30 cm. Soil compaction causes a dense soil with few large pores, poor drainage and reduced aeration, especially in wet soils with low organic matter content and high proportions of silt or clay. With compacted subsoil layers, roots will be concentrated more in the upper layers and thus explore a smaller soil volume. This will lead to reduced water and nutrient uptake, reduced yields and low nutrient utilization efficiency. In this review article, we describe the interactions between root development and soil conditions for potatoes and carrots, with special focus on sub-optimal conditions caused by soil compaction. We also discuss the effects of tilling strategies, organic material, irrigation and fertilization strategies and controlled traffic systems on root and yield development. To reduce subsoil compaction there is a need to implement practises such as controlled traffic farming, new techniques for ploughing, better timing of soil operations, crop rotations with more perennial crops and supplements of organic material. Moreover, there is a need for a stronger focus on the impacts of farm machinery dimensions.

Keywords: mechanical resistance; porosity; root measurements; root morphology; subsoiling

Introduction

Northern temperate and subarctic cool and humid climates are challenging for plant and root development and economic crop production. Depending on location, the soils are usually frozen during winter, leaving 3–6 months for growth during the summer. Some soils are also shallow due to their geological origin and relatively low pedological age (Wohlfarth et al. 2008). High bulk densities caused by glacial pressure are still often found in the subsoil. With global warming, the mean annual precipitation and temperature are now gradually increasing in Northern Europe (Olesen et al. 2011). Intense rainfall has become more frequent and the proportion of winter precipitation falling as rain has increased (Hov et al. 2013). Hence, high soil moisture contents are likely to occur more often, resulting in lower resistance to mechanical loads. In addition, with the decreasing number of farmers, farm machinery has become larger and heavier and tillage operations are often carried out under unfavourable (wet) soil conditions. In such cases, with low mechanical resistance in the soil, soil compaction and increased bulk density may occur. From this follows a reduction in the volume of macropores, which are important for both drainage and soil aeration. Scandinavian studies have

*Corresponding author. Email: tor.johansen@bioforsk.no

shown that this situation may persist in the subsoil for more than a decade (Berisso et al. 2013; Etana et al. 2013). The implications of soil compaction for plant and root growth are often easily seen on field headlands.

The importance of soil as a medium for plant growth, and the impact of soil conditions on root growth, water uptake and nutrient acquisition, have been long acknowledged (Russel 1912). Weaver (1926) also stressed that root growth is greatly affected by interactions between physical, chemical and biological conditions in the soil. More recently, Unger and Kaspar (1994) reviewed previous work and concluded that the most important effect of soil compaction is altered root distribution, with consequent limitation of water and nutrient uptake. However, they also focused on the ability of roots to find their way to zones of looser soil and on possible alleviation of compaction through soil management and tillage. New perspectives on plant root physiology have been presented by Passioura (2002) and Svistoonoff et al. (2007) who focused on the ability of roots to sense and signal limiting conditions in the soil (e.g. compaction or nutrient availability) with accordingly regulation of leaf or root growth. As concluded by Passioura (2002), such mechanisms may reduce productivity in annual crops.

Potato (*Solanum tuberosum* L.) and carrot (*Daucus carota* L.) crops are the main row crops grown in the Nordic countries. They have high economic value and require expensive inputs. The two species have very different development patterns and root growth. Potatoes have a widely branched adventitious root system developed from underground stems (stolons) and carrots have fibrous roots extending directly from a taproot emerging from the seed. In commercial production, possible yield declines caused by increased soil compaction from heavier machinery are hard to document, as other factors such as cultivars, fertilizer levels and climate have also changed over time. In controlled field experiments, however, ample evidence may be found for reduced yields of these crops due to both topsoil and subsoil compaction (Olymbios & Schwabe 1977; Strandberg & White 1979; Agung & Blair 1989; Hatley et al. 2005).

There is reason to believe that restricted root growth due to wet conditions and soil compaction will be an increasing problem for row crop producers in the Nordic countries. Hence, there is a need to gain more knowledge of root growth processes. Such knowledge is fundamental for optimizing soil tillage and the use of agricultural machinery as well as for irrigation and fertilizing strategies. Our main objectives are therefore to describe the root development of potatoes and carrots and discuss the interactions of soil conditions, including soil compaction, on root growth and crop yields.

Root growth and root function

Almost all plants require roots to provide anchorage and to take up water and nutrients. Plant roots are usually branched, but vary greatly in their morphology. Characteristics of special importance for nutrient uptake and plant growth are the root/shoot ratio, the root system dimensions, their topological properties (the pattern of root branching) and the distribution of the roots within the soil profile (Tinker & Nye 2000). In undisturbed soil there may be large differences in the function of different root parts, and some studies indicate that only about 10% and 30% of the total root length (TRL) is active in nitrate and water uptake, respectively (Hodge et al. 2009).

Root architecture may be understood as the spatial configuration of the number and length of lateral organs that comprise the root system (Hodge et al. 2009). Roots elongate by growth from the root tip, as a result of cell division in the meristem (tip) and cell growth within the elongation zone. This axial growth determines the root length and direction, and leads to exploration of new soil zones. The root tip is pushed forward into the soil, and especially by the formation of lateral roots and root hairs, the plant becomes anchored in the soil. For taproot crops with little lateral root development, the depth of the root has a significant impact on the plants' resistance to being vertically uprooted and/or blown over (Micovski 2002). Strong mechanical resistance in the soil is the most common physical limitation to soil exploration by roots (Hodge et al. 2009). Roots therefore follow the paths of least mechanical resistance, such as cracks and biopores.

Root development is flexible and roots may proliferate towards patches rich in nutrients (Drew & Saker 1975). This implies that placement of fertilizer plays a role in the roots' ability to acquire nutrients, as shown by Kristensen and Thorup-Kristensen (2007) who distributed soil inorganic N vertically by different management of cover crops. Shallow placement of N favoured N-uptake in shallow-rooted crops while deep placement favoured deep-rooted crops and increased their root depths. This ability of directed root growth varies strongly between species, and these authors proposed that knowledge about potential root growth should be considered when designing crop rotations for optimal N-use efficiency.

Dependent on the mineralization rate and their mobility in the soil, applied nutrients may reach the root surface by means of mass flow and diffusion fluxes rather than by root proliferation (Chapman et al. 2012, and references therein). However, for nutrients with restricted mobility, such as phosphorus (P), root proliferation and rhizosphere activity such as phosphatase extraction is very important. Other factors affecting the ability of roots to take up water and nutrients are soil temperature and aeration. Low temperatures decrease uptake due to high water viscosity, low cell membrane permeability and reduced metabolic activity of plants (Brar & Reynolds 1996). Reduced aeration may lead to hypoxia (low O_2) with effects on both root growth and root function (Hodge et al. 2009).

In a comparative study of root development in various crops on a loam soil in Norway, Riley (1989) found that potatoes had highest uptake of labelled P at 30–40 cm depth measured from the ridge-top, whereas the uptake in carrots was mainly from the topsoil. In the same study, potatoes took up water from somewhat greater depth than did carrots. Neither of the crops appeared to deplete soil moisture appreciably at depths greater than 70 cm in this soil type, probably because of very high bulk densities in the subsoil (>1.8 Mg m^{-3}).

Measurements of root growth

Root studies are demanding due to their position below the soil surface. High variability in root growth due to variable edaphic conditions, such as soil compactness, adds to this challenge (Micovski 2002). Several traditional methods used to study root systems were comprehensively reviewed by Smit et al. (2000) and Iwama (2008). 'Core sampling' is probably the most common method, in which several soil samples of a constant volume are taken from different soil depths to characterize root growth. In row crops, this method involves digging a trench across the rows, followed by root sampling, washing, scanning and calculation of their length by means of data software. Another common method is the installation of plexiglass tubes (minirhizotrons) diagonally into the soil, to allow the study of root development by means of repeated camera recordings (e.g. Rewald & Ephrath 2013).

New and non-invasive methods are developing and would be an appropriate tool for in-situ studies of roots (see Gregory et al. 2013), and they could also give information on soil physics and water distribution around single roots. However, such methods (as X-ray and neutron-radiography) have had too many limitations to be fully adopted (Hinsinger et al. 2009). In Norway, X-ray computed tomography (CT) was explored by Rosenfeld et al. (2002) for measuring taproot growth in carrot.

Common parameters for the description of root growth status are root length density (RLD) per unit soil volume (cm cm^{-3}), root dry weight (RDW) per soil surface area (g m^{-2}), total root length (TRL) per soil surface area (km m^{-2}) and maximum root depth (D_{max}, cm) (Stalham & Allen 2001). The rate of root growth may also be measured. In studies of the fine fibrous root system of carrots, TRL and RDW are often measured per plant instead of per soil volume or soil surface area. In addition, the total fibrous root surface area per unit plant weight (cm^2 g^{-1} dry root) is commonly measured (Pietola & Smucker 1998).

Root growth in potato

In potato plants, the greatest above-ground growth occurs 30–45 days after emergence (Kolbe & Stephan-Beckmann 1997a). This is also the period of maximum uptake of water and nutrients, in which more than 40% of total nitrogen uptake occurs. The stage of maximum biomass of roots coincides with that of maximum above-ground biomass, about two months after emergence (Kolbe & Stephan-Beckmann 1997b).

The roots which form from potato tubers are adventitious (nodal), as opposed to the primary roots of seed plants (Cutter 1992). Initially, they grow mainly horizontally and to no deeper than about 20 cm (Figure1a; Weaver 1926; Cutter 1992). There are relatively few roots directly below individual plants due to their initial horizontal growth. In plant rows, however, the roots will infiltrate throughout the entire soil volume after some time. The downward growth of roots (Figure 1b) is normally rapid in the first 3–5 weeks after emergence (1–2 cm d^{-1}), followed by a period with slow growth (<1 cm d^{-1}) which gradually ceases towards the end of season (Stalham & Allen 2001). A similar initial root growth rate (1.5–2 cm d^{-1}) was found in a Norwegian study on a loam soil (Riley 1989). The reduction, or cessation, in root growth rate after 3–5 weeks is preceded by a corresponding reduction or cessation of leaf growth some days earlier. Thus the root development of different potato varieties may be characterized indirectly through observations of leaf development (Stalham & Allen 2001).

Within the potato ridges, RLD may typically reach 1–2 cm cm^{-3}, but below the ridges it is seldom more than 1 cm cm^{-3} (Vos & Groenwold 1986). Beneath the furrows there is initially less root development than within the ridges, but this can equalize later in the growth period. At about 50 cm soil depth, roots are normally homogenously distributed about 35 days after emergence (Stalham & Allen 2001). In a study of RLD at different sampling positions, Stalham and Allen (2001) found a maximal RLD of 5.5 cm cm^{-3} at 20 cm depth in the flank of the ridge. These authors state that the root system of

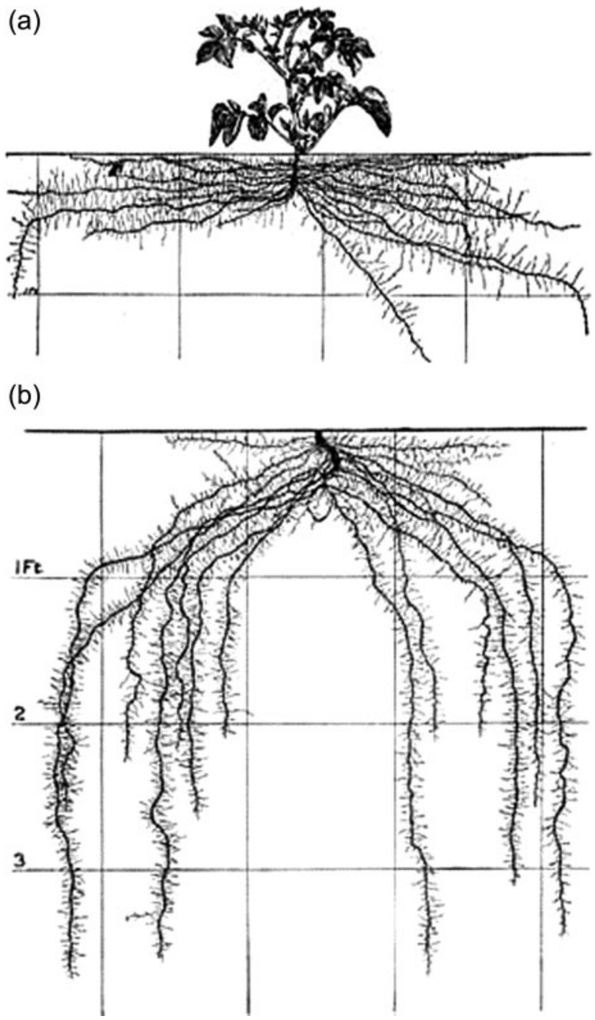

Figure 1. Illustration of early (a) and fully developed (b) roots in potato.
Source: Weaver (1926).

potato is generally less surface-orientated than suggested in most of the current literature. In their vertical measurements of RLD, when TRL was close to its maximum, an average of about 50% and 61% of roots were concentrated in the 0–30 cm soil layer under non-irrigated and irrigated conditions, respectively. Besides irrigation, soil physical conditions will influence the distribution of roots in different soil depths (Ahmadi et al. 2011).

Although RLD is generally higher in potato than in other vegetable crops, the levels are lower than those usually found in wheat, maize and sugar beet (Iwama 2008). Regarding TRL, Iwama (2008) reported measurements of 10–20 km m^{-2} in potatoes. Root depth of potato may vary between cultivars and soil conditions, and the maximum value (D_{max}) that we have come across was as much as 140 cm (Stalham & Allen 2001). Both RDW and TRL may vary between cultivars. Under favourable growth conditions, late cultivars normally develop a larger root mass than do earlier cultivars. Under dry soil conditions, however, different drought tolerance may cause high variation between cultivars within both early and late maturity classes (Iwama 2008). In general, genotypes with large root masses are less susceptible to drought stress than those with smaller roots (Deguchi et al. 2010; Wishart et al. 2014), and there is a positive correlation between total root mass and final tuber yield (Iwama 2008; Wishart et al. 2013).

Root hairs represent significant extensions of the root surface, and may be of great importance for rhizosphere activities. Most plants have root hairs, and Dechassa et al. (2003) have reported an average length of 0.18 mm in potato. These authors also found that root hairs contributed to about 50% of the total P uptake in potatoes.

Root development in potato seems to be strongly affected by irrigation regime, and is deepest when soil moisture is moderate in the upper layers (Stalham & Allen 2001). Deep root development can thus be achieved by limiting irrigation during early growth phases. Deep roots reduce the need for irrigation in dry periods. This may account for the positive yield responses after early drought periods that were found in several Scandinavian irrigation trials (Linnér 1984; Dragland 1985; Riley 1990), provided adequate soil moisture was maintained later.

Root growth in carrots

Carrots give priority to shoot growth for a long period after emergence and may reach a maximum photosynthetic capacity as late as 90–130 days after sowing. The most intense growth of the edible roots starts late and continues throughout the autumn in late-harvested crops (Salo 1999; Suojala 2000). The edible roots are storage organs for assimilates and consist of an enlarged fleshy taproot where the upper 2–3 cm has developed from the hypocotyl (Weaver & Bruner 1927). According to these authors, the upper part of the taproot may reach a diameter of 4–6 mm about 1.5 months after sowing, tapering to about 1 mm at about 80 cm depth. During this first growth period, few branches occur on the taproot (Figure 2a). These results correspond well with Norwegian reports of limited uptake of labelled P in carrots until four weeks after emergence (Riley 1989).

Weaver and Bruner (1927) found that the upper 15–20 cm of the taproots had reached a thickness of about 2.5 cm two to three months after sowing. Deeper than this, the taproots became gradually thinner and were found to a depth of 1.3–1.5 m (Figure 2b). At this stage several 40–60 cm long lateral fibrous root branches developed, mainly horizontally, in the upper 20 cm soil layer. These were further branched with short roots. At the time

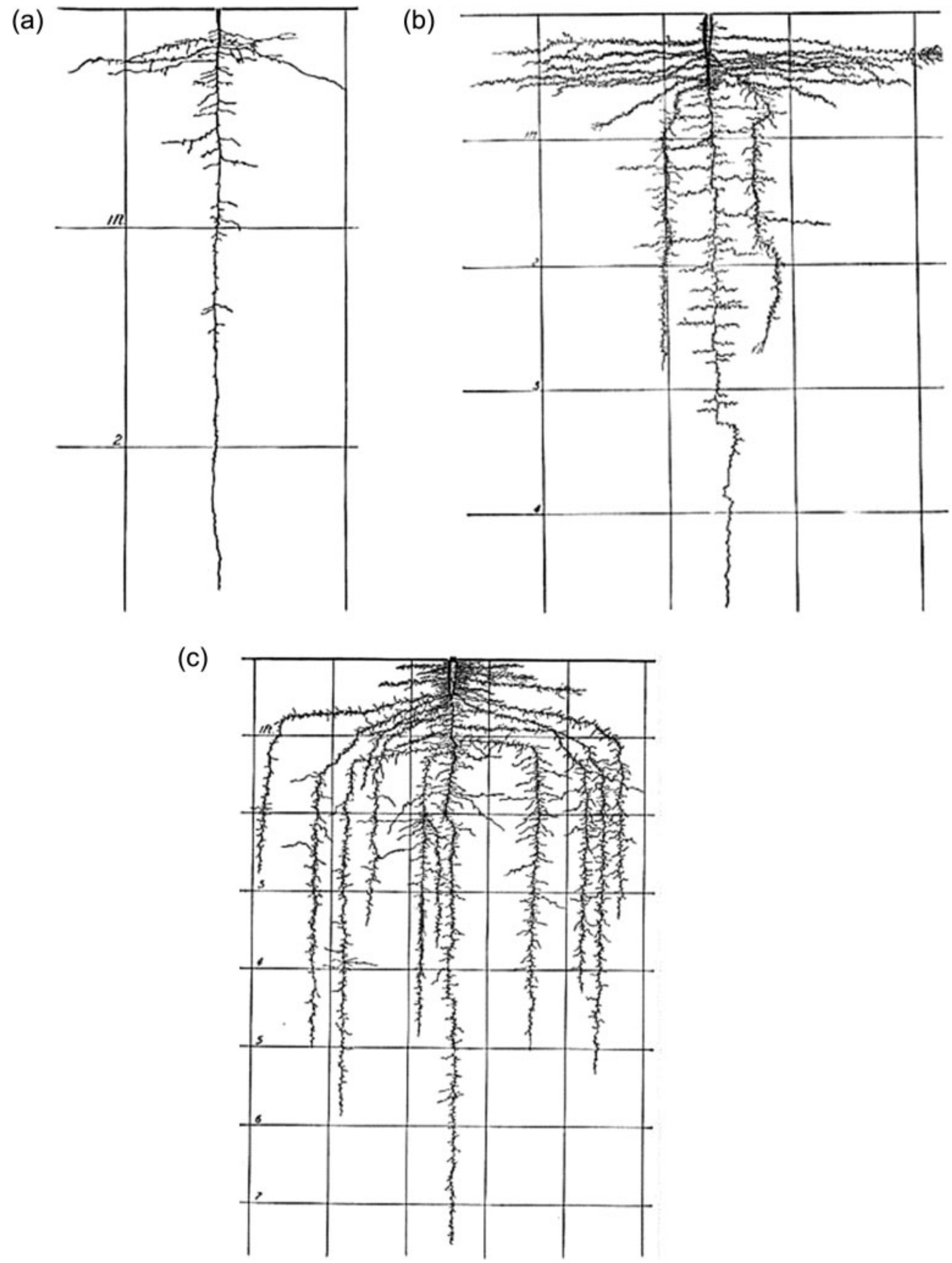

Figure 2. Illustration of early (a), medium (b) and fully developed (c) roots in carrot.
Source: Weaver and Bruner (1927).

of harvest (3.5 months after sowing), most of the root branches had started to grow vertically downward and had reached a depth of 90–180 cm (Figure 2c). The maximum depth of the thin taproot was 2.3 m at this stage. These early descriptive measurements of carrot growth have been supplemented by more recent studies of root growth in 150 cm deep polyvinyl chloride (PVC) pipes (Westerveld et al. 2006). In the latter study it was shown that the carrot root system extended to about 150 cm depth and that more than 50% of the lateral root system was found below 30 cm depth.

Root development studies using minirhizotrons have shown a linear relationship between root depth and accumulated temperature (degree days, °C) based on measurements within the 10–90 cm rooting depths (Thorup-Kristensen & Van den Boogaard 1999; Kristensen & Thorup-Kristensen 2007). The average rate of rooting depth was about 0.75 mm per degree day. Extrapolation of this growth rate until harvest would give a final rooting depth of about 1.6 m (Thorup-Kristensen & Van den Boogaard 1999), which corresponds well with the findings of Weaver and Bruner (1927). In a study of N-uptake by different plant species, carrots had a significant uptake down to 1.3 m depth, whereas white cabbage took up N even below 2 m depth (Kristensen & Thorup-Kristensen 2004). By contrast, more shallow-rooted crops, such as onion and lettuce, have maximum root depths of approximately 0.3 and 0.6 m, respectively (Thorup-Kristensen 2006).

Measurements of carrot roots within PVC cylinders show that 75–90% of the TRL of carrot roots consists of very fine fibrous side roots, with a diameter of about 0.15 mm and a TRL per plant ranging from 130 to 305 m (Pietola & Smucker 1998). This implies a very large root surface area of 1500–2000 cm^2 g^{-1} dry root weight. Furthermore, the RLD was measured to 0.2–1.0 cm cm^{-3} in the 0–30 cm soil layer, which is a lower density than that of potatoes. Kristensen and Thorup-Kristensen (2004) measured a TRL in carrots of 11 km m^{-2}, which is comparable to the levels found in potato.

Root hairs on carrot roots are very short, with an average length of only 0.03–0.04 mm (Itoh & Barber 1983; Dechassa et al. 2003). This is only about 20% of the root hair length found in potato, and root hairs in carrots do not seem to contribute to more than 0.3% of the P uptake (Dechassa et al. 2003). The most important characteristic to ensure P uptake in carrots seems to be a large root area per unit of plant weight (Itoh & Barber 1983).

Based on X-ray CT of carrot storage root growth, root elongation appears to be a continuous process (Rosenfeld et al. 2002). It seems to elongate faster at low temperatures (9–12°C) than at higher temperatures (18–21°C; Rosenfeld et al. 1998; 2002). The formation of a rounded root tip was completed about 45 days after seed germination, irrespective of temperature within the range from 12°C to 21°C (Rosenfeld et al. 2002). Although these carrots had well-rounded root tips, they continued to elongate until harvest. At the lowest temperatures (9–12°C) this elongation partly took place by bulbous growth below the rounded root end, which later became part of the storage root. At higher temperatures (18–21°C) storage roots appeared to elongate by a continuous increase in thickness of the lower parts.

Soil compaction and root growth

Soil compaction, mainly from heavy traffic, is a result of soil aggregates being forced together causing a decline in the amount of large pores (>30 μm), poor drainage and reduced aeration (Wolkowski & Lowery 2008). The soils most susceptible to compaction appear to be wet soils, especially those with low organic matter content and high proportions of silt and clay. Sandy soils, although forming weaker aggregates, may also be compacted (Wolkowski & Lowery 2008). Once compacted, sandy soils show little natural recovery as, unlike clay soils, they have low swelling and shrinkage. In addition to direct restriction of root growth, soil compaction may lead to long-term negative effects such as increased emissions of greenhouse gases, increased run-off and erosion, as well as increased requirements for fertilizer and traction power (Soane & van Ouwerkerk 1995).

Three main sources of mechanical resistance restrict root penetration into the soil (Bengough et al. 2011). These are the pressure required to expand cavities, the pressure to overcome soil friction and, finally, the turgor expanding cell vacuoles which must overcome the tension in their cell walls. In cultivated soils used for row crops, a dense compacted layer often underlies loosened topsoil. When root systems encounter such hard zones, they may proliferate in zones of looser soil, resulting in more concentrated root growth in upper soil layers (Lipiec et al. 2003). This flexibility in root development has been reported in several experiments, showing that although the TRL per plant may be maintained in compacted soils (Montagu et al. 2001), the roots will then explore a smaller volume of soil.

Soil compaction causing reduced root distribution will lead to reduced water and nutrient uptake, mainly due to greater distance between neighbouring roots (Lipiec et al. 2003). This will necessarily also limit yields, and result in lower utilization efficiency of applied nutrients. Research in crop plants such as barley, wheat and sunflower has indicated that soil compaction may reduce yield levels also by means of inhibitory signals from the roots about root growth restrictions (Passioura 2002). However, increased soil bulk density does not always lead to reduced yields. This is because a moderate degree of compaction under dry conditions may benefit the root system by improved unsaturated hydraulic conductivity and a better root-soil contact (Lipiec et al. 2003).

Soil mechanical resistance as measured with a soil penetrometer may pose a major limitation to root growth at about 2 MPa (Bengough et al. 2011). The soil water content may also limit root growth, because mechanical resistance increases and hydraulic conductivity declines with decreasing moisture content. Root growth stops completely at the permanent wilting point (matric potential of –1.5 MPa). Therefore, the relationship between soil matric potential (i.e. the force of adhesion of water to solid particles in soil) and soil strength is an important determinant of root elongation (Bengough et al. 2011).

Soil compaction may be especially detrimental in the subsoil, where drainage capacity can be reduced and ameliorative amendments are difficult and/or expensive. Compaction damage to subsoil is dependent on soil type, moisture status and protection by the overlying soil layer (Spoor et al. 2003). The total porosity of mineral soils lies normally between 30% and 70%. Root growth may be restricted below 35% porosity on sandy soils and below 50% on clay soils (Hatley et al. 2005). Compacted soils are also easily waterlogged with a risk for extensive surface run-off, and gas diffusion is extremely slow under such conditions.

Physical tilling and subsoiling to repair compaction damage may increase yields but seems to have only a temporary effect (Hoorman et al. 2009, with references therein). Precipitation, gravity and traffic will often recompact the soil again. Extensive tillage also reduces soil organic matter content. This may increase compaction damage as organic matter acts as a sponge to absorb weight and water (Hoorman et al. 2009), in addition to helping the formation of stable aggregates. In Norwegian compaction trials with cereals, subsoiling was found to remove the harmful effect of compaction, but conventional ploughing often had an equally beneficial effect (Riley 1986 and unpublished results). Another way of controlling compaction is the use of controlled traffic farming (CTF). This is now increasingly being adopted internationally and may include use of the same traffic lanes over several years, thus ensuring zero wheel traffic on most of the tilled area (Wolkowski & Lowery 2008). However, farm implements for different operations are not produced with equal widths, and this has limited farmers' interest in this method. A modified CTF system has been developed that is adopted within single seasons except for harvest and primary tillage, but not on a permanent basis (Vermeulen & Mosquera 2009). Satellite-based navigation systems increase the relevance of CTF, and seasonal CTF is used on commercial organic farms in the Netherlands. However, due to the careful preparation of ridges for row crops such as carrot, positive effects of CTF was only found for flat-bed crops such as spinach, onions and vining peas. Especially the latter benefitted from seasonal CTF, with yield increases of up to 30% (Vermeulen & Mosquera 2009).

Soil compaction effects in potatoes

Potatoes are sensitive to soil compaction throughout its growth period, but especially 3–5 weeks after emergence when root growth rates are at its maximum in loose soils (Stalham & Allen 2001). The risk is increased because potato producers often perform continuous arable cropping without grass leys, which contributes to depletion of the soil organic matter content. Furthermore, repeated operations with heavy machinery are required in potato production, and the soil conditions may not always be favourable (Ball et al. 1997).

In a series of British field experiments, Stalham et al. (2007) established a relationship between cone penetrometer resistance and rates of root penetration into the soil. Under ideal conditions, root growth rates were about 20 mm d^{-1} in the upper cultivated zone, but were halved as the resistance reached a value of 1.5 MPa. At a resistance above 3 MPa, roots grew less than 2 mm d^{-1}. Rooting density (km m^{-3}) was also reduced by compaction, especially between 10 cm and 40 cm depth. A survey of 602 commercial potato fields in Britain by the same authors showed that two out of three fields had a mechanical resistance above 3 MPa within the upper 55 cm of the soil. Under such conditions, compaction may prevent downward root growth from reaching its potential depth, and thereby reduce water and nutrient uptake.

In practice, soil compaction reduces canopy development in potatoes and thereby yields (Hatley et al. 2005), although there are examples of opposite effects with more rapid early plant development. For example, in sandy loam subsoil compaction can increase capillary water transport with improved early plant growth. Later in the season, with more drought stress, this effect may cease and yields may nevertheless be reduced compared to non-compacted fields (Hatley et al. 2005). From experimental records, Hatley et al. (2005) reported up to 37% potato yield reduction in compacted soil in the Netherlands, as compared to soil with a more favourable structure. Stalham et al. (2005) reviewed 16 experiments with artificial compaction in potato since 1940 and 13 of them showed a significant yield decrease. On average compaction reduced yields with 18 t/ha. In a Norwegian study with two and four tractor wheelings, total yield was reduced with 8% and 13%, respectively, compared with no wheelings (Guren 1985). From all these experiments, there is no doubt that potatoes may be severely affected by compaction.

Autumn ploughing of wet soils may lead to especially severe soil compaction in potato fields, as the tractor tyres run directly above the subsoil in the bottom of deep furrows. In addition, wheelslip may cause smearing (Davies et al. 1973), which is detrimental at this soil depth (Hatley et al. 2005). Premature tilling in spring, under wet conditions, may also cause soil compaction and reduce yields. Experiments including this practice the UK showed delayed emergence, a reduced rate of foliage development and a shorter duration of canopy cover (Stalham et al. 2007). This resulted in restricted light interception and consequently reduced yields. It was concluded that it was clearly better to postpone tillage and planting for some days to allow the soil to dry, rather than to risk significant yield losses due to soil compaction. Another way to maintain better soil structure is to use the same wheel tracks for seedbed preparation, planting and weed control (Spoor et al. 2003).

A CTF system, with permanent compacted traffic lanes, has been shown to decrease the energy use and increase potato yields significantly (Lamers et al. 1986), mainly due to increased O_2 availability in the subsoil under wet soil conditions. The average penetration resistance under the lanes was 3.5 MPa, and compaction occurred down to 0.8 m depth. Average yield levels (1976–1984) were 3% higher with CTF in traditional potatoes, and 7% higher in seed potatoes. The latter are harvested earlier with a shorter growing season and are hence more susceptible to adverse soil conditions. Average energy savings for primary tillage was calculated to be 48%, and less soil tare was found on the potatoes. Since the costs of adapting all working operations to a CTF system may comprise about 30% of the farmer's total production costs per year, CTF was only recommended for small arable farms specialized in expensive crops that react positively to loose soil, such as seed potatoes, tulips and onions (Lamers et al. 1986).

Subsoiling may mitigate severe compaction in potato, but this is not always the case, and should be carefully assessed in each occasion. In fact, in a review of results only 28 out of 83 experiments with subsoiling or reduced traffic in potato showed significantly increased yields (Stalham et al. 2005). Furthermore, in the cases with subsoiling, most of these yield increases were small, and yield increase originated from operations before rather than after planting. It should be noted that subsoiling is only relevant when it breaks a compacted soil layer, and in many of these experiments the level of compaction prior to cultivation was not described. In a more recent study by Copas et al. (2009), under controlled compaction levels, no consistent effects of subsoil tillage was reported and support the conclusions by Stalham et al. (2005). There are, however, also reports of significant yield increases following subsoiling. Especially in strongly compacted subsoil, subsoiling under dry conditions has been shown to be an effective way of reducing soil resistance and increasing potato yields (Stalham et al. 2007). Other studies have shown 10% yield increases by combining subsoiling and controlled traffic lanes in seed potatoes (Lamers et al. 1986), and Albertsson et al. (2010) found a significant increase in starch yields (0.9–1.4 t/ha) following subsoiling in sandy soils with compacted plough pans. Albertsson et al. (2010) suggest that differences in cultivation depths, timing of management and machinery used are important factors that might explain different results of subsoiling in potato.

Frequent supply of manure or other organic material to the soil improves soil structure and aggregate stability, and has been shown to benefit root development in potato (Opena & Porter 1999). Many growers expect extra irrigation and fertilization to compensate for compaction damage, but such measures can never eliminate the problem (Stalham et al. 2007). Instead, extra irrigation may lead to waterlogging when the drainage is impeded, whilst extra fertilization implies lower nutrient use efficiency and probably a larger environmental impact.

Soil compaction effects in carrots

The growth rate of young carrot taproots, the length of edible taproots and the final carrot yields is reduced by compaction on most soil types, compared to loosened soils (Olymbios & Schwabe 1977; Strandberg & White 1979; Agung & Blair 1989). Olymbios and Schwabe (1977) found that carrots grown in compacted soil (bulk density 1.46 g cm^{-3}) had 32% lower commercial root weights than those grown in medium compacted soil (1.31 g cm^{-3}). Experiments have also shown a clear relation between high penetrometer resistance and reduced growth of the edible taproots in fine sand, while compaction of organic soil had less effect (Pietola 1995). Severe compaction in the upper soil layers may also lead to deformed roots and higher numbers of conical-shaped roots (Strandberg & White 1979; Taksdal 1984; Agung & Blair 1989; Pietola 1995). In a Norwegian trial with compaction at high axle load on loam soil, the reduction in carrot yield was far greater than that found in potatoes and cereals (Riley 1994). In this trial compaction reduced both the total and marketable carrot yields by about 20%. In another Norwegian trial with different intensities of tractor wheelings, Guren (1985) found a reduction in total yields of 13% and 30% with two and four wheelings, respectively. Furthermore, the fraction of misshapen roots increased significantly with more intensive wheeling.

Finnish studies have also indicated that the growth of the fibrous roots of carrots may suffer from soils being too loose (Pietola & Smucker 1998). This is because a minimum of soil compaction in the upper soil layer is necessary for water and nutrient absorption, especially during crop establishment and early growth. In an experiment with three passes of a tractor (weight 3 Mg) on both fine sand and organic soil, the above authors found that TRL per plant and the corresponding root surface area and total root volume were stimulated by soil compaction. Others have made similar findings. Thus, the carrot yields in very loose soil (1.02 g cm^{-3}) were lower than at an intermediate soil density (1.31 g cm^{-3}; Olymbios & Schwabe 1977).

Concluding remarks

At optimal soil conditions, most of the root mass of both potato and carrots is distributed within the upper 100 cm of soil, but roots may reach down to about 140 cm in potato and more than 200 cm in carrots. Both species are thereby relatively deep-rooted crops. Nevertheless, concentration of roots in the upper soil layers is often observed in practice. This is mainly due to soil pans and subsoil compaction which strongly affects root growth.

With current global warming, the growing season is expected to become longer in the Nordic regions. However, with generally more precipitation, more frequent rainstorms and increasingly heavier farm machinery, field operations that result in soil compaction are expected to occur more often. This may lead to reduced root development, limitations on water and nutrient uptake, reduced yields and economic losses. Yield reductions of 20–30% have already been reported for both crops. In addition, especially carrot quality is reduced in compacted upper soil layers, due to increased levels of misshaped storage roots. Besides restrictions on root growth from soil compaction, there is also a risk for increased emission of greenhouse gases, more run off of water and pollutants, and less effective fertilizer and energy use.

Ameliorations by physical tilling and subsoiling seem to have a limited effect on yields, except when carried out under dry conditions on strongly compacted subsoils. The effect is often only temporary. The most important factor is therefore to reduce the risk of damage to the soil structure. Once the subsoil is compacted, the damage, measured as reduction of macropores, may persist for more than a decade.

There are several options for avoiding subsoil compaction and obtaining better root growth, and some of them should be implemented to avoid yield decreases. First of all, farm machinery should be dimensioned with a realistic level of soil strength in mind. In most cases this means that reduced weights should be aimed for. CTF may be an interesting supplement, but is challenged by the lack of coordination within the farm machinery industry. Alternative techniques for ploughing with all wheels running on the topsoil, or possibly without axle loads, e.g. by winching, may also reduce subsoil compaction significantly.

Optimal timing of soil operations, with the soil structure in mind, is a well-known factor, and is often the most readily achievable strategy. This involves avoiding autumn ploughing on wet soils and postponing tilling and planting in spring until the soil has dried. With regard to the cultivation system, crop rotations with more perennial crops and also supplements of organic material would improve the soil structure, making it more resistant to compaction.

We recommend that further research focuses on the plant's physiological responses to soil conditions. How do adverse conditions explored by the roots affect shoot growth and yield potential? Can observations of the shoot growth give useful information about the extent of O_2 limitation and/or soil compaction in different soil types? Gene-based techniques for easier and more precise measurements of root mass should also be elaborated.

In conclusion, increased soil compaction and thereby restricted root growth may explain recent yield reductions in potatoes and carrots, and is a threat to a future economic and environmentally sound production in the Nordic regions. To improve this situation, it is urgent to implement new practices. These should be based on current physical and biological knowledge, such as that presented in this review article, along with further research.

Acknowledgements

Eldrid L. Molteberg, Ragnhild Nærstad and two anonymous referees have made useful contributions in the presentation of this review.

References

Ahmadi SH, Plauborg F, Andersen MN, Sepaskhah AR, Jensen CR, Hansen S. 2011. Effects of irrigation strategies and soils on field grown potatoes: root distribution. Agric Water Manage. 98:1280–1290.

Albertsson J, Ekelöf J, Råberg T. 2010. Subsoiling starch potato. Report from landscape planning, horticulture and agricultural science. SLU Alnarp: Swedish University of Agricultural Sciences. Report 40; 15 p.

Agung IGAM Sri, Blair GJ. 1989. Effects of soil bulk density and water regime on carrot yield harvested at different growth stages. J Hortic Sci. 64:17–25.

Ball BC, Campbell DJ, Douglas JT, Henshall JK, O'Sullivan MF. 1997. Soil structural quality, compaction and land management. Eur J Soil Sci. 48:593–601.

Bengough AG, McKenzie BM, Hallett PD, Valentine TA. 2011. Root elongation, water stress, and mechanical impedance: a review of limiting stresses and beneficial root tip traits. J Exp Bot. 62:59–68.

Berisso FE, Schjønning P, Keller T, Lamande M, Simojoki A, Iversen BV, Alakukka L, Forkman J. 2013. Gas transport and subsoil pore characteristics; anisotropy and long term effects of compaction. Geoderma. 195–196:184–191.

Brar GS, Reynolds CM. 1996. Soil physical environment and root growth in northern climates. Hanover, New Hampshire: US Army Corps of Engineers, Cold Regions Research and Engineering Laboratory. Special Report 96–13; 23 p.

Chapman N, Miller AJ, Lindsey K, Whalley R. 2012. Roots, water, and nutrient acquisition: let's get physical. Trends Plant Sci. 17:701–710.

Copas ME, Bussan AJ, Drilias MJ, Wolkowski RP. 2009. Potato yield and quality response to subsoil tillage and compaction. Agron J. 101:82–90.

Cutter EG. 1992. Structure and development of the potato plant. In: Harris PM, editor. The potato crop. London: Chapman & Hall; p. 65–161.

Davies DB, Finney JB, Richardson SJ. 1973. Weight and wheel-slip in causing soil compaction. J Soil Sci. 24:399–409.

Dechassa N, Schenk MK, Claassen N, Steingrobe B. 2003. Phoshorous efficiency of cabbage (*Brassica oleraceae* L. var *capitata*), carrot (*Daucus carota* L.) and potato (*Solanum tuberosum* L). Plant Soil. 250:215–224.

Deguchi T, Naya T, Wangchuk P, Itoh E, Matsumoto M, Cheng X, Gopal J, Iwama K. 2010. Aboveground characteristics, yield potential and drought tolerance in "Konyu" potato cultivars with large root mass. Potato Res. 53:331–340.

Dragland S. 1985. Drought at different growth stages of four potato varieties. Forskning og Forsøk i Landbruket. 36:159–167. Norwegian with English summary.

Drew MC, Saker LR. 1975. Nutrient supply and the growth of the seminal root system in barley. II. Localized, compensatory increases in lateral root growth and rates of nitrate uptake when nitrate supply is restricted to only part of the root system. J Exp Bot. 26:79–90.

Etana A, Larsbo M, Keller T, Arvidsson J, Schjønning P, Forkman J, Jarvis N. 2013. Persistent subsoil compaction and its effects on preferential flow patterns in a loamy till soil. Geoderma. 192:430–436.

Gregory PJ, Atkinson CJ, Bengough AG, Else MA, Fernández-Fernández F, Harrison RJ, Schmidt S. 2013. Contributions of roots and rootstocks to sustainable, intensified crop production. J Exp Bot. 64:1209–1222.

Guren TA. 1985. Jordpakking i rotvekster [Soil compaction in root crops] [dissertation]. Ås: Norwegian University of Life Sciences NMBU; 128 p. Norwegian.

Hatley D, Wiltshire J, Basford B, Royale S, Buckley D, Johnson P. 2005. Soil compaction and potato crops. Oxford: British Potato Council, Research Review R260; 57 p.

Hinsinger P, Bengough AG, Vetterlein D, Young IM. 2009. Rhizosphere: biophysics, biochemistry and ecological relevance. Plant Soil. 321:117–152.

Hodge A, Berta G, Doussan C, Merchan F, Crespi M. 2009. Plant root growth, architecture and function. Plant Soil. 321:153–187.

Hoorman JJ, de Moraes Sá JC, Reeder R. 2009. The biology of soil compaction. Ohio: Agricultural and natural resources, The Ohio State University; 7 p. Fact sheet.

Hov Ø, Cubasch U, Fischer E, Höppe P, Iversen T, Kvamstø NG, Kundzewicz ZW, Rezacova D, Rios D, Santos FD et al. 2013. Extreme weather events in Europe: preparing for climate change adaptation [Internet]. Oslo: Norwegian Meteorological Institute; [cited 2013 Nov 20]. Available from: http://www.dnva.no.

Itoh S, Barber SA. 1983. Phosphorus uptake by six plant species as related to root hairs. Agron J. 75:457–461.

Iwama K. 2008. Physiology of the potato: new insights into root system and repercussions for crop management. Potato Res. 51:333–353.

Kolbe H, Stephan-Beckmann S. 1997a. Development, growth and chemical composition of the potato crop (*Solanum tuberosum* L.). I. Leaf and stem. Potato Res. 40:111–129.

Kolbe H, Stephan-Beckmann S. 1997b. Development, growth and chemical composition of the potato crop (*Solanum tuberosum* L.). II. Tuber and whole plant. Potato Res. 40:135–153.

Kristensen HL, Thorup-Kristensen K. 2004. Uptake and 15N labeled nitrate by root systems of sweet corn, carrot and white cabbage from 0.2–2.5 meters depth. Plant Soil. 265:93–100.

Kristensen HL, Thorup-Kristensen K. 2007. Effects of vertical distribution of soil inorganic nitrogen on root growth and subsequent nitrogen uptake by field vegetable crops. Soil Use Manage. 23:338–347.

Lamers JG, Perdok UD, Lumkes LM, Klooster JJ. 1986. Controlled traffic farming systems in the Netherlands. Soil Tillage Res. 8:65–76.

Linnér H. 1984. The influence of soil moisture on evapotranspiration, growth, nutrient uptake, yield and quality of the potato (*Solanum tuberosum* L.). Alnarp: Sveriges Lantbruksuniversitet, Inst. för markvetenskap, avd. för hydroteknik. Rapport 142. 153 p. Swedish with English summary.

Lipiec J, Medvedev VV, Birkas M, Dumitru E, Lyndina TE, Rousseva S, Fulajtár E. 2003. Effect of soil compaction on root growth and crop yield in Central and Eastern Europe. Int Agrophys. 17:61–69.

Micovski SB. 2002. Anchorage mechanisms of different types of root systems [dissertation]. Manchester: University of Manchester, School of Biological Sciences, Division of Integrative Biology.

Montagu KD, Conroy JP, Atwell BJ. 2001. The position of localized soil compaction determines root and subsequent shoot growth responses. J Exp Bot. 52:2127–2133.

Olesen JE, Trnka M, Kersebaum KC, Skjelvåg AO, Seguin B, Peltonen-Sainio P, Rossi F, Kozyra J, Micale F. 2011. Impacts and adaptations of European crop production systems to climate change. Eur J Agron. 34:96–112.

Olymbios CM, Schwabe WW. 1977. Effects of aeration and soil compaction on growth of carrot. J Hortic Sci. 52:489–500.

Opena GB, Porter GA. 1999. Soil management and supplemental irrigation effects on potato: II. Root growth. Agron J. 91:426–431.

Passioura JB. 2002. Soil conditions and plant growth. Plant Cell Environ. 25:311–318.

Pietola L. 1995. Effect of soil compactness on the growth and quality of carrot. Agric Sci Finland. 4:144–237.

Pietola L, Smucker AJM. 1998. Fibrous carrot root responses to irrigation and compaction of sandy and organic soils. Plant Soil. 200:95–105.

Rewald B, Ephrath JE. 2013. Minirhizotron techniques. In: Eshel A, Beeckman T, editors. Plant roots: the hidden half. New York: CRC Press; p. 1–15.

Riley H. 1986. Forsøk med jordløsning ved bruk av Paraplow [Subsoiling with paraplough] [poster]. NJF-seminar nr. 99, Sigtuna. Norwegian.
Riley H.1989. Irrigation of cereals, potato, carrot and onion on a loam soil at various levels of moisture deficit. Norw J Agric Sci. 3:117–145.
Riley H. 1990. Drought at different stages of growth of five potato varieties: I. Field experiments. Norsk Landbruksforsking. 4:279–300. Norwegian with English summary.
Riley H. 1994. The effect of traffic at high axle load on crop yields on a loam soil in Norway. Soil Tillage Res. 29:211–214.
Rosenfeld H, Dalen KS, Haffner K. 2002. The growth and development of carrot roots. Das Wachstum Gartenbauwissenschaft. 67:11–16.
Rosenfeld HJ, Samuelsen RT, Lea P. 1998. The effect of temperature on sensory parameters, chemical composition and growth of carrots (*Daucus carota* L.) I. Constant diurnal temperature amplitude. J Hortic Sci Biotechnol. 73:275–288.
Russel EJ. 1912. Soil conditions and plant growth. London: Longmans.
Salo T. 1999. Effects of band placement and nitrogen rate on dry matter accumulation, yield and nitrogen uptake of cabbage, carrot and onion. Agric Food Sci Finland. 8:157–232.
Smit AL, Bengough AG, Engels C, Van Noordwijk M, Pellerin S, Van de Geijn SC. 2000. Root methods: a handbook. Berlin: Springer.
Soane BD, van Ouwerkerk C. 1995. Implications of soil compactions in crop production for the quality of the environment. Soil Tillage Res. 35:5–22.
Spoor G, Tijink FGJ, Weisskopf P. 2003. Subsoil compaction: risk, avoidance, identification and alleviation. Soil Tillage Res. 73:175–182.
Stalham MA, Allen EJ. 2001. Effect of variety, irrigation regime and planting date on depth, rate, duration and density of root growth in the potato (*Solanum tuberosum*) crop. J Agric Sci. 137:251–270.
Stalham MA, Allen EJ, Herry FX. 2005. Effects of soil compaction on potato growth and its removal by cultivation. Oxford: British Potato Council, Research Review R261; 60 p.
Stalham MA, Allen EJ, Rosenfeld AB, Herry FX. 2007. Effects of soil compaction in potato (*Solanum tuberosum*) crops. J Agric Sci. 145:295–312.
Strandberg JO, White JM. 1979. Effect of soil compaction on carrot roots. J Am Soc Hortic Sci. 104:344–349.
Suojala T. 2000. Pre- and postharvest development of carrot yield and quality [dissertation]. Helsinki: University of Helsinki, Department of Plant Production; 47 p.
Svistoonoff S, Creff A, Reymond M, Sigoillot-Claude C, Ricaud L, Blanchet A, Nussaume L, Desnos T. 2007. Root tip contact with low-phosphate media reprograms plant root architecture. Nat Genet. 39:792–796.
Taksdal G. 1984. Effect of tractor wheelings on carrot quality. Acta Hortic. 163:255–260.
Thorup-Kristensen K. 2006. Root growth and nitrogen uptake of carrot, early cabbage, onion and lettuce following a range of green manures. Soil Use Manage. 22:29–38.
Thorup-Kristensen K, Van den Boogaard R. 1999. Vertical and horizontal development of the root system of carrots following green manure. Plant Soil. 212:143–151.
Tinker PB, Nye PH. 2000. Root system architecture, density, and measurement. In: Tinker PB, Nye PH, editors. Solute movement in the rhizosphere. Oxford: Oxford University Press; 444 p.
Unger P, Kaspar TC. 1994. Soil compaction and root growth: a review. Agron J. 86:759–766.
Vermeulen GD, Mosquera J. 2009. Soil, crop and emission responses to seasonal-controlled traffic in organic vegetable farming on loam soil. Soil Tillage Res. 102:126–134.
Vos J, Groenwold J. 1986. Root growth of potato crops on a marine-clay soil. Plant Soil. 94:17–33.
Weaver JE. 1926. Root development of field crops. Chapter XV. Root habits of the potato. New York: McGraw-Hill.
Weaver JE, Bruner WE. 1927. Root development of vegetable crops. Chapter XXII. Carrot. New York: McGraw-Hill.
Westerveld SM, McKeown AW, McDonald MR. 2006. Distribution of nitrogen uptake, fibrous roots and nitrogen in the soil profile for fresh-market and processing carrot cultivars. Can J Plant Sci. 86:1227–1237.
Wishart J, Georg TS, Brown LK, Ramsay G, Bradshaw JE, White PJ, Gregory PJ. 2013. Measuring variation in potato roots in both field and glasshouse: the search for useful yield predictors and simple screen for root traits. Plant Soil. 368:231–249.
Wishart J, Georg TS, Brown LK, White PJ, Ramsay G, Jones H, Gregory PJ. 2014. Field phenotyping of potato to assess root and shoot characteristics associated with drought tolerance. Plant Soil. 378:351–363.
Wohlfarth B, Björck S, Funder S, Houmark-Nielsen M, Ingólfsson Ó, Lunkka J-P, Mangerud J, Saarnisto M, Vorren T. 2008. Quaternary of Norden. Episodes. 31:73–81.
Wolkowski R, Lowery B. 2008. Soil compaction: causes, concerns, and cures. Madison: University of Wisconsin, Cooperative Extension Learning Store (A3367); 8 p.