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Abstract

Roots of annual species would be able to conserve soil properties during traffic induced compaction. The objective of this study was to determine and compare root traits and soil shear strength for three crop species with contrasted root types and morphological traits to see if roots of annual species are able to increase soil shear strength and thus explain the soil properties conservation. The experiment was performed under controlled conditions in steel cylinders containing a repacked loamy sand, with initial dry bulk density of 1.2 g cm^{-3} and that was kept moist. Soil shear strength parameters, i.e. cohesion and angle of internal friction, were determined from direct shear tests for soil cores at a soil matric potential of -10 kPa (i.e. water content at field capacity). The direct shear tests were performed with six external normal stress levels (25, 34, 44, 63, 83 and 93 kPa) and at a constant shear rate of 3 $mm.min^{-1}$, and applying Mohr Coulomb equation. The difference of root type, root length density, root density, specific root length and root dry matter content among crop species was not related to a difference in soil shear strength. The root volume density was the main trait involved in both soil cohesion and the angle of internal friction. This study highlights the effect of roots of annual crop species on soil shear strength by comparing their root traits to the apparent cohesion of soil core where they grow. *Vicia faba* would be a good candidate to improve soil shear strength for soil conservation. This study constitutes a step towards improving the understanding of plants' effects on soil shear strength with regards to selecting species and designing cropping systems for soil conservation.

Keywords: Soil cohesion, angle of internal friction, root traits, soil shear strength, crop species, compaction

Abbreviations

ARD: Average Root Diameter (mm)

ATRD: Average Taproot Diameter (mm)

DMC: Dry Matter Content (mg g^{-1}, root dry weight divided by the root fresh weight)

RD: Root Density ($g.m^{-3}$)

RLD: Root Length Density ($cm.cm^{-3}$)

RVD: Root Volume Density ($cm^3.cm^{-3}$)

SRL: Specific Root Length ($m.g^{-1}$)

TRVD: Taproot Volume Density ($cm^3.cm^{-3}$)

Introduction

Soil compaction is known as a major threat to soil quality in Europe (Berge et al., 2017; Stolte et al., 2015). Soil compaction in agroecosystems results from three-dimensional stress propagation in the soil (Horn et al., 2003), which is mainly caused by traffic during agricultural operations in the field. The soil compaction observed in agrosystems results from the combination of two processes: compression and shearing (Horn et al., 2003). Both processes negatively impact the soil pore system. Compression mainly reduces pore volume, while shearing affects pore system continuity (Berisso et al., 2013; Huang et al., 2022). These modifications to the pore system reduce the capacity of air exchange between the soil and the atmosphere, and impair water transport through the soil profile. Compression and shearing present heavy impacts on soil functions given as they make root penetration more difficult, decrease soil permeability, reduce the availability of nutrients and, therefore, reduce yields (Soane et al., 1980; Schjønning et al., 2016). These soil functions are essential for plant growth (Unger and Kaspar, 1994). Technological and agronomical solutions that can mitigate the detrimental effects of compaction on soil functions are needed. This mitigation can be achieved by reducing the mechanical stress applied during traffic or by improving soil mechanical resistance to deformation (Batey, 2009). Reinforcement of soil shear strength by roots has been investigated in the prevention of landslides and improvement of riverbank stability (Pollen and Simon, 2005; Stokes et al., 2009).

Potentially, plant roots can help enhance the soil's mechanical strength, and this protective function of plants could be included in the design of cropping systems (Bodner et al., 2021).

Soil shear strength parameters, cohesion and angle of internal friction, are classically determined from the Coulomb (1776) equation (Eq. 1):

$$\tau = c + \sigma tan\varphi$$

where τ is the shear strength (kPa), σ is the normal stress acting on the failure surface (kPa), C is the cohesion (kPa) and φ is the angle of internal friction (°).

Plant roots could potentially influence both of these two shear strength parameters. Roots increase soil shear strength directly through their mechanical resistance, and their anchoring in the soil, and indirectly through water removal from the soil by transpiration (Pollen and Simon, 2005). A decrease in the soil water potential increases both the soil resistance to compression (Schjønning and Lamandé, 2018) and to shearing (Fredlund Delwyn, 2006; Schjønning et al., 2020).Several studies examining the effects of roots on soil shear strength have highlighted the direct effect of the root tensile strength (the root's capacity to resist tension) and in most cases, effects of a range of root properties on cohesion: root area ratio (the surface proportion of a plane occupied by roots) (Operstein and Frydman, 2000); root density (the dry weight of roots per volume of soil) (Tengbeh, 1989; Ali and Osman, 2008); and root length density (the length of roots per volume of soil) (Osman and Barakbah, 2006). Physiological root traits (root exudates) and plant–soil microorganisms interactions involved in soil aggregation can contribute also to the increase of soil cohesion and soil shear strength (Rillig et al., 2015; Poirier et al. 2018; Garcia et al., 2019). Effects of the root architecture or root type (i.e. taproot or fibrous) on cohesion have also been highlighted (Ghestem et al., 2014; Li et al., 2017).

Only scarce evidence of root effects on soil internal friction exist (Graf et al., 2009). However, more research is needed to identify the specific root traits involved in the increase of soil friction (Yildiz et al., 2018). In our context, soil friction increase by root traits could be due to the impact of high normal forces applied during compaction by traffic which will amplify the role of friction. In our context,

shear is also not restricted to a single shear plane as it could be in landslide. Traffic indeed induce shear stress gradually in the whole soil profile. Root density and distribution in the soil could be key factors as they could be related to a homogeneous soil reinforcement.

Fundamental differences in soil properties, root traits, and the rate and magnitude of deformation exist between the contexts of landslide prevention or riverbank stability on the one hand and traffic-induced compaction of agricultural soils on the other hand. In agroecosystems, there is a high frequency and abundance of annual species, presenting a specific gradient of root traits. In addition, transient mechanical stresses are applied at very high rates during traffic to agricultural soils (Keller and Lamandé 2010). Vertical stresses applied by agricultural machinery can be much larger than overburden stress (e.g. Lamandé and Schjønning, 2011b). Shearing during traffic occurs in the shallow soil layer (<0.3 m depth) (Berisso et al., 2013), where the soil is not necessarily saturated with water, but where roots of annual species are the most densely present (Osman and Barakbah, 2006).

Direct shear tests with increasing normal stress are needed to determine the cohesion and angle of internal friction using the classical Coulomb approach (Eq. 1). It is challenging to specifically identify the effects of crop roots on soil cohesion and on the angle of internal friction. This requires the use of a direct shear apparatus adapted to reproduce the compression and shearing of the magnitude of what is observed beneath a running tyre (Giadrossich et al., 2017), and allowing measurements on soil cores large enough to include roots systems of annual crops. In addition, effects of crop roots on soil shear strength could be quite small as compared to the soil shear strength (Amiri Khaboushan et al., 2018). This can be overcome by performing tests using a repacked soil, presenting therefore a low cohesion in the range of 4 to 30 kPa for degrees of saturation from 20 to 70% (Hemmat et al., 2010). The aim of this study was to investigate the effects of root traits on soil shear strength parameters for three crop species with contrasting root types and morphological traits. Root morphological traits, cohesion and angle of internal friction were compared between crop species and soil without plants to identify the root traits involved in soil reinforcement.

Materials and methods

Experimental design and plant materials

A greenhouse experiment was conducted over two and a half months, from October to December 2019. The greenhouse light was turned on between 8:00 AM and 10:00 PM, and the temperature was regulated at 24°C during the simulated daylight and 18°C during the simulated night. The experiment included four treatments: soil without plants (reference treatment); soil with *Brassica napus* L. which is the second oil crop in the world and an important source of edible oil, animal fodder, vegetables, condiments and biodiesel, and presents a taproot; soil with *Secale cereale* L. which is a grass cereal grown extensively as a grain, a cover crop and a forage crop, and presents a fibrous root; and soil with *Vicia faba* L. which is a major food and feed legume because of the high nutritional value of its seeds (rich in protein and starch) and presents a taproot system with larger fine roots than *Brassica napus* (Forster et al., 2020). These three species could be used as cash or cover crops. The soil consisted of a 2:1 ratio mix of Luvisol (IUSS Working Group WRB, 2015: 20.5 g $100g^{-1}$ of clay, 69.4 g $100g^{-1}$ of silt and 10.1 g $100g^{-1}$ of sand) and of river sand previously sieved at 5 mm and dried (at 105°C during 24 h) and manually mixed.

Each treatment included 12 replicates divided into three blocks, with each block containing 16 randomly placed pots. Pots were made of two stacked steel cylinders 0.1 m in height and 0.16 m in inner diameter with the wall thickness of 4 mm (Fig. 1.b). Pots were packed with soil to reach a dry bulk density of 1.2 g cm^{-3}. To do so, pots were filled and compact three consecutive times. Soil was added and compact at 7 cm, 14 cm and 20 cm. Each time, the right quantity was added to reach the aimed bulk density and compact by hand using a handmade wooden disk. Pots size were selected to be large enough to allow roots of young crop to develop normally without too much space restriction and small enough to reduce the amount of dead weight needed to reach a maximum normal stress 100 kPa during the shear tests (See next paragraph for details). For the crop species treatment, three seeds were planted closed to the centre per pot. After two weeks, the healthiest plant in each pot was selected and others were removed. To avoid possible heterogeneous light exposure in the greenhouse, the placement of the pots was changed on the second, fourth and sixth weeks. Each time, pots were placed close to the light, each replacing its neighbouring pot, while the pot closest to the light was moved to

139 the farthest space. Each pot was irrigated once a week during the first month and then twice a week
140 until the end of the experiment. After two and a half months of growth, root of these crop species
141 occupied the bottom of the pot (i.e. 20 cm of deep) below the shear plane located at 10 cm.

142

143 **Soil shear strength**

144 A direct shear apparatus was built especially for this study to perform shear tests directly on the pots,
145 thus avoiding unnecessary manipulation of the repacked soil cores (Fig. 1). The size of the soil cores
146 to be used for the shear tests followed the ASTM recommendation of ratio between the size of the
147 sample and the maximum particle size of the material to be tested (ASTM Standard D 420–D 4914,
148 Soil and Rock, Annual Book of ASTM Standards Vol. 04.08, ASTM International, West
149 Conshohocken, PA). Two pots per treatment were subjected to a direct shear test at six external
150 normal stress levels, σ_n (25, 34, 44, 63, 83 and 93 kPa), resulting in twelve shear tests per treatment,
151 each test being performed on a new pot (i.e. no consecutive shear test on the same pot). The external
152 normal stress was applied using a dead weight system. The direct shear tests were performed two and
153 a half months after sowing. Two days before the tests, each pots were saturated with tap water. Twice
154 a day, the soil matric potential was measured at 0.08 m depth for each treatment using tensiometers
155 (SMS 2030S1 type, SDEC, Reignac-sur-Indre, France) placed in three pots chosen randomly for each
156 treatment. Shear tests were performed when the soil matric potential reached approximately -10 kPa,
157 which correspond to a water content at field capacity, i.e. where most of macro- and mesopores (i.e.
158 eq. pore diameter > 30 µm, Luxmoore, 1981) are air-filled (Table 1). The upper part of the soil core
159 was moved horizontally at a constant rate of 3 $mm.min^{-1}$, and the test was stopped when a total
160 horizontal displacement of 25 mm was reached. Horizontal displacement rate was controlled using an
161 actuator monitored by a software called "Kollmorgen WorkBench". During the test, the force required
162 to displace the upper part of the soil core was recorded by a H3-C3 500 kg load cell every 0.095
163 seconds. The shear stress was calculated from the load cell readings (kg) and the contact area between
164 the upper and the lower part of the soil core. This contact area was considered as a lens formed by the
165 intersection of section area of the two parts of the soil core. The horizontal displacement (mm) was

derived from the duration of the test (s) and the rate of horizontal displacement ($mm.s^{-1}$). We quantified the steel-steel friction forces between the upper- and lower cylinders when empty. The mean friction measured for fourteen tests was 0.66 kPa (standard deviation of 0.15 kPa), which was low as compared to the level of maximum shear stress recorded for the tests with cylinders repacked with soil.

The maximum shear stress, τ_{max} (kPa), was determined graphically on each shear stress-displacement curve according to the shape of the curve, following the methodology of Ghestem et al., (2014). When no clear yielding point was identifiable, the maximum shear stress was defined as the inflexion point of the curve. For unsaturated soils, the negative pore water pressure will contribute to the cohesive forces. During the test, soil will deform until shear failure, and the pore water pressure will change accordingly. We chose a high shearing rate to get a good representation of the shearing during traffic in the field (Schjønning et al., 2020). The high shearing rate prevented measuring the pore water pressure at failure, and we are thus not able to distinguish between the effective cohesion, from physicochemical interaction between material particles, and the cohesive forces from the negative pore water pressure at failure. Therefore, the cohesive forces detected in our study will be labelled the "apparent cohesion", c_{app} (kPa), as also suggested by Schjønning et al., (2020). Similarly, we will not be able to identify the effects of the negative pore water pressure at failure on the friction forces. The friction forces determined in our study will then be labelled φ_{app} (°). Consequently, c_{app} and φ_{app} were derived using the Coulomb equation (Eq.1) assuming a linear relationship between the maximum shear stress measured and the normal load applied during the direct shear test (Eq. 2):

$$\tau_{max} = c_{app} + \sigma_n \tan\varphi_{app}$$

Root trait characterisation

After the shear tests, all pots were emptied, and roots were manually separated from the soil. Soil was then placed two consecutive times in a 5 mm sieves to extract the remaining roots. Six root traits were then measured: the average root diameter (ARD, mm), which represents the average diameter of the fibrous system; the root length density (RLD, $cm.cm^{-3}$), which is the root length divided by the soil volume; the root density (RD, $g.m^{-3}$), which is the roots' dry weight divided by the soil volume; the

root volume density (RVD, $cm^3.cm^{-3}$), which is the roots' volume divided by the soil volume; the specific root length (SRL, $m.g^{-1}$), which is the root length divided by the root dry weight and the dry matter content (DMC) which is the root dry weight divided by the root fresh weight. Trait measurements were performed following the method described by Ristova and Barbez (2018).

All roots found in each pot were weighed and scanned in a film of water using the Epson Perfection V850 Pro at a resolution of 600 dpi. The software WinRhizo 2016 (Regent Instrument Inc., Instruments, Québec, Canada) was used to quantify the root length and root volume. The taproot volume (TRV) and the average taproot diameter (ATRD) were determined separately using the ImageJ freeware (Schneider et al. 2012). TRV was calculated using the sum of homogeneous volume sections in terms of diameter. The diameter and the length of each sections were used to calculate ATRD with the length of each section used to proportionally calculate the mean diameter. Each volume section was determined by its length and mean diameter. TRV was then divided by the soil volume to obtain the taproot volume density (TRVD) which could be compared to the RVD. TRV and TRVD were not used as a trait but were used to compare the root type of the species. Fresh roots were weighed and then dried at 105°C for 24 h and then weighed again to obtain the DMC and SRL. The dry weight, length and volume were then divided by the total volume of the pot to obtain the RD, RLD and RVD.

Statistical analysis

Root traits values did not follow a normal distribution. A nonparametric Kruskal–Wallis rank sum test followed by a pairwise Wilcoxon test were thus performed to identify differences between species in each root trait. Spearman's correlation was then used to identify correlation between root traits. Shear strength values followed a Gamma distribution and were not subjected to any transformation. A variance analysis was performed using the Coulomb linear regression model (Eq. 2) to test the differences in intercept and slope of the shear strength vs. normal stress relationship between the four treatments.

Results

Root traits and root type comparison among species

All root traits were found to be significantly different between species: ARD (Chi square = 23.36, p-value = <0.001, df = 2), DMC (Chi square = 29.12, p-value = <0.001, df = 2), RD (Chi square = 26.08, p-value = <0.001, df = 2), RLD (Chi square = 8.06, p-value = 0.018, df = 2), RVD (Chi square = 19.92, p-value = <0.001, df = 2) (Table 2 and Fig. 2). For *Vicia faba*, significant differences from the other two species were observed in five of the six measured traits. *Vicia faba* had the highest ARD, RD and RVD, and had the lowest SRL and DMC. *Secale cereale* had the highest SRL and the lowest RD. *Brassica napus* had the highest DMC. RLD did not differ between *Brassica napus* and *Vicia faba* (Table 2 and Fig. 2).

The correlation matrix showed that RLD was the only trait not correlated with another. RD, RVD and ARD were positively correlated, and SRL and DMC were positively correlated. RD, RVD and ARD were negatively correlated with SRL and DMC (Table 3).

No differences in TRVD nor in ATRD were found between *Vicia faba* and *Brassica napus. Vicia faba* did not consistently grow a taproot. A taproot was observed in six pots out of twelve, generating a higher standard error for the TRVD and ATRD of *Vicia faba*. *Vicia faba* combined the taproot and fibrous systems.

Species effects on soil shear strength

Apparent cohesion and angle of internal friction for each species and for the control without plants are reported in Table 4. *Vicia faba* reached an angle of internal friction of 17.9° and a cohesion of 20.2 kPa, while *Brassica napus* reached an angle of internal friction of 15.6° and a cohesion of 4.9 kPa and *Secale cereale* reached an angle of internal friction of 12.6° and a cohesion of 8.8 kPa. For the reference treatment, we measured an angle of internal friction of 10.5° and a cohesion of 9.6 kPa (Figure 3). The variance analysis of the regressions showed that only *Vicia faba* had a higher angle of

internal friction and cohesion than the reference treatment, while both *Secale cereale* and *Brassica napus* did not have significantly different angle of internal friction or cohesion than the reference treatment.

Discussion

The main hypothesis of the present study was that roots of annual crop species would increase soil cohesion. The effect of roots on the soil shear strength was determined for three annual crop species with contrasting traits: *Brassica napus*, *Secale cereale* and *Vicia faba* (Table 4 and Fig. 3). However, only the presence of *Vicia faba* lead to an increase in apparent cohesion. Surprisingly, *Vicia faba* also present a significant higher angle of internal friction, as indicated by the increase compared to the reference treatment (Fig. 3). Our results suggest that some annual crop species could have a positive effect on soil shear strength.

No increase in soil shear strength was observed for *Brassica napus* or *Secale cereale* (Table 4, Fig. 4), even though the two species showed contrasting root types: a taproot in *Brassica napus* and a fibrous root system for in *Secale cereale* (Table 2, Fig. 2). This indicate that a rooted soil did not present systemically a higher shear strength, and that the potential soil reinforcement did not rely on the root type. These results suggest that the effects of roots on shear strength would be controlled by root traits. In that case, characterisation of root traits would be necessary to improve our understanding of root–soil interactions with regards to soil conservation in agroecosystems.

Previous studies examining the relationships between root traits and mechanical soil properties have shown that the RLD (Osman and Barakbah, 2006, Stokes et al., 2009), the RD (Ali and Osman, 2008), the root area ratio, the root tensile strength, which is negatively correlated to root diameter (De Baets et al., 2008, Ali and Osman, 2008, Operstein and Frydman, 2000), and the root type (Ghestem et al., 2014, Li et al., 2017) were influencing soil shear strength, with regard to the soil's protection against landslides. Gravity is the most important force component acting on soil that cause shear stresses susceptible to trigger landslides. Slow shearing of sloppy soil masses at constant volume may be

accompanied by a decrease in pore water pressure, i.e. a decrease in apparent cohesion that can lead to failure (landslide). In that context, the plants with high root length density and root area ratio are efficient for landslide prevention. The direct shear test method used in the present study reproduce shearing processes similar to the ones acting for shearing of agricultural soils during traffic: high shear rate and large normal load. In comparing root traits and soil shear strength with and without three plant species, the present study has allowed the identification of the main traits involved in the increase in soil shear strength by annual crop roots. Out of the five traits that distinguish *Vicia faba* from the two other species, three root traits (RD, DMC and SRL) differed between *Brassica napus* and *Secale cereale* (Fig. 2) while the cohesion and the angle of internal friction remained similar. It indicates that these three root traits do not directly influence the soil shear strength under these controlled conditions (plants in pots, remoulded soil). In moist sands, the shear strength is due to frictional resistance between grains, which is a combination of rolling and sliding friction, and to interlocking (the stress required to supply the energy for sands being expended in volume), and to apparent cohesion due to the pore water pressure. In the present study, in addition to that, only a limited true cohesion is expected from the silt and clay particles as the soil was remoulded. In contrary to the observations from studies about protection against landslides (Osman and Barakbah, 2006; Stokes et al., 2009), our results showed that RLD of the three annual crop species did not influence shear strength as it did not discriminate *Vicia faba* from the other two species. The low RLD of the three crop species investigated here (2.1-2,8 $cm.cm^{-3}$) compared to the RLD measured for perennial herbaceous, shrub and tree species (more 300 $cm.cm^{-3}$), might explain the absence of relationships between RLD and the soil shear strength observed in the present study. Interestingly, annual crop species with low RLD can positively influence soil shear strength. Our results showed that soil shear strength was largest when the ARD and RVD were high. RVD *in Vicia faba* reflects the number of roots and was expected to participate in the increase of the soil shear strength. The divergence of some root traits effects on soil shear strength in the literature could be explained by the various methods (Freschet et al., 2021): different soil conditions (e.g. saturated or unsaturated), different soil core sizes, different order of magnitude of the root traits between annual crops and perennial plants (Roumet et al., 2006). Perennial plants (shrubs, trees) are usually investigated in studies related to prevention of landslides (Freschet et

297 al., 2021). These differences may prevent the direct transfer of the findings from these studies to
298 agroecosystems. However, other root traits not measured in this study could also be related to
299 differences in soil shear strength, such as the insertion angle of the roots or the roots' vertical and
300 horizontal distribution in the soil (Stokes et al., 2009). Future studies examining the effects of root
301 traits on soil shear strength should include a larger range of root traits in crop species.

302 In our study, *Vicia faba* was found to be related to a larger cohesion and angle of internal friction.
303 RVD appeared to be the root trait involved in increase of both soil cohesion and the angle of internal
304 friction (figures 2 and 3). Here, higher RVD value for *Vicia faba* was mainly due to its fibrous system
305 and not due to a large taproot as observed in *B. napus*. It was thus related to the root capacity to spread
306 and colonize the soil. An explanation could be that the replacement of soil air by roots (i.e. roots
307 filling up the macropores) helped to reinforce the soil, without influence of the roots capacity to resist
308 tension. Species with large taproot present a low RLD, RVD and root tensile strength, and would not
309 be thus good candidates to increase soil shear strength.

310 The positive roots effects on the angle of internal friction is in accordance with the study by Graf et al.,
311 (2009). They applied a maximum normal stress of 100 kPa during the shear tests, which was larger
312 than the maximum normal stress used in other studies showing no evidence of roots' effect on the soil
313 angle of internal friction. A low maximum normal stress applied during shear tests might prevent
314 identifying this effect (Giadrossich et al., 2017). Our results indicated an increase of 0.14 kPa kPa^{-1} in
315 the slope of Eq. 2 for *Vicia faba* compared to the reference treatment without plants (figure 3). In the
316 contexts of landslide protection and riverbank stability, normal stress is applied by overburden soil and
317 is therefore lower (Yildiz et al, 2018). A small increase in soil shear strength by friction could thus
318 easily be outcompeted by a significant increase in cohesion due to the large perennial plants roots. It
319 could explain why roots effects on the angle of internal friction were not identified in this study. From
320 our results, the angle of internal friction increase by annual plant roots could participate to soil
321 shearing prevention during traffic in agricultural fields. Our results provide a step toward a better
322 understanding of the effects of crop roots on soil shear strength in controlled conditions through the

increase of both soil cohesion and angle of internal friction. There is now an urgent need to evaluate the potential of annual plant roots to reinforce the shear strength of structured agricultural soils.

Conclusion

The present trait-based study allowed the identification of the effects of annual crop roots on soil shear strength and provided information about which root traits might be relevant for the mitigation of traffic-related soil compaction. Our results showed crop species with low root length density could improve the soil shear strength, and that the root volume density may be the main root trait correlated to a larger apparent cohesion and angle of internal friction. These results provide an evidence of the possible effect of roots on soil shear strength in agroecosystems and demonstrate the potential of designing cropping systems with improved soil structure protection. To do so, further experiment should study roots effects on soil shear strength by using larger root traits gradient and for various soil conditions, including using undisturbed soil sample from agricultural fields at a range of soil water potentials.

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Table 1 Mean soil water content and soil matric potential for each of the three species and for the reference treatment. The letters showed differences between treatments.

	Soil water content (g.g-1)	**Soil matric potential (kPa)**
Brassica napus	0,11 ± 0,02[a]	-20.8 ± 6.07[a]
Vicia faba	0,07 ± 0,01[b]	-6.73 ± 0.04 [a]
Secale cereale	0,11 ± 0,03 [a]	-7.93 ± 0.31 [a]
Bare soil	0,12 ± 0,01 [a]	-6.2 ± 1.7 [a]

Soil water content values are the mean and standard error of 12 replicates.
Soil matric potential values are the mean and standard error of 3 replicates.
Means with the same letter within the same column were not significantly different at a 5% level based on the Pairwise Wilcoxon test.

Table 2: Root traits' mean and standard error per species. The letters showed differences between species. ARD = Average root diameter, ATRD = Average Taproot Diameter, DMC = Dry Matter Content, RD = Root Density, RLD = Root Length Density, RVD = Root Volume Density, SRL = Specific Root Length, TRVD= Tap Root Volume Density

	ARD (mm)	**DMC ($g.g^{-1}$)**	**SRL ($m.g^{-1}$)**	**RLD ($cm.cm^{-3}$)**	**RVD ($cm^3.cm^{-3}$)**	**RD ($g.m^{-3}$)**	**TRVD ($cm^3.cm^{-3}$)**	**ATRD (cm)**
Brassica napus	0.35 ± 0.06^{b}	0.18 ± 0.03^{a}	38.6 ± 9.1^{b}	2.05 ± 0.85^{b}	0.0063 ± 0.0054^{b}	525.1 ± 133.8^{b}	0.001 ± 0.0005^{a}	0.53 ± 0.08^{a}
Secale cereale	0.34 ± 0.05^{b}	0.13 ± 0.01^{b}	77.4 ± 14.2^{a}	2.82 ± 0.91^{a}	0.0055 ± 0.003^{b}	373.6 ± 138.3^{c}	0	
Vicia faba	0.95 ± 0.12^{a}	0.09 ± 0.01^{c}	15.7 ± 3.7^{c}	2.14 ± 0.44^{ab}	0.0203 ± 0.0076^{a}	1397.6 ± 309.3^{a}	0.0008 ± 0.001^{a}	0.64 ± 0.16^{a}
Kruskal–Wallis test results	Chi square = 23.36, p-value = <0.001, df = 2	Chi square = 29.12, p-value = <0.001, df = 2	Chi square = 29.32, p-value = <0.001, df = 2	Chi square = 8.06, p-value = 0.018, df = 2	Chi square = 19.92, p-value = <0.001, df = 2	Chi square = 29.12, p-value = <0.001, df = 2	Chi square = 1.35, NS	Chi square = 2.54, NS

Values are the mean and standard error of 12 replicates*

**Vicia* faba's TRVD and ATRD values are the mean and standard error of 6 replicates

Means with the same letter within the same column were not significantly different at a 5% level based on the Pairwise Wilcoxon test. NS = non-significant

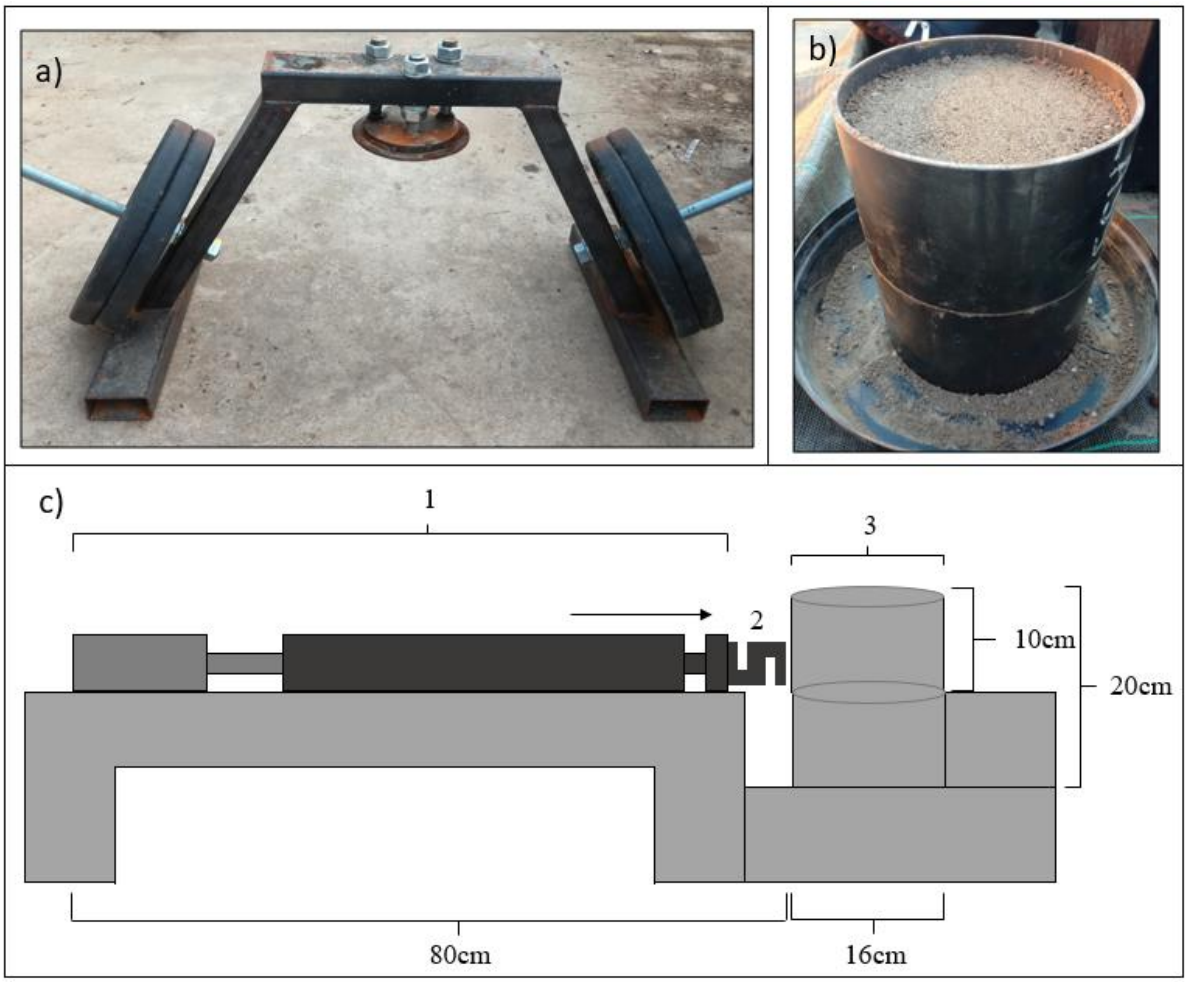
*Table 3: Correlation matrix of root traits. Multiplying factors are shown using the significance of each correlation with p-value > 0.05 = NS, p-value <0.05 = *, p-value<0.01 = ** and p-value<0.001 = ***. ARD = Average root diameter, DMC = Dry Matter Content, RD = Root Density, RLD = Root Length Density, RVD = Root Volume Density, SRL = Specific Root Length*

	ARD	**DMC**	**RD**	**RLD**	**RVD**	**SRL**
ARD	1.00					
DMC	-0.76***	1.00				
RD	0.81***	-0.62***	1.00			
RLD	0.02NS	-0.32NS	0.02NS	1.00		
RVD	0.93***	-0.77***	0.85***	0.30NS	1.00	
SRL	-0.73***	0.42*	-0.86***	0.46**	-0.63***	1.00

Table 4: Apparent cohesion and angle of internal friction, and linear regression coefficient R^2 for the fit with Eq. 2 for each species and the reference treatment without plants.

	Angle of internal angle	**Apparent cohesion (kPa)**	**R^2**
Vicia faba	17.9°[a]	20.19 [a]	0.63
Brassica napus	15.6° [b]	4.87 [b]	0.71
Secale cereale	12.6° [b]	8.78 [b]	0.44
Control without plant	10.5°[b]	9.58 [b]	0.68

Figures caption



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520 *Figure 1: Components and schema of the shear box: a) Homemade system built to apply normal stress on the soil cylinder b)*
521 *Soil cylinders filled with remoulded soil used in the experiment. c) Shear box schema. 1) The computer-controlled motor and*
522 *actuator 2) The H3-C3 500kg load cell 3) The soil cylinders*

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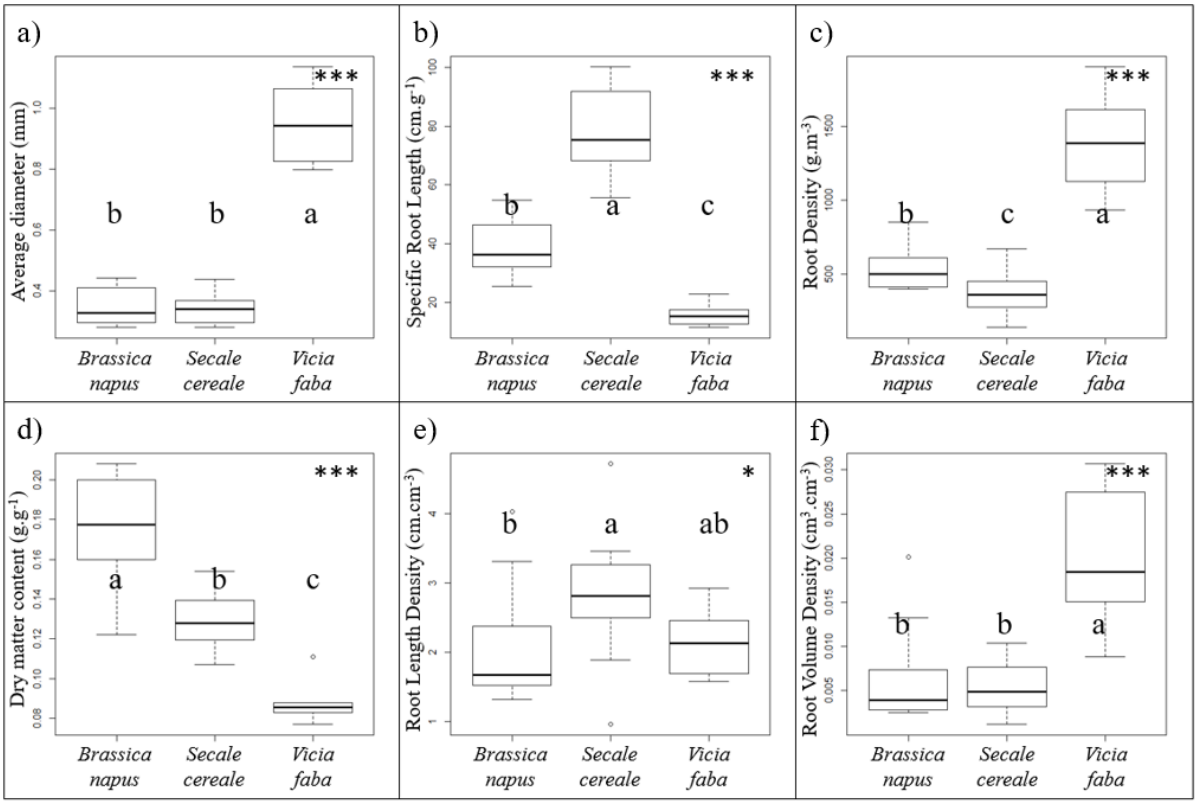
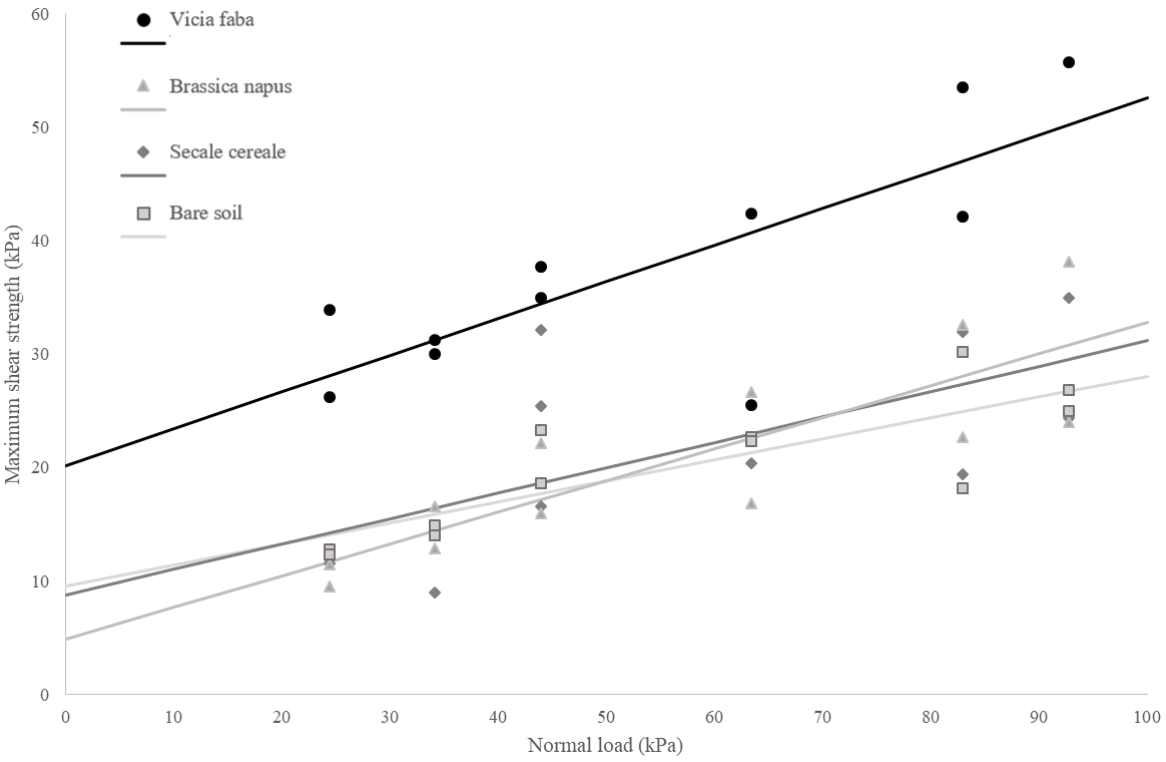


*Figure 2: Boxplots of each root traits for each species: a) the average diameter (mm), b) the specific root length ($cm.g^{-1}$), the root density ($g.m^{-3}$), the dry matter content ($g.g^{-1}$), the root length density ($cm.cm^{-3}$), the root volume density ($cm^3.cm^{-3}$). Stars indicate significant differences between species according to the Pairwise Wilcoxon test: *** = p-value < 0.001, ** = p-value < 0.01, * = p-value < 0.05. Means with the same letter were not significantly different at a 5% level based on the Pairwise Wilcoxon test.*



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533 *Figure 3: Linear regression $\tau = c + \sigma \tan \phi$ for each species and the control without plants.*