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# Root growth conditions in the topsoil as affected by tillage intensity

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ABSTRACT

Many studies have reported impeded root growth in topsoil under reduced tillage or direct drilling, but few have quantified the effects on the least limiting water range for root growth. This study explored the effects of tillage intensity on critical soil physical conditions for root growth in the topsoil. Samples were taken from a 7-year tillage experiment on a Danish sandy loam at Foulum, Denmark (56°30′ N, 9°35′ E) in 2008. The main crop was spring barley followed by either dyer's woad (*Isatis tinctoria* L.) or fodder radish (*Raphanus sativus* L.) cover crops as subtreatment. The tillage treatments were direct drilling (D), harrowing 8–10 cm (H), and ploughing (P) to 20 cm depth. A chisel coulter drill was used in the H and D treatments and a traditional seed drill in the P treatment. Undisturbed soil cores were collected in November 2008 at soil field moisture capacity from the 4–8 and 12–16 cm depths.

We estimated the critical aeration limit from either 10% air-filled porosity ($\varepsilon_a$) or relative gas diffusivity ($D/D_0$) of 0.005 or 0.02 and found a difference between the two methods. The critical limit of soil aeration was best assessed by measuring gas diffusivity directly. Root growth was limited by a high penetration resistance in the D and H soils (below tillage depth). Poor soil aeration did not appear to be a significant limiting factor for root growth for this sandy loam soil, irrespective of tillage treatment. The soil had a high macroporosity and $D/D_0$ exceeded 0.02 at field capacity. Fodder radish resulted in more macropores, higher gas diffusivity and lower pore tortuosity compared to dyer's woad. This was especially important for the H treatment where compaction was a significant problem at the lower depths of the arable layer (10–20 cm depth). Our results suggest that fodder radish could be a promising tool in the amelioration of soil compaction.


## 1. Introduction

Despite the major potential economic and environmental benefits from low-intensity tillage systems, the adoption of reduced tillage and, especially, direct drilling is still low in humid temperate regions such as Northwestern Europe. The reason for this is that low-intensity tillage often results in lower crop yields than in the traditional mouldboard-ploughed system (Feiziene et al., 2006; Hansen et al., 2010). Drawbacks have been identified relating to problems with soil compaction, germination and early growth of cereals, residue management, and weed and pest control (Alakukku, 2003; Feiziene et al., 2007; Munkholm et al., 2003; Rasmussen, 1999; Riley et al., 1994).

In a recent study, Munkholm et al. (2008) found decreased early season root and shoot growth of winter wheat with decreasing tillage intensity on two humid sandy loam soils. This is consistent with previous studies on small grain cereals (Braim et al., 1992; Kirkegaard, 1995). Munkholm et al. (2008) linked the poor early growth to excessive compaction of the topsoil layer. This conclusion was mainly based on penetration resistance (PR) measurements performed in the field at field moist conditions and on visual evaluation of the topsoil carried out by Ball et al. (2007). Thus, the conclusion was not explicitly supported by hard quantitative data on the effect of tillage on critical conditions for root growth.

Non-limiting water range (NLWR) was introduced by Letey (1985) to quantify the window in water contents that gives optimal conditions for root growth. In reality, critical conditions for root growth are gradual rather than rigid limits and therefore da Silva et al. (1994) introduced the term LLWR. The advantage of the LLWR concept is that optimal physical conditions for root growth can be assessed by use of only one parameter. Root growth may be limited by the physical factors: water, aeration, temperature and penetration resistance as highlighted by e.g. Letey (1985) and Glinski and Lipiec (1990). In wet conditions, poor aeration is considered as the limiting factor, whereas water availability and penetration resistance are considered limiting factors in dry conditions. In most studies the wet critical limit for root growth has been estimated as the water content at 10% air-filled porosity under the assumption that oxygen diffusion

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approaches zero at < 10% air-filled porosity (Grable and Siemer, 1968). Actually, Grable and Siemer (1968) concluded that their data indicated that 12–15% air-filled porosity would be a safer limit. The critical values of relative gas diffusion ($D/D_0$) have been assessed for different crops in the range of 0.005 to 0.02 according to Grable and Siemer (1968) and references therein. Generally, the dry limit for root growth has been determined as the water content where PR exceeds 2 MPa or the wilting point at a matric potential of −1.5 MPa (e.g. Betz et al., 1998). The 2 MPa PR limit should be regarded as a rule of thumb as it is based on measurements of root growth in sieved homogeneous soil (Taylor and Ratliff, 1969). However, this limit is sensitive to soil structure and plant species. Boone et al. (1994) used 1.5 and 3.0 MPa respectively, as the lower and upper critical limits for Dutch sandy loams. Ehlers et al. (1983) suggested two different PR limiting oats root growth for the tilled (3.6 MPa) and for the untilled (4.6–5.1 MPa) grey brown podzolic loess soil. According to Ehlers et al. (1983) this difference in the soil strength–root growth relationship is explained by the continuous biopore system in untilled soil, created by earthworms and the roots from preceding crop, which can be utilized by subsequent crop roots. Munkholm et al. (2008) reported that winter wheat root growth had been reduced at PR of 1.5–2.0 MPa under reduced tillage for a Danish sandy loam soil. They also concluded that temperate sandy loams are prone to topsoil compaction when reducing tillage intensity, a conclusion consistent with results of Carter (1991), Munkholm et al. (2003) and Ball et al. (2007).

In this study, we explored and quantified the physical conditions for root growth in the above-mentioned tillage experiment. For this purpose we applied the least limiting water range (LLWR) concept. The main objective was to explore the effect of tillage intensity on critical soil physical conditions for root growth in the topsoil (0–20 cm layer). Our hypothesis was that reduced tillage would impair conditions for root growth below the tilled layer due to both insufficient aeration in wet conditions and high penetration resistance in dry conditions. A secondary objective was to compare the effect of first-year established two *Brassica* cover crops (fodder radish and dyer's woad) into a seven-year tillage experiment on topsoil pore characteristics.

## 2. Materials and methods

### 2.1. Study site description

The experiment was established in autumn 2002 on a Danish sandy loam at Foulum (56°30′ N, 9°35′ E) in Western Denmark. The soil is classified as a *Mollic Luvisol* according to the WRB (FAO) system (Krogh and Greve, 1999) and has 9% clay, 13% silt (2–20 μm), 44% fine sand (20–200 μm), 31% coarse sand (200–2000 μm) and 3.1% organic matter in the 0–25 cm layer (Munkholm et al., 2008). The experiment was a split-split-plot in four blocks (replications) with two factors: crop rotation as main plot and tillage as sub-plot. In this study, we used three blocks of rotation R5 for experiments with cover crops. In 2008, the main crop of rotation R5 was spring barley (*Hordeum vulgare* L.). The sub-plot tillage systems were: direct drilling (D), harrowing 8–10 cm (H), and ploughing to 20 cm (P). A chisel coulter drill was used in the H and D treatments and a traditional seed drill in the P treatment. Each tillage treatment consisted of two 3-m wide by 72.2 m long plots. In 2008, these tillage sub-plots were split into ten sub-sub-plots for different cover crop establishment. The gross area of each sub-sub-plot was 13.7 × 3 m. The two cover crop: dyer's woad (*Isatis tinctoria* L.) and fodder radish (*Raphanus sativus* L.) were established in four (each cover crop in two sub-sub-plots) of ten sub-sub-plots. Dyer's woad (DW) seeds were sown a few days after the sowing of the spring barley crop. Fodder radish (FR) seeds were spread out 2 weeks before the planned harvest of the spring barley crop.

### 2.2. Soil sampling

Soil sampling took place in November 2008 when soils have near field capacity soil moisture content. Undisturbed soil cores (6.1 cm diameter, 3.4 cm height, 100 $cm^3$ volume) were collected in stainless steel cylinders from the 4–8 and 12–16 cm depth increments. Six soil samples were collected from each of the three tillage treatments × two cover crops × three blocks, what gave a total of 108 samples taken per depth increment. We also collected two disturbed soil samples from each plot, (a total of 36 samples per depth) for −1500 kPa water potential analysis. All samples were stored field moist at 2 °C until further processing. Laboratory measurements were conducted between April and August 2009.

### 2.3. Laboratory measurements

Undisturbed soil cores were adjusted to −0.4, −1, −3, −10, −30 and −100 kPa matric potentials ($\psi_m$). Adjustment of $\psi_m$ took place at 20 °C using tension tables for potentials from −0.4, −1, −3 and −10 kPa and ceramic plates for potentials −30 and −100 kPa. The time period needed to reach a given $\psi_m$ ranged from 1 day (−0.4 kPa) to 30 days (−100 kPa). The $\psi_m$ of −1500 kPa was adjusted by draining disturbed soil samples on 1500 kPa ceramic plates for one month. The soil cores were analysed for gas diffusivity at −3 and −10 kPa $\psi_m$. The diffusivity was measured by a non-steady-state method as suggested by Taylor (1949) using the technique described by Schjønning (1985). Soil cores were placed into the special chambers made for diffusivity apparatus, using rubber rings to avoid any gas leaking between soil core and chamber. Before measuring the diffusivity soil was gently pressed at the very age of the metal ring to minimize the risk of air diffusing or leaking along the boundary between soil and ring. Oxygen was used as the diffusing gas. Prior to the measurements, oxygen was flushed out in the chamber above the soil core with nitrogen free of oxygen.

After adjustment to −100 kPa $\psi_m$, the soil cores were split into four groups for penetration resistance (PR) measurements at different $\psi_m$ (−3, −10, −30 and −100 kPa). Each group consisted of 54 soil cores (nine soil cores per three tillage treatments and two depths). The soil cores for adjusting −3, −10 and −30 kPa $\psi_m$ were resaturated on tension tables slowly from a −10 kPa start, decreasing by −2 kPa every day until full saturation was reached. After full saturation all soil cores were adjusted at −3 kPa and after that two out of three groups of soil cores were separated for adjustment at −10 and −30 kPa $\psi_m$. Before PR measurements (after the required $\psi_m$ equilibrium had been reached) the soil cores were put into plastic bags and stored at 2 °C for 1 week to ensure a uniform water distribution throughout the soil sample.

Penetration resistance was measured to 20 mm depth at four points per soil core using a fully automated micropenetrometer with a probe consisting of a 30° semi-angle stainless steel cone of 2.9 mm diameter (Munkholm et al., 2002). The four points were located in a grid 10 mm apart. Penetration rate was 10 mm $min^{-1}$, with values recorded for each mm (every 6 s). When analysing the penetration resistance data, we did not use data recordings of the top 5 mm depth to avoid the influence of top zone of the soil sample. Thus gave us 15 readings per each point or 60 readings per each soil core. After PR measurements, soil cores were oven-dried at 105 °C for 24 h. Samples were weighed at each potential and after oven-drying.

### 2.4. Calculations

Soil pore size fractions were derived from water retention measurements, assuming an approximate relation; $d = -3000/10\ \psi_m$, where $d$ is the pore diameter in μm and $\psi_m$ is the matric potential in kPa. Relative gas diffusivity $D/D_0$ is a ratio of the measured air