Development of Mechanical Soil Stability In An Initial Homogeneous Loam And Sand Under In-Situ Field Conditions

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Research Article

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Abstract

Purpose

Soil structure evolving from physical and biological processes is closely related to soil mechanical characteristics and texture. A soil plot experiment in Bad Lauchstädt, Germany, allowed us to study the influence of substrate and genotype on the initial development of mechanical traits, differences between depths, and changes over the course of two years.

Methods

Plots were homogeneously filled with a loam and a sand and planted with two maize (Zea mays L.) genotypes (wild type (WT) and rth3 mutant) with contrasting root hair attributes. Undisturbed soil cores were taken in 2019 and 2020 at 14 and 34 cm depth. Confined uniaxial compression tests were performed to determine pre-compression stress ($\sigma_{pc}$), compressibility ($C_c$, $C_s$) and elasticity index (EI). Mechanical energy was calculated based on penetration resistance tests with a penetrometer needle resembling root geometries.

Results

$\sigma_{pc}$, $C_c$ and $C_s$ were significantly higher in loam as compared to sand, whereas the factor genotype proved to be negligible. Over time, $\sigma_{pc}$ increased and $C_c$ decreased in loam from 2019 to 2020 and $C_s$ declined in both substrates. Higher mechanical energies were observed in loam and partially in WT. Required energy was higher at 14 cm than at 34 cm depth and decreased from 2019 to 2020 in sand. Airdry sand samples required four times as much energy than those at -50 kPa.

Conclusion

For the development of the mechanical traits examined texture proved to be the dominating factor and changes in soil stability could be observed within a short period of time.

1 | Introduction

Soil mechanical characteristics evolve from the interplay of texture and structure of a soil, structure itself being influenced by a variety of biological, physical, and chemical factors. Root growth constitutes a major biological factor for the formation of soil structure and depends on the plant’s characteristics and the prevailing environmental conditions. In search for water and nutrients, root systems can reach astonishing depths of more than 50 m reported for some tree species and an average maximum rooting depth of 2.1 m for cropland (Canadell et al., 1996). Roots are able to exert high forces with axial and radial root growth pressures of 0.5 MPa measured for pea (Pisum sativum cv. Greenfeast) seedlings (Misra et al., 1986).
How root growth re-organises the pore system and aggregate size distribution, largely depends on soil texture. Bacq-Labreuil et al. (2019) showed that phacelia (*Phacelia tanacetifolia* Benth.) decreased soil porosity in a sandy loam as compared to the unplanted control but did not alter porosity of a clayey soil. The changes in $\rho_b$ induced by root growth are mainly determined by soil structure and particle size. When roots grow in homogeneous soil, particles are rearranged, whilst in a more structured soil the existing pore space is utilized (Phalempin et al., 2021). Growth of coarse roots increase macropores, whereas finer roots display a high flexibility and improve micro-porosity (Bodner et al., 2014). Roots do not only greatly contribute to the creation of biopores but also improve connectivity of the pore system (Lucas, 2020). Furthermore, they have an influence on soil aggregation. In an agriculturally reclaimed mining area, macro-aggregate size distribution remained similar throughout the 24 years reclamation age (Pihlap et al., 2019), whereas aggregates <1000 µm increased in a clay through phacelia growth (Bacq-Labreuil et al., 2019).

Mucilage released at the root tip (Oleghe et al., 2017; Naveed et al., 2017) and an intact root tip (Iijima, 2004; Bengough & McKenzie, 1997) ease the roots’ way through the soil. Roots provide a habitat for soil microorganisms and their exudates have a major impact on bacterial community structure in the rhizosphere (Haichar et al., 2008). Roots contribute indirectly to soil structural evolution even after the plant’s death, by providing nutrient and carbon to soil organisms (Li et al., 2015, Pett-Ridge & Firestone, 2017), increasing both functional and taxonomic diversity though root detritus (Nuccio et al., 2020) and altering microbial activity through the spatial organisation of the pore network (Nunan et al., 2017). Furthermore, former root channels constitute an important root growth pathway in soil layers with a high mechanical impedance (Han et al., 2015). Both root exudates (Burak et al., 2021, Galloway et al., 2020) and existence of root hairs (Carminati et al., 2017) contribute to the formation of a rhizosheath, which in turn can strengthen soil structure (Wang et al., 2017) and affect both porosity and connectivity of the surrounding pores (Koebernick et al., 2017). In the light of these processes plant growth affects soil structure formation and stabilization by a wide range of interacting mechanisms, which in turn ultimately influences soil mechanical parameters.

Physiological and morphological characteristics such as nutrient and moisture requirements and the type of root system might limit the establishment of a plant. Soil moisture and nutrients can present problems if they are too high or too low, as might unfavourable mechanical and chemical conditions. Competition with other plants or the presence of pests or pathogens are a possible biological hindrance to plant growth. Roots may encounter layers which they are not able to penetrate, because of waterlogging or elevated mechanical impedance. For instance, Bengough et al. (2011) mentioned penetrometer resistances of 2 MPa reducing root elongation rates in maize by 50% compared to non-impeded roots.

It is a combination of both abiotic and biotic factors that influences structure formation in a soil (Barto et al., 2010). Physical factors such as climatic conditions and weather, influence soil structural development directly by freezing and thawing or swelling and shrinking cycles and indirectly through affecting plant growth. Leuther & Schlüter (2021) examined the impact of freezing and thawing cycles on soil structure and found that even only two of these cycles might already lead to a fragmentation of soil clods and an
increase of unsaturated hydraulic conductivity. Wetting and drying leads to swelling and shrinking processes in the soil which affect macro- and mesoporosity and greatly depend on clay content and mineralogy (Diel et al., 2019). Stronger organic bonds leading to an increase in macroaggregates and their stability, can be expected between 2:1 clay minerals compared to a soil in which 1:1 clay minerals dominate (Denef & Six, 2005). In managed grasslands Barto et al. (2010) showed that a higher percentage of sand in a soil interferes with soil aggregation.

The experimental site we examined consisted of plots that were homogeneously filled with two defined substrates and planted with two maize genotypes (Vetterlein et al., 2021). This set-up gave us the unique opportunity to study the development of soil mechanical properties following an initial homogeneous state under field conditions. The aim of this study was to quantify the effect of the factors substrate and genotype on soil mechanical parameters, namely $\sigma_{pc}$, $C_c$, $C_s$, EL, PR, and mechanical energy required for root growth and to describe their spatial and temporal development.

We hypothesized substrate to be the driving factor with higher stability and compressibility expected in loam as the higher clay content promotes soil aggregation thus enhancing soil stability. Bronick & Lal (2005) describe the important role of clay in the formation of compound particles that contribute greatly to soil aggregation. Shrinking and swelling processes in soils containing clay are crucial in soil structure formation (Dixon, 1991). Higher clay contents and a greater level of aggregation in loam bring about a higher initial void ratio and its more pronounced decline when stresses exceed $\sigma_{pc}$ (Lebert & Horn, 1991). The sand on the other hand is a single-grain substrate with weak cohesion between particles (Lebert & Horn, 1991), less potential for aggregation and a pronounced primary pore system that leaves little room for compression. The two genotypes employed in the experiment differ in their capability to form root hairs. The wild type (WT) forms root hairs, whereas in the $nth3$ mutant their elongation is suppressed. Root hairs play a central role in the cohesion between roots and soil particles (De Baets et al., 2020) and might therefore lead to higher stabilisation.

Concerning the development over time and space, we expect $\sigma_{pc}$ to be higher at 14 cm depth compared to 34 cm depth, caused by the influence of environmental conditions, mainly effects of drying and re-wetting, being more distinctive closer to the soil surface. As structural development takes time, stability is likely to increase from one year to the next and compressibility to decrease. Regarding penetration resistance, we expect higher values in loam compared to sand and a possible influence of genotype relating to their root system. We further hypothesize the heterogeneity to be greater at 14 cm depth and to increase with time due to the development of soil structure, all in all leading to higher values in the second year. Our overall hypothesis is, that in sand changes in mechanical characteristics caused by processes of structural formation will be less pronounced than in a loam.

2 | Materials And Methods
2.1 | Soil plot experiment
The soil plot experiment was established in October and November 2018 in the frame of the DFG priority programme 2089 “Rhizosphere Spatiotemporal Organisation - a key to rhizosphere functions”. The site is located at the experimental station of the Helmholtz Centre for Environmental Research in Bad Lauchstädt in Germany (N 51° 23.425440, E 11° 52.555980). Field plots were excavated and filled with two homogeneous substrates, a loam and a sand (loam: 32.5% sand, 47.9% silt, 19.5% clay; sand: 91.8% sand, 5.6% silt, 2.6% clay (Vetterlein et al., 2021)), and planted with maize genotypes WT (wild type) and rth3 (mutant with disturbed root hair elongation). The randomized block design consisted of six plots for each combination of texture and genotype, resulting in six field replicates. Fertilization ensured an equal supply with nutrients in both substrates. Maize was first sown in April 2019. Details regarding the experimental set-up including filling of field plots, fertilization, and agronomic measurements are described in Vetterlein et al. (2021).

2.2 | Sampling and sample preparation

Two sets of undisturbed soil cores were taken at growth stage BBCH83 (early dough) (Meier & Biologische Bundesanstalt für Land- und Forstwirtschaft, 1997) in 2019 and 2020, one for a confined uniaxial compression test, the other for penetration resistance measurements. For the compression tests, cylinders with a diameter of 10 cm and a height of 3 cm were employed, whereas for the remainder of the experiments cylinders with a diameter of 10 cm and a height of 6 cm were utilized. Samples were taken at a specific location in each field plot at two different depths (14 cm and 34 cm upper cylinder edge) and stored in the dark at 4°C until further use. In preparation for the measurements, samples were saturated with tap water and subsequently put on ceramic suction plates until weight consistency was reached to obtain the desired matric potentials (Ψ_m) of -50 kPa for the uniaxial compression test and a sequence of -3, -12.5 and -50 kPa for the penetration measurements with an additional airdry step in 2020.

2.3 | Confined uniaxial compression test

Undisturbed soil samples were measured at Ψ_m -50 kPa with an oedometer (Fig. 1; Eijkelcamp 08.67 Compression test apparatus, Giesbeek, Netherlands) and the software Physical soil test Version 2.0.4 (Eijkelcamp, Giesbeek, Netherlands) to obtain information on σ_{pc}, compressibility, and EI. Sampling cylinders had a ratio of diameter to height of 3.33 in accordance with the International Organization for Standardization (ISO, 2017)). To level out any irregularities at the sample surface, the device exerted a pre-pressure of 5 kPa for 20 s, which we defined as the actual start of the test. This was followed by 11 log-equidistant loading steps ranging from 10 to 575 kPa and a final unloading step of 5 kPa. The duration of each step was 20 min for loam and 5 min for sand to account for different consolidation times of these substrates and was established in a pretest prior to the experiment. The oedometer is furthermore equipped with a ceramic suction cup to allow measurement of matric potential throughout the experiment. Applied stress, vertical settlement and matric potential were logged every 2 s. For the necessary calculations \( \rho_b \) was determined by drying the soil cores at 105°C for 48 h after measurements; particle density (loam 2.46 g cm\(^{-3}\) and sand 2.62 g cm\(^{-3}\), Roskopf et al., 2021) had been quantified at an earlier stage.
Evaluation of $\sigma_{pc}$ was based on the methods of Casagrande (1936) and the logistic function suggested by Gregory et al. (2006). The slope of the virgin compression curve is called the $C_c$, and was calculated by dividing the difference of its initial and final $\epsilon$ through the difference of its final and initial $\log \sigma$. The $C_s$ was calculated in the same way using $\epsilon$ and $\sigma$ of the elastic rebound curve. The EI was calculated for the final loading step of 575 kPa with as used by Peth et al. (2010). The ratio ranges from 0 (completely plastic behaviour) to 1 (completely elastic behaviour).

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EI = \frac{\Delta \epsilon_{\text{rebound}}}{\Delta \epsilon_{\text{loaded}}}
\]

### 2.4 Penetration resistance experiment

For the PR experiment a stainless-steel cover was devised to ensure correct positioning of the tests with sufficient distance between penetration sites and cylinder edge, and to prevent evaporation during the experiment, as only the hole in use was left uncovered. As the samples were sufficiently large to accommodate 12 penetrations, the experiment was performed at three different matric potentials (-3, -12.5, and -50 kPa and an additional air-dry step in 2020) with three replicates per cylinder. For air-drying, samples were placed on a wire mesh and put underneath a fume hood at room temperature until no further weight loss occurred. A material testing machine (100 kN Allround Table Top Zwick/Roell, Ulm, Germany) was employed to push a penetration needle at a constant rate of 120 mm h$^{-1}$ to a depth of 20 mm into the soil. The effect of the penetration rate on force measurements had been evaluated before suggesting that at a rate of 120 mm h$^{-1}$ realistic forces similar to penetration velocities in the order of real root growth rates are determined (Rosskopf et al., 2021). The penetrometer probe was non-recessed with a diameter of 1 mm (Oleghe et al., 2017) and a 15° semi-angle resembling root geometries (Ruiz et al., 2017). The use of a non-recessed shaft allowed us to retract the PR needle at insertion speed to estimate shaft friction, which was performed for one of the three replicate measurements per cylinder. The sensitive microsensor with a nominal force of 10 N accurately captured the resulting forces (accuracy grade 1 according to ISO 7500-1 (ISO, 2018) down to 0.02 N). Forces were logged every 10 µm. Results of three measurements per cylinder at each matric potential were averaged and corrected for shaft friction. The measured axial penetration force ($F_{Z,m}$) was divided by the cross-sectional area of the conus to obtain PR. To calculate the mechanical energy demand per unit length according to Ruiz et al. (2017), the area below the displacement-force curve between 2 mm and 18 mm depth was calculated and results subsequently normalized to the length of one metre. Within that range full contact between the cone and the soil had been established and values for all replicates were available. Samples were weighed after drying for 48 h at 105°C to calculate $\rho_b$.

### 2.5 Statistical analysis

To test the effects of substrate and genotype and their interaction on the variables measured, multi-factorial ANOVA was calculated sorting the data according to year and depth. Where applicable, a subsequent Tukey HSD-test was performed. The same approach was applied to determine differences
between depths and years. The energy data derived from penetration measurements did not meet pre-requisites for ANOVA, so data transformations had to be carried out beforehand. For this purpose, data for the groups according to depth and year were log-transformed prior to ANOVA, subsequently significant differences for the factors substrate, genotype and their interaction within each matric potential were quantified. Airdry samples were analysed separately, as only sand values in 2020 were available. Here, one-factorial ANOVA was used to determine differences according to genotype and to substrate. Splitting the data into loam and sand we then calculated whether the factors depth and year caused any differences within energy values. For all tests, $H_0$ was specified as no differences occurring between observation groups and the significance threshold ($\alpha$) was set at 0.05. Statistical tests were executed with the open-source software RStudio version 1.3.1093 (RStudio Team, 2020). Figures were prepared with R-package ggplot2 version 3.3.5 (Wickham, H., 2016).

3 | Results

3.1 | Effect of substrate and genotype on bulk soil mechanical parameters

Result tables for all parameters including mean values and standard errors for all groups can be found in the online resource (table S1) alongside full ANOVA tables (tables S2-S5). Stress-strain relationships of both substrates tended to have a slightly S-shaped curve with $\epsilon$ deviating from the virgin compression line at high loading steps. The impact of substrate and genotype on $\sigma_{pc}$ is graphically presented in Fig. 2. Values ranged from 19-71 kPa in loam and from 15-48 kPa in sand. Higher values in loam compared to sand were found in all groups apart from 34 cm in 2019. Group 34 cm in 2019 stands apart with the only differences in $\sigma_{pc}$ caused by the factor genotype ($p=0.033$) with higher $\sigma_{pc}$ values for $rth3$ compared to WT and the only significant interaction ($p=0.015$) between the two factors (higher $\sigma_{pc}$ for WT in loam and for $rth3$ in sand; not shown).

Compressibility was influenced by the factor substrate (Fig. 3), which led to strongly contrasting values with loam displaying a much higher compressibility than sand in both the virgin compression and the re-compression curve. $C_c$ were significantly higher in loam in all groups with p-values of 4.7E-14, <2E-16, 6.5E-15, and <2E-16 at 14 cm in 2019, 34 cm in 2019, 14 cm in 2020, and 34 cm in 2020, respectively. Accordingly, p-values indicating differences within $C_s$ were 1.8E-08, 3.3E-09, 0.00042, 8.4E-07 for the groups as above. Both ranges and inter-quartile ranges of $C_c$ in sand were remarkably low. In loam $C_s$ values differed considerably according to depth and year, whereas values in sand were more similar to each other. Contrarily, neither $C_c$ nor $C_s$ indices were affected by the factor genotype (not shown). No interactions occurred in any of the compressibility statistics.

EI were considerably higher in sand with mean values of 0.120-0.129 as opposed to loam with mean values between 0.045 and 0.052 (not shown). P-values were well below the significant threshold with
values of 5.6E-05, 3.9E-04, 1.4E-05, 2.8E-08 for 2019 14 cm, 2019 34 cm, 2020 14 cm, and 2020 34 cm, respectively. Again, no influence of genotype on soil elasticity could be discerned.

Significant correlations were observed in loam between $\rho_b$ and $\sigma_{pc}$, $C_c$, and $C_s$ (Fig. 4). All correlations were stronger in 2020 compared to 2019. $\sigma_{pc}$ and $C_c$ or $C_s$, respectively, were negatively correlated (Fig. 5), whereas a positive relationship was found between $C_s$ and $C_c$. Again, the same pattern occurred with lower $R^2$ and higher $p$-values in 2020.

In sand the corresponding correlations were much weaker and mainly not significant (data not shown). The only significant differences were found between $\rho_b$ and $C_c$ (2019: $R^2 = 0.37, p = 0.0016$ and 2020: $R^2 = 0.27, p = 0.012$), $\sigma_{pc}$ and Cs 2019 ($R^2 = 0.2, p = 0.026$, and $C_s$ and $C_c$ 2019 ($R^2 = 0.19, p = 0.0034$).

3.2 | Effect of depth and year on bulk soil parameters

The influence of the factors depth and year was analysed here more specifically and is graphically presented in figures 6-8, along with indication of statistical significance. Full statistical tables are included in the online resource (table S6-S10). In sand, $\rho_b$ was lower at 34 cm depth than at 14 cm, and the factor year did not result in significant differences (Fig. 6). The opposite was the case in loam with similar values according to depth but higher bulk densities in 2020 compared to 2019. In none of the treatments $\sigma_{pc}$ (Fig. 7) was affected by depth, but it increased for both genotypes in loam from 2019 to 2020.

Regarding the compressibility (Fig. 8), depth did not influence $C_c$, and higher $C_s$ values were measured at 34 cm depth in loam, significantly for WT. Year turned out to be the dominant factor for changing soil stability leading to lower compressibility (tendency in $C_c$ in L rth3) in loam in 2020 compared to 2019. In sand, $C_c$ remained constant over depths and years with a remarkably low range. Lower $C_s$ values in 2020 could also be observed in sand, albeit not significant for rth3. Concerning EI, no significances occurred in any of the treatments, but a tendency to higher EI in 2020 as opposed to 2019 was evident in sand (data not shown).

3.3 | Effect of substrate and genotype on energy required for root growth

Generally, the energy needed for one metre root growth increased with decreasing matric potential. To better understand the effect of the factors substrate and genotype, data were grouped according to depth and year, as these groups displayed distinct patterns (Fig. 9). In 2019 no significant differences occurred, but there was a trend to higher energy values in sand at both depth at $\psi_m$ -3 kPa. In 2020 differences between energy values in loam and sand had developed in 14 cm at $\psi_m$ -50 kPa and in 34 cm depth at $\psi_m$ -12.5 and -50 kPa. Highest values of up to about 2 J (~2.5 MPa) were found at -50 kPa in loam. The samples from 34 cm depth in 2019 displayed the lowest range of values. The respective statistical table is S11.
The factor genotype proved to be of minor relevance with significant differences in only two groups out of twelve (Fig. 10). Higher energy values for WT roots were observed in 14 cm 2019 at -12.5 kPa and in 34 cm 2020 at -50 kPa. No interactions between substrate and genotype could be observed.

Additional graphs depicting the course of the PR curves are located in the online resource (fig. S1 and S2). In 2019 at 34 cm depth all treatments displayed similar curves. The most pronounced differences occurred at -50 kPa in 2020 with loam WT being distinctly higher than loam rth3 which in turn was higher than sand.

### 3.4 | Effect of depth and year on energy required for root growth

When visually depicting the influence of the factors depth and year on penetration energies (Fig. 11), a clear pattern becomes visible. At 14 cm depth values were higher in both substrates with significant differences for four out of six groups. Required energy in loam remained constant over the years, whereas energy in sand declined significantly from one year to the next. In loam an interaction between the factors occurred at -12.5 kPa (p = 0.0207) with higher values at 14 cm depth compared to 34 cm in 2019 and vice versa in the following year. The inter-quartile range of both loam and sand values was reduced from one year to the next. ANOVA tables are available in the online resource (table S12).

Due to technical limitations, measurements at air-dry conditions (Fig. 12) could only be carried out in sand and only a few were done in loam, not enough to be analysed statistically. In sand, no differences caused by depth or genotype occurred. As the soil becomes drier, the plant must overcome much higher resistances and therefore invest more energy in root growth. Even in sand, penetration resistances reach approximately 5 MPa.

Regarding significant correlations between any of the other parameters with energy values, correlations could be observed between bulk densities and energy in sand (Fig. 13). The respective correlations in loam were not significant and displayed no differences between years (data not shown). The air-dry sand samples of 2020 did not significantly correlate with \( \rho_b \).

### 4 | Discussion

#### 4.1 | Influence of substrate and genotype on bulk soil mechanical parameters

Geological history and mechanical loading are factors influencing \( \sigma_{pc} \) which can be ruled out in the present setup, because the plots were artificially filled and all use of machinery for agronomic measures were avoided, and the soil was not tilled. We drained all oedometer samples to -50 kPa \( \Psi_m \) to provide a comparable starting point for our measurements. In the present experiment the factor substrate had a major impact on \( \sigma_{pc} \) with higher values in loam compared to sand. This is in accordance with our
hypothesis, as pronounced aggregation in loam leads to increased mechanical soil strength (Horn et al., 1994), especially at clay contents of more than 15% (Lebert & Horn, 1991) which was the case for the loam used. Soil strength is a function of forces between particles, interparticle friction and cohesion as well as the number of particle contacts per volume. In a single grain structure as for sand, the number of particle contacts and the forces between particles are much lower compared to a loam with a variety of particles sizes (Lebert & Horn, 1991). Thawing-and-freezing as well as drying-and-wetting processes further increase soil stability (Dexter, A.R., 1988), additional factors are the presence of organic matter, biological processes and the consequences of anthropogenic impacts (Dexter, 1988; Horn et al., 2019). Horn et al., 1994 stated that $\sigma_{pc}$ in a homogeneous substrate corresponds to the effective stress as a function of pore water pressure. In a structurally unstable soil, the previous highest hydraulic stress (most negative pore water pressure) affects the range of the re-compression curve and $\sigma_{pc}$ (Mosaddeghi et al., 2003). Tang et al., (2009) discussed the shape of the stress-strain curves obtained for both remoulded and undisturbed soil cores and observed S-shaped curves particularly when soil had little structure, as it is the case for remoulded and not for undisturbed samples, which tended to display a bilinear curve. Even though the samples in the present experiment were taken as undisturbed samples, they are – technically speaking – remoulded samples, as the plots were artificially packed with homogenized substrate. As the pore space is filled with air and water and reduced during the deformation process, the relative amount of water in the pores and subsequently the matric potential increases, with $\Psi_m$ reaching values close to 0 kPa in some cases, which provides a further explanation for the S-shaped curves, as the deformation behaviour of a soil also depends on the mobility of these phases (Horn et al., 1994; Tang et al., 2009).

In loam we found a positive correlation between $\rho_b$ and $\sigma_{pc}$, which is in accordance with An et al. (2015) and Mosaddeghi et al. (2003), who reported a weak positive correlation. Rücknagel et al. (2007) used $\rho_b$ and aggregate density as input for multiple linear regression to estimate $\sigma_{pc}$ and revealed that an increase in $\rho_b$ results in an increment of $\sigma_{pc}$. According to Lebert & Horn, (1991) with a higher degree of aggregation caused by a higher clay content, the importance of $\rho_b$ as determining factor for soil strength decreases. This might result in great soil strength even though $\rho_b$ is low. Remarkably, in the present study no significant correlation between $\rho_b$ and $\sigma_{pc}$ existed for sand. To explain this contradiction, it has to be noted, that the sand samples were in fact very unstable from the beginning. According to Dexter (1988), one of the critical issues of soil stability is its ability to resist the influence of water. During sample preparation in our study (saturation to a standard $\Psi_m$), sand samples consolidated considerably and lost on average 1.72 mm of their initial height. This led to an unavoidable stabilisation of these samples with a mean decline in $\rho_b$ of 0.11 g cm$^{-3}$. Without it we could have expected a more pronounced curvature of the stress-strain relationship and therefore lower $\sigma_{pc}$ in sand and a noticeable correlation between $\rho_b$ and $\sigma_{pc}$.

The compressibility of loam was higher compared to sand both along the re-compression curve ($C_s$) and the virgin compression curve ($C_c$). The sand, on the other hand, with a single grain structure showed only little potential to be compressed as the majority of grains was of similar size and the pore system
dominated by primary pores. This becomes evident when looking at the remarkably low range and interquartile range of $C_c$ in sand. Compressibility values and ranges in sand were further reduced due to the complications just mentioned. In loam $\rho_b$ was negatively correlated with $C_c$ and $C_s$, so the compressibility in both the re-compression and the virgin compression curve declined with increasing $\rho_b$. A negative correlation between $\rho_b$ and $C_c$ for two agricultural soils was reported by An et al. (2015). The corresponding correlations in sand were weaker than we expected as compressibility had already been reduced due to consolidation.

Keller et al. (2011) discovered that particle size and aggregate size distributions hardly influence compression properties of a soil. Instead, they revealed initial void ratio as the determining factor for $\sigma_{pc}$, $C_c$, and $C_s$ with low void ratios resulting in higher resistance to compression and therefore decreasing $C_c$ and $C_s$ and higher $\sigma_{pc}$. This is explained by a higher number of particle contacts leading to increased frictional forces, less available pore space and more energy necessary to relocate water during compression if the initial void ratio is low. However, they noted that this behaviour is also a consequence of using a semi-logarithmic curve as basis for the calculations, which is the common approach and was also used here. Low initial void ratios and their weak decline during compression dominated in sand and more defined curves were observed in loam in the present study, which is in agreement with Gregory et al. (2006).

EI was higher in sand than in loam which at first glance seems to be an unexpected result. However, EI was based on a final un-loading step after maximum loading of 575 kPa. The EI related the changes in void ratio of this final step to the overall changes in void ratio of the entire curve, which were much higher in loam compared to sand. So even though, absolute void ratio changes in the unloading step were in fact higher in loam than in sand, the resulting ratio, i.e., the EI, was lower.

Maize genotype was not of importance for the bulk soil properties measured. A possible explanation is the fact that samples were taken between plant rows and the percentage of rhizosphere soil is bound to be too low to influence the measured bulk soil mechanical parameters. Even examining the rhizosphere only, an influence of root hairs on $\rho_b$ could be neither detected in barley (Koebernick et al., 2019) nor in maize (Phalempin et al., 2021). Roots play a crucial role in the formation of aggregates as they enmesh particles and release organic compounds into the rhizosphere. The aggregates are stabilized by bacterial colonization and wetting-and-drying cycles, especially if clay particles are present (Bronick & Lal, 2005). Two studies of aggregation with barley root genotypes WT and a root hair-less mutant were carried out, one in heterogeneous soil similar to inter-aggregate pore space (Koebernick et al., 2017) and the other in a homogenous substrate as a model for intra-aggregate pore structure (Koebernick et al., 2018). They concluded that barley root hairs have a stronger effect on the inter-aggregate pore space, creating a higher pore volume and a higher percentage of small pores in the rhizosphere thus compensating for the compaction created by roots. We consider it plausible that differences between genotypes in the field might build up after a few more years of re-planting the site with the two genotypes and might be ascertained in a future sampling.
4.2 | Spatial and temporal development of bulk soil mechanical properties

We hypothesized structural development to be higher at 14 cm than in 34 cm depth, because closer to the soil surface the influence of environmental factors associated with more intensive wetting and drying and freeze-thaw action can be expected to be stronger. Anyhow, in our study, differences in mechanical parameters were not very pronounced and only occurred for sand, where $\rho_b$ was lower at 34 cm depth and $C_s$ in loam with higher values at lower depth. Rain was scarce in both years and as the bottom of the plots (1 m) was filled with a 25 cm gravel layer with a drainage textile placed on top, plants could not access water from below the plots but depended on precipitation alone. Both the effects of precipitation and drought start from the top thus increasing the variability of $\Psi_m$ in the topsoil layer resulting in wetting-and-drying cycles at 14 cm, but not at 34 cm depth (Jorda et al., in preparation).

The temporal development was more pronounced than the spatial one. A general setting of soil could be observed with higher $\rho_b$ in 2020 compared to 2019 in loam, which is not surprising regarding the substrates had been filled-in homogeneously. In loam $\sigma_{pc}$ increased and $C_c$ decreased with time. The potential for further compaction, i.e., reduction of the pore space, had already been greatly reduced in sand in 2020, which becomes evident when looking at the extremely narrow ranges of $C_c$. Within the range of the re-compaction curve changes between years are even more pronounced with declining $C_s$ in both substrates. These temporal changes in bulk soil mechanical parameters coincide with higher root length densities in all treatments in 2020 compared to 2019 (Vetterlein et al., in preparation). Increased root length densities bring about a stabilization of structure, hence higher $\sigma_{pc}$ and lower compression values. This corresponds to the declining relevance of $\rho_b$ for the bulk soil mechanical parameters and the decreased correlations between them. A possible explanation for the less pronounced correlations in sand are the existence of loamy lumps which resulted from the mixing and filling process of the plots.

4.3 | Required energy and penetration resistances

It is commonly known that decreasing $\Psi_m$ leads to an increase in forces needed for soil penetration (Quang, 2012; Elbanna, 1987; Wang et al., 2016). The moistest samples displayed no differences between treatments for substrate and genotype, whereas differences according to substrate were more pronounced at lower $\Psi_m$ as PR responds stronger to $\Psi_m$ at higher clay contents (Costantini, 1996). Both sampling years were very dry, with cumulative precipitation amounts of 180 mm in 2019 and 210 mm in 2020 from sowing until sampling at BBCH83 (German Meteorological Service, 2021). This resulted in low soil moistures dropping even below the permanent wilting point (Jorda et al., in preparation). With the current experimental set-up, it was not possible to measure PR at air-dry conditions in loam, as the penetrometer needle did not resist the occurring forces. In order to be able to tackle this problem in the future, we are presently working on a comparison of a 1 mm and a 2 mm diameter needle, which will allow us to measure PR at drier conditions and relate the results to the ones obtained so far. Nevertheless, the few measurements that were made in air dry loam give us an idea of the resistances the roots
encountered in the field. PR values of over 50 MPa were reached in loam in five measurements out of 17. Even in sand average values around 5 MPa were around five times higher compared to measurements done at -50 kPa. A lab experiment using the same loam yielded energies twice as high at the permanent wilting point compared to −50 kPa (Rosskopf et al., 2021). However, when transferring the results to natural root systems it has to be taken into account that a real root does not grow straight into the soil as the PR needle does but is able to avoid compacted regions, and to utilize the available pore system in search of nutrients and water. In the first season in 2019 no secondary pore system has yet been established, so the actual forces the roots encountered in the field are likely to be different from 2020. A similar issue is the divergence between sand and loam, with the primary pore system being the dominant one in sand but not in loam. Phalempin et al. (2021) observed for the same substrates how roots push aside particles in homogeneous soil and take advantage of existing pores where structure is present. Therefore, we conclude that we were able to reflect the situation for roots on the field quite well. Our measurements allow a systematic comparison of the effects of soil conditions on the mechanical resistances that roots potentially experience.

In a laboratory experiment employing the same loam and sand, samples with a defined \( \rho_b \) of 1.26 g cm\(^{-3}\) for loam and 1.47 g cm\(^{-3}\) for sand were produced and PR and energy were measured at the water contents corresponding to the same matric potentials as used in the present study (Rosskopf et al., 2021), thus resembling a perfect homogeneous state that might come close to initial field conditions. In the present study using undisturbed field samples, energy values in loam were an order of a magnitude higher than in the lab. Similar were the results in sand with 2019 values being about ten times as high as the corresponding lab samples. An explanation can be found in the respective sieving and filling procedures resulting in much more homogeneous samples in the lab, where substrates were sieved to 1 mm and mixed and filled in in small portions. Reproducing relationships between PR, \( \rho_b \) and soil moisture in the field with repacked samples in the lab was not possible due to structural variability as shown in a study by Costantini (1996).

Generally, a tendency to higher energy values could be observed in WT, which was also the genotype with higher root length densities at all depths at BBCH83 (Vetterlein et al., in preparation). In particular, the combination of loam and WT resulted in higher forces compared to the other treatments at more negative matric potentials, possibly caused by a higher degree of aggregation through root hairs and a greater percentage of clay particles. Differences regarding root hairs and exudates could provide a possible explanation. Burak et al. (2021) uncovered that both root hair length and density influence rhizosheath formation. In case no root hairs are present, root exudation is an important factor for the development of a rhizosheath. In their experiment, maize WT bound 1.8 times more soil than its \( rth3 \) counterpart and its exudates were more adhesive. Root hairs like those of maize WT can facilitate root penetration by providing anchorage to pore walls (Bengough et al., 2016). Maize WT roots were found to have a higher anchorage force than \( rth3 \) roots which results in increased root tip penetration and higher amounts of displaced soil (Bengough et al., 2016). These are aspects of real root growth that cannot be simulated with PR measurements. In the present experiment, WT had significantly higher shoot dry weight.
compared to *rth3* (Vetterlein et al., in preparation) in both years, resulting in higher water demand for WT and subsequently an earlier onset and a more severe drought stress. This process is reflected in the $\Psi_m$ measurements in sand made by Jorda et al. (in preparation). A possible explanation for higher energy values in WT might therefore be both the direct impact of increased rooting and the indirect effect of water depletion through roots.

In all treatments penetration energy was higher at 14 cm depth as opposed to 34 cm which is in line with our hypothesis of the evolution of structure being more pronounced closer to the soil surface. We assume the higher soil moisture variability and therefore more frequent drying out processes up to the permanent wilting point (Jorda et al., in preparation) to be of major importance in this context. A further aspect might have been higher root length densities at BBCH83 at 14 cm depth in sand in both years and in loam in 2020 (Vetterlein et al., in preparation).

Our hypothesis that advancing structural development leads to an increase of required energy over time could not be affirmed, in fact penetration energies for sand decreased from one year to the next while for loam no changes were observed. With time, differences between the substrates emerged, indicating a stronger structural development in loam, as hypothesized. It seems likely that areas of higher and of lower resistance have balanced each other out, so that differences between years did not appear. $\rho_b$ correlated with energy values in sand, but these parameters showed no relationship in loam. It is essential that not only the adjusted $\Psi_m$ but also maximum pre-drying plays an important role for the mechanical strength of soils (Hartge, 1986). Precipitation was altogether higher in the second season which might give us a possible explanation, when additionally considering the differences in water holding capacity of the substrates. It takes much less water to fill up the sand plots with their higher $\rho_b$ and lower porosity compared to the loam plots which resulted in the sand being wetter in the second season compared to the first and compared to loam. This brought about the very uniform force-displacement curves in theses samples. Wang et al. (2016) observed that with subsequent wetting-and-drying cycles soil structure evolves resulting in higher heterogeneity of strength and a simultaneous decrease of both maximum and overall PR values.

5 | Conclusions

Substrate with its implications for soil structure was the determining factor for stability, compressibility, and elasticity in the two years following the establishment of the present field experiment, whereas the overall effect of genotype proved negligible on bulk soil mechanical properties considered. Our overall hypothesis of stronger changes of soil mechanical parameters in loam as opposed to sand could be confirmed. After only a year, higher $\sigma_{pc}$ and lower compressibility, especially in the range of the re-compression curve were measured, indicating a stabilisation of structure with time in loam but only marginally in sand, in which measurements showed an altogether more uniform behaviour. The sand proved problematic for our measurements, as it consolidated during saturation, distorting the stress-strain relationship and the resulting parameters. Differences of bulk soil parameters between depths were
less pronounced but indicated stronger structural development in the top layer. Regarding energy needed for root growth higher values were found in loam with stronger differences between substrates in drier conditions. Higher PR in the top layer confirm our hypothesis of stronger stabilization processes close to the soil surface. Temporal development did not change PR in loam and decreased it in sand. In a further field campaign, an adjusted technical set-up with stronger penetration needles will provide us with more detailed information about PR at drier conditions, also accounting for small-scale heterogeneity of values within samples and including a methodological comparison of 1 mm and 2 mm diameter PR needles. Furthermore, we are evaluating PR values in relation to root length densities in a column experiment using substrates and genotypes as in the present study to give us further insights on the effect of the actual root system on PR.

Abbreviations

$C_c$ Compression index

$C_s$ Swelling index

$E_l$ Elasticity index

$\varepsilon$ Void ratio

$R^2$ Coefficient of determination

$rth3$ Maize mutant with suppressed root hair elongation

$\rho_b$ Bulk density

$\sigma_{pc}$ Pre-compression stress

PR Penetration resistance

WT Maize wild type

Declarations

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Conflicts of interest/Competing interests

The authors have no competing interests to declare that are relevant to the content of this article.

Availability of data

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Code availability

Not applicable

Authors' contributions

According to CRediT (Contributor Roles Taxonomy):

Conceptualization: Stephan Peth, Daniel Uteau; Formal analysis, Investigation and Visualization: Ulla Rosskopf; Funding acquisition and Project administration: Stephan Peth, Daniel Uteau; Supervision and Validation: Stephan Peth; Writing (original draft): Ulla Rosskopf; Writing (review & editing): Stephan Peth, Daniel Uteau, Ulla Rosskopf

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**Figures**
Figure 1

Uniaxial confined compression device with built-in soil sample
Figure 2

Effect of substrate (left) and genotype (right) on pre-compression stress. Data were grouped according to year and depth, \( n = 24 \). Significant differences are indicated by contrasting letters.

![Box plot for substrate effect on pre-compression stress](image1)

![Box plot for genotype effect on pre-compression stress](image2)

Figure 3

Compression (left) and swelling (right) indices as affected by substrate. Data were grouped according to year and depth, \( n = 24 \). Different letters indicate significant differences.

![Graph for substrate effect on compression index](image3)

![Graph for substrate effect on swelling index](image4)

Figure 4

Correlations in loam between initial bulk density and pre-compression stress, compression index, and swelling index, respectively. Data were split according to year, \( n = 24 \). In pre-compression data three outliers were removed. Coefficient of determination \( R^2 \) and p-values are given.

![Graph for correlation between bulk density and pre-compression stress](image5)

![Graph for correlation between bulk density and compression index](image6)

![Graph for correlation between bulk density and swelling index](image7)
**Figure 5**

Correlations in loam between pre-compression stress and compression and swelling index, respectively. Data were separated by year, n = 23. Three outliers in pre-compression stress were removed. Right graph shows correlation between swelling and compression index. Coefficient of determination $R^2$ and p-values are indicated.

**Figure 6**

Bulk density in loam and sand according to the factors depth (left) and year (right), n = 48. Each value is a mean of two measurements. Significant differences are indicated by different letters.

**Figure 7**

Pre-compression stress of the individual treatments (n = 24) L WT (loam wild type), L rth3 (loam rth3 mutant), S WT (sand wild type), and S rth3 (sand rth3 mutant) according to the factors depth (left) and year (right), n = 24. Significant differences are indicated by different letters.
Figure 8

Compressibility of the individual treatments (n = 24) L WT (loam wild type), L rth3 (loam rth3 mutant), S WT (sand wild type), and S rth3 (sand rth3 mutant) as affected by the factors depth (left) and time (right). The upper graphs display the compression indices and the lower ones the swelling indices. Letters indicate differences according to the respective factor for each treatment.

Figure 9

Energy required for a root with 1 mm diameter to grow 1 m in the respective substrate (loam and sand). Penetration resistance is displayed as secondary y-axis. Data were grouped according to depth (14 and 34 cm) and year (2019 and 2020). Data were log-transformed for statistical analysis and subsequently rescaled to the original data range for plotting. Measurements were taken at three matric potentials. Different letters within each matric potential (n = 24) signify differences between the substrates.
Energy required for a root of a defined maize genotype (WT = wild type, \(rth3\) = root hair-less mutant) with 1 mm diameter to grow 1 m. Data were grouped according to depth (14 and 34 cm) and year (2019 and 2020). Data were log-transformed for statistical analysis and subsequently rescaled to the original data range for plotting. Measurements were taken at three matric potentials (-3, 12.5, and -50 kPa). Different letters within each matric potential (n = 24) signify differences between genotypes

Figure 11

Energy needed for a 1 mm diameter root to grow 1 m in loam (top) and sand (bottom) as a function of depth (14 and 34 cm, left) and year (2019 and 2020, right), respectively. Loam data were log-transformed prior to statistical analysis and were rescaled to the original scale for plotting. Significant differences are indicated for each matric potential, n = 24

Figure 12

Results of penetration resistance measurements at airdry conditions in sand in 2020, n = 12

Figure 13

Correlations between bulk density and energy at matric potentials of -3, -12.5, and -50 kPa in sand, data were split by year, n = 24. Coefficient of determination \(R^2\) and respective p-values are given

Supplementary Files

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- supplinfoDevelopmentofsoilstability.pdf