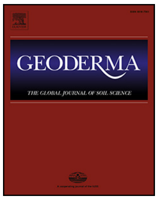
Geoderma 265 (2016) 1–5

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma



Effect of sand grain shape on root and shoot growth of wheat seedlings

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ARTICLE INFO

Article history:
Received 11 August 2015
Received in revised form 27 October 2015
Accepted 30 October 2015
Available online xxxx

Keywords:
Rounded sand
Rough sand
Physical properties
Young wheat
Root morphology

ABSTRACT

Sandy soils are used in agriculture worldwide, and sandy material is a suitable growth medium in pot cultures. The global shape and surface roughness of sand grains affect inter-particle contact junctions and internal frictional resistance. Less rounded sands have greater inter-particle frictional resistance that may diminish the capability of roots to displace surrounding particles during growth. The aim of this study was to evaluate the effects of two silica sands of rounded (fluvioglacial) and rough (aeolian) origin on root and shoot growth of wheat seedlings. The greater shape irregularity of the rough compared to the rounded sand was shown by the circularity values and two surface structure parameters. Seedlings were grown for five days in 100 cm^3 steel cylinders filled with the respective sands with water content 0.20 kg kg^{-1}, corresponding to field water capacity. The rough sand compared to rounded had higher water permeability ($P < 0.05$). Seedlings grown in rough compared to rounded sand were characterized by more tortuous root growth and significantly lower ($P < 0.05$) root length (by 19.8%), root dry weight (by 15.9%) and greater root diameter (0.45 vs. 0.50 mm). These root responses in rough sand were attributed to hindered displacement of the sand particles due to interlocking. The seedlings in rough sand had significantly ($P < 0.05$) shorter shoots (by 9.8%), lower dry mass (by 11.7%) and leaf area (by 16.9%). These results imply the need to consider the effects of particle shape in sand-based growth media that are used in screening approaches to initial plant growth, particularly in plant genetics.

1. Introduction

Sandy soils are used in agriculture in many regions of the world (Bronick and Lal, 2005; Thorsen et al., 2010; Jankowski et al., 2011). In Poland 50% of soils were developed from sands (Białousz et al., 2005). The global shape and surface roughness of sand grains are set during formation and are later affected by weathering and transportation breakage under load (Cho et al., 2006). The roundness of fluvioglacial-origin sand is largely influenced by the intensity and timespan of washing and sorting by melting (Woronko and Pochocka-Szwarc, 2013), and that of aeolian sand deposits by wind streams and abrasion during the transportation process (Al-Dousari and Al-Hazza, 2013). Furthermore, the sand particles in tilled compared to forest soils have a more regular shape (Turski and Witkowska-Walczak, 2004). Thus, the shape of soil particles reflects the formation history of the grains (Cho et al., 2006).

Morphological variations in individual grains and pore space organization influence many soil processes (Pagliai and Vignozzi, 2002; Anderson and Croft, 2009). Particle shapes and surface roughness have been shown to affect densification, compressibility and shear strength of soils (de Bono and McDowell, 2015) through alterations in the pressure distribution which develop at inter-particle contact junctions and friction (Horn, 2011). Hence, increased shape irregularity and surface roughness of sand particles require greater packing energy during densification (Cruse et al., 1980) and result in lower tendency towards creeping (Cho et al., 2006) under stress. In the study by Darbha et al. (2012) an increase in roughness enhanced colloid deposition on granodiorite surfaces. The shape of the sand grains needs to be considered in terms of the determination of soil particle size distribution using laser diffraction methods (Polakowski et al., 2014).

The presence of non-erodible roughness elements, including coarse and rough sand particles, reduce wind soil erosion and thus the emission of mass flux through the reduction of wind stress on neighbouring erodible areas and the increase of the threshold friction velocity (Turpin et al., 2010; Furieri et al., 2013).

Sandy materials are also widely used in plant breeding as growth media for screening root and shoot characteristics under defined growth conditions (Materechera et al., 1991; Bengough et al., 2011; Senger et al., 2014). Such media are preferred because they have negligible inherent cohesive strength and provide opportunities to create a range of relatively uniform growth factors. For example, the single effect of mechanical impedance can be received by loading the sand during plant growth (Whalley et al., 2000), and the negative effects of insufficient aeration and nutrient stress can be avoided by circulating or flushing aerated nutrient solution (Young et al., 1997).

A literature review indicates that most research was devoted to the effects of particle shape and roughness of sand on material behaviour rather than to root growth, even though a well-developed root system is important in sandy soils containing scarce supplies of water or nutrients (Bengough et al., 2011). Furthermore, it has been suggested that

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http://dx.doi.org/10.1016/j.geoderma.2015.10.022
0016-7061/

plant roots can be impeded by rigidly interlocked sand particles that are not readily moved apart by growing roots (Batey, 1988; Sakrabani et al., 2012).

The aim of this study was therefore to evaluate the effects of silica sands of rounded and rough shape on the root and shoot growth of wheat seedlings. We hypothesised that the increased irregularity of sand particles decreases root and shoot growth of wheat. The work is inspired by earlier experimental investigations which indicate that impedance experienced by roots (tips) due to friction on the root–soil interface can be reduced by the lubricating action of mucilage secretion and the sloughing off of root cap cells (Iijima et al., 2004; Bengough et al., 2011; McKenzie et al., 2013) during growth.

2. Material and methods

The 100–500 μm fraction of two sands that had different shaped grains from fluvioglacial and aeolian deposits were selected. The fluvioglacial deposit was taken in Kiełczów (N 51° 08′ 42′′; E 17° 09′ 19′′) and the aeolian deposit from the dorsal part of the inland stabilized dune in Wilkocin — (N 51° 22′ 55′′; E 16° 00′ 12′′) in the south-west part of Poland. The fluvioglacial and aeolian deposits were referred to as rounded sand and rough sand, respectively.

The material was initially purified by removing mechanical impurities, dried to an air-dried state and sieved through a 2 mm sieve. Then, hexametaphosphate with sodium carbonate (ISO 11277: 2009) was added to 200 g of the sample in order to ensure that all the particles were suitably separated. This was ensured particularly by the abruption of fine particles of silt and clay particles from the sand surface. After dispersion, wet sieving (carried out to remove all the small particles which were washed out using hexametaphosphate) using Annalysette 3 (Fritsh, Germany) was performed to separate the investigated fraction.

To determine the shape parameters of the sands, the optical microscope Morphologi G3 with a Sample Dispersion Unit (Malvern, UK) was used. This microscope is equipped with a camera which allows scanning of an image and provides software for image analysis (Morphologi, 2008). In order to obtain sharp images of all grains of sand, it was necessary to separate them into two sub-fractions: fine sand (100–250 μm) and medium sand (250–500 μm). The sizes of the separated fractions were dependent on the depth of field of the lenses used. For the sub-fraction 100–250 μm, 247 times magnification was used (pixel size for this magnification was 0.54 μm). For the sub-fraction 250–500 μm, 123 times magnification was used (pixel size for this magnification was 1.08 μm). Images of 1000 grains of each fraction were registered.

Three shape parameters that best differentiate the examined grains were chosen on the basis of the preliminary tests: one characterizing the circularity and two characterizing the surface structure. The elongation parameters were not used because they were not suitable for differentiating the investigated deposits.

The circularity was calculated according to Cox (1927):

$$\theta = \frac{4\pi A}{P^2} \tag{1}$$

where A is the area and P the perimeter of the investigated particle.

The surface structure was characterized by:

- the κ_1 parameter defined by Mora and Kwan (2000):

$$\kappa_1 = \frac{A}{A_{\text{convex}}} \tag{2}$$

where A, as previously, is the area and A_{convex} is convex area of the investigated particle

- the κ_2 parameter defined by Riley et al. (2003), called *compactness* by them:

$$\kappa_2 = \frac{4\Pi A}{P_{\text{convex}}} \tag{2}$$

where A, as previously, is the area and P_{convex} is the convex perimeter of the investigated particle.

Steel cylinders of 100 cm^3 were filled with the air dried sand and then moistened to a water content of approximately 0.20 kg kg^{-1} (field water capacity). Pre-germinated seeds of wheat (*Triticum aestivum* cv. Tonacja) were placed at 8–10 mm depth (two seeds per cylinder). Ten cylinders were used for both rounded and rough sand. To minimize evaporation, the surface of the sand was covered with a 5 mm thick layer of perlite. Cylinders were randomly distributed in a growth chamber (climatic chamber KK 1200, POL-ECO Aparatura, Poland) and were grown for five days at daytime (16 h) and night time (8 h) temperatures of 22 °C and 16 °C, respectively, a relative humidity of 60%, and photosynthetically active radiation (PAR) of 240–280 μmol s^{-1} m^{-2}. The short period of growth prevented water stress that might limit plant growth and, therefore, no water was added during growth. The experiment was repeated twice. At the end of the five-day growing period, the height of plants and their leaf area were measured. Whole aboveground plants were taken to evaluate for dry mass (after drying at 65 °C for 48 h). Roots were washed out and the WinRHIZO 2007 (Regent Instruments Inc.) programme was used to calculate root length, average diameter and area, and leaf area for each plant separately. Afterwards, root dry mass was measured (after drying at 65 °C for 48 h). Specific root length (SRL) was calculated by dividing dry mass by length. The shoot-to-root ratio was calculated on a dry weight basis.

We arranged another set of eight replications of each treatment for penetrometer resistance measurements. We measured the resistance with a strength testing device (Zwick/Roell) using a 15° semi-angle cone-shaped steel tip at constant speed of 2 mm min^{-1}. The cone tip had a maximum diameter of 1 mm. The measurements were done at the same water content as that used for wheat growth. The 10 mm upper and lower layer readings were excluded, and therefore only the readings from the central 30 mm depth were considered. Two penetrations were made in each sand core, making a total of 16 replications. The third sets of eight replications each was used to determine water permeability using a constant-head (2–3 mm) hydraulic conductivity test. The sands were preliminary saturated with water. Bulk density was determined by the core method in eight replicates (Blake and Hartge, 1986).

2.1. Statistical analysis

Statistical analysis was performed using STATISTICA 8.0 (StatSoft, Inc., Tulsa, OK, USA).

Significant difference between mean values was determined by the t-test procedure.

3. Results

3.1. Shape characteristics and physical properties of the sands

Significantly larger ($P < 0.05$) values of all shape characteristics in the rough compared to rounded sand indicate greater irregularity in the former (Fig. 1). Relatively, the largest differences occurred with the circularity (θ).

Bulk density and water permeability differed significantly ($P < 0.05$) between types of sand (Table 1). Bulk density increased from 1.59 in the rounded sand to 1.63 g cm^{-3} in rough sand, whereas penetrometer