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Relationships between Root Traits and Soil Physical Properties after Field Traffic from the Perspective of Soil Compaction Mitigation

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Abstract: Compaction due to traffic is a major threat to soil functions and ecosystem services as it decreases both soil pore volume and continuity. The effects of roots on soil structure have previously been investigated as a solution to alleviate compaction. Roots have been identified as a major actor in soil reinforcement and aggregation through the enhancement of soil microbial activity. However, we still know little about the root's potential to protect soil from compaction during traffic. The objective of this study was to investigate the relationships between root traits and soil physical properties directly after traffic. Twelve crop species with contrasting root traits were grown as monocultures and trafficked with a tractor pulling a trailer. Root traits, soil bulk density, water content and specific air permeability were measured after traffic. The results showed a positive correlation between the specific air permeability and root length density and a negative correlation was found between bulk density and the root carbon/nitrogen ratio. This study provides first insight into how root traits could help reduce the consequences of soil compaction on soil functions. Further studies are needed to identify the most efficient plant species for mitigation of soil compaction during traffic in the field.

Keywords: root traits; soil compaction; air permeability

1. Introduction

Soil compaction is known as one of the three major threats to soil quality in Europe [1,2]. It occurs when mechanical resistance (soil strength) is lower than the force transmitted onto it (soil stress) [3]. Soil compaction is the consequence of two deformation processes: compression and shearing. Compression mainly leads to a loss of pore volume, while shearing modifies the shape of the pore system. Both processes make root penetration more difficult, decrease soil permeability, reduce the availability of nutrients and, therefore, reduce yields [3–5].

At present, there is an increase in the size and weight of farming equipment that enhances the magnitude of mechanical stress transmitted to the soil [6]. Technological solutions, such as tyre innovation, cannot cope alone with this increase [7]. Therefore, agricultural and agroecological practices that could play a role in the mitigation of traffic-induced soil compaction should be investigated. The effects of plants in agrosystems have only been examined as a solution to alleviate compaction when biopores are formed during the root growth in compacted layers [8]. However, understanding the role of plants in soil reinforcement as a way of mitigating soil compaction during traffic is still lacking. Studies showed that roots are able to increase soil shear strength and therefore, its resistance to landslides [9], water erosion [10], and increase streambank stability [11]. Other effects could be involved in reducing soil compaction during traffic. These include strengthening the soil through the uptake of water by the plants [12]; roots increasing soil strength to compression, which was demonstrated on streambank soil [13]; the effect of plant–soil microorganisms on soil aggregation [14]. The functional trait approach characterises the morphological, architectural, physiological and chemical root trait responses to soil properties and functions [15]. Traditionally used in semi-natural ecosystems, the functional trait approach may apply to address key issues in agrosystems [16], such as relationships between root traits and soil functions after key disturbance associated with traffic. Agrosystems are characterised by (1) the abundance of annual species presenting specific gradients of root traits; (2) the very short yet intense vertical and horizontal stresses applied to the soil's surface by tyres, which also propagate in the soil profile [17]; (3) the compressive stresses beneath the tyres or tracks are much greater than the overburden stress [18]; (4) the shallow shearing (<30 cm in depth) [19] of often unsaturated soils where the roots of annual species are most dense [20]; (5) the distribution of principal stresses beneath a tyre is uneven and changes during loading [21].

In this context, we aim to examine the relationships between root traits and soil physical properties directly after traffic to obtain a preview of the potential effects of roots on compaction mitigation. We hypothesised that root density traits (length or dry matter of roots per soil volume) would positively influence specific air permeability and bulk density by conserving or improving pore morphology.

2. Materials and Methods

The experiment took place on a farm belonging to the Institute Polytechnic UniLaSalle in Beauvais, France (49°27′44.97′′ N, 2°4′23.23′′ E). It lasted for four months from April to early August 2018. During this period, the total rainfall recorded was 299.5 mm. The temperature varied between 6.7 °C and 28.7 °C with a mean temperature of 17.1 °C (Figure S1). The soil, defined as Luvisol (IUSS Working Group WRB, 2015), was composed of 20.2% clay, 68.9% silt, 8.9% sand, 1.8% organic matter and 0.2% $CaCO_3$ with a pH of 7.1. The soil particle density was calculated using the clay and organic matter content [22]. The soil particle density was 2.54 g.cm^{-3}. The experimental design used was a complete randomised block design, consisting of three blocks with 16 randomly distributed square plots with a side length of 2.5 m in each block. These included four plots of bare soil and one plot for each of the 12 selected crop species (Figure 1). The experiment took place in a barley field in a barley–rapeseed–wheat cropping system. The barley was destroyed in order to sow crop species. The experiment was conducted where bulk density was the most homogeneous at a ~0.1 m depth (measured from the top of the cylinder) in the field (1.24 ± 0.046 g.cm^{-3}) after a shallow tillage (≤5 cm depth) that did not disturb the soil at the measurement depth. All plots were protected from traffic during the growing period. Stress was applied to the soil in August, four months after the sowing date, by driving a tractor with a trailer used for slurry application over the field at a constant speed of 1.1 m.s^{-1}. Each plot was driven over once by four wheels—one front and one rear wheel of the tractor and two wheels of the trailer (Figure 1). The make of the front wheels of the tractor was 600/70 R30 159D and that of the rear wheels was 710/70 R42 179D TL. The make of the trailer wheels was 600/55 R26.5. The wheel load of the tractor's front wheel was approximately 2.2 Mg and the rear wheel was approximately 4 Mg. The wheel load of each trailer wheel was 4.5 Mg. Tyre inflation for the tractor was 110 kPa for the front wheels and 140 kPa for the rear wheels. Inflation pressure was 290 kPa for the trailer wheels. The plants and soil were sampled directly after the traffic event.

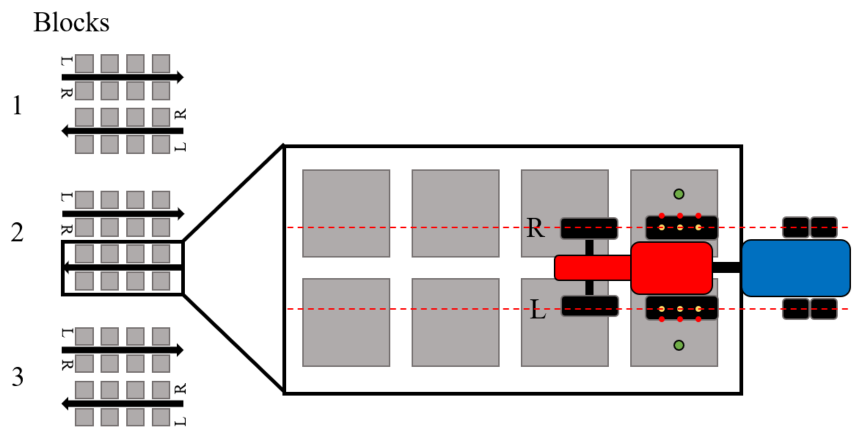

Figure 1. The experiment design included three blocks of 16 square plots with a side length of 2.5 m; four plots of bare soil; one plot per species for the twelve selected species. Each plot was driven over by four wheels of the right side of the combination (R) or the left side (L). The red dotted lines represent the centre of the track. The yellow dots represent the soil cylinders sampled under the middle of the track. The red dots represent the soil cylinders sampled under the edge of the track, at 0.3 m from the middle. The green dots represent the cylinder sampled on each plot for the root trait measurements.

2.1. Plant Material

Twelve plant species of interest were selected from cover crop species and of different phylogenetic families. The plant species selected were frost resistant to avoid loss of species, easily destructible and were non-invasive to avoid creating problems for the farmer. The twelve species were selected from the following four families: Poaceae (*Avena strigosa* Schreb., *Secale cereale* L.), Brassicaceae (*Brassica juncea* L., *Brassica napus* L., *Brassica rapa* L., *Raphanus sativus* L.), Fabaceae (*Lathyrus sativus* L., *Melilotus officinalis* L., *Pisum sativum* L., *Trifolium incarnatum* L., *Vicia faba* L.) and Linaceae (*Linum usitatissium* L.). The objective was to create gradients of architectural, morphological and chemical root traits.

2.2. Characterisation of Root Traits

After four months of cultivation, five easily measurable root traits were assessed (two architectural, one morphological and two chemical) (Table 1). In terms of architectural traits, Root Length Density (RLD) and Root Mass Density (RMD) were used to gather information on the root distribution within the soil. The morphological trait, Specific Root Length (SRL) was used to obtain information on plant growth strategies and root type (thinner or thicker roots). Both chemical traits, Carbon/Nitrogen ratio (C/N) and Dry Matter Content (DMC), were used to analyse root composition. Trait measurements were examined according to Ristova and Barbez [23]. Soil cylinders of 2×10^{-3} m^3 (0.1 m height and 0.16 m inner diameter) were collected at ~0.05 m depth (measured on the top of the cylinder) on each plot containing plants. The cylinder was placed on a representative spot of the plot with a plant at the centre. Each cylinder was then emptied, and roots were manually separated from the soil. The roots were washed gently with running water to remove the soil from the cylinders. All roots found in each soil cylinder were weighted and scanned in a film of water (Epson Perfection V850 Pro) with a resolution of 600 dpi. The software WinRhizo 2016 (Regent Instrument Inc., Instruments, Québec city, QC, Canada) was used to measure the total root length. Roots were then dried at 105 °C for 24 h and weighed to obtain the DMC and the SRL. The dry weight and length were then divided by the total volume of the soil cylinder to obtain the RLD and RMD.

For each species, determination of C/N was carried out on subsamples of roots that were representative of the whole root system and reserved for chemical analyses (Table S1). Only *Melilotus officinalis*, *Brassica rapa*, *Raphanus sativus* and *Secale cereale* provided enough material for several subsamples while the other species did not provide enough materiel and only one measurement was taken. Carbon and nitrogen concentrations were determined using an elemental analyser [24,25].

Table 1. List of measured traits, their abbreviations, units and the formula used.

Root Traits Studied	Abbreviation	Unit	Formula
Root Length Density	RLD	m.m^{-3}	RLD = root length/soil volume
Root Mass Density	RMD	g.m^{-3}	RMD = root dry mass/soil volume
Specific Root Length	SRL	m.g^{-1}	SRL = root length/root dry mass
Carbon/Nitrogen ratio	C/N	g.g^{-1}	C/N = g of carbon/g of nitrogen
Dry Matter Content	DMC	g.g^{-1}	DMC = root dry mass/root fresh mass

2.3. Characterisation of Soil Physical Properties

As the stress induced could be heterogeneous in type and in range under the tyre [19], two different locations (the centre of the track and 0.3 m from the centre) at the same depth were observed. At each plot, six undisturbed 100 cm^3 soil cores (inner diameter 0.05 m, height 0.051 m) were sampled at ~0.1 m depth (measured on the top of the cylinder). Three soil cores were sampled beneath the centre and three at 0.3 m from the centre (Figure 1). Air permeability (k_a, µm^2) was measured for each soil core using the method described by Iversen et al. [26] with a pressure gradient of 5 hPa. Bulk density (ρ_b, g.cm^{-3}) and soil water content (θ, g.g^{-1}) were then calculated using the gravimetric method. Air filled porosity (ε_a, m^3.m^{-3}) was then calculated as follows:

$$\varepsilon_a = 100 - \left(\frac{W_s}{\rho_s}\right) - \left(\frac{W_w}{\rho_w}\right) \tag{1}$$

where W_s is the dry weight of the soil (g), ρ_s is the soil particle density (g.cm^{-3}), W_w is the weight of the soil water (g), and ρ_w is the water density (g.cm^{-3}). Finally, specific air permeability (k_{as}, µm^2) was calculated by dividing k_a by ε_a, as suggested by Groenevelt et al. [27], which provided an indicator of air-filled pore continuity (Table S1).

2.4. Statistics

A Generalised Linear Mixed Model (GLMM) was used to examine the fixed effects of the species, distance to the tyre's centre and their interactions with the physical properties of the soil with block as a random effect. The geometric means of the soil properties were calculated on each plot. One-way Analysis of Variance (ANOVA) was used to test the species' effects on each trait measured to check if gradients were produced with the selected species. Pearson correlation was then used to identify the relation between root traits and soil properties.

Finally, Generalised Linear Models (GLMs) were used to check the effects of trait combinations on ρb. The second order of Akaike's Information Criterion (AICc) was used to identify whether the models using trait combinations as predictors were better than the model using a single trait. The model with the lowest AICc was considered the best model [28].

3. Results

3.1. Species and Distance Effects on Soil Physical Properties

GLMM showed a significant effect of species on water content (p-value < 0.001) while non-significant effects were found for bulk density (p-value = 0.64) and specific air permeability (p-value = 0.93). Non-significant effects of distance were found on water content (p-value = 0.89), bulk density (p-value = 0.78) and specific air permeability (p-value = 0.54). Non-significant effects of the species–distance interactions were found on water content (p-value = 0.31), bulk density (p-value = 0.77) and specific air permeability (p-value = 0.99). Soil physical properties were thus pooled from both track positions according to the GLMM results for each species (Table 2).

Table 2. Soil physical properties value per species.

	ρ_b (g.cm^{-3})	θ (g.g^{-1})	k_{as} (μm^2)
Bare soil	1.38 ± 0.02 ^{a}	0.18 ± 0.02 ^{d}	83.24 ± 12.66 ^{a}
Avena strigosa	1.3 ± 0.06 ^{a}	0.13 ± 0.03 $^{b.d}$	99.3 ± 60.61 ^{a}
Brassica juncea	1.32 ± 0.06 ^{a}	0.08 ± 0.01 $^{a.b}$	80.44 ± 13.26 ^{a}
Brassica napus	1.32 ± 0.05 ^{a}	0.08 ± 0.01 $^{a.b}$	106.51 ± 26.43 ^{a}
Brassica rapa	1.37 ± 0.1 ^{a}	0.1 ± 0.02 $^{a.b}$	68.14 ± 16.34 ^{a}
Lathyrus sativus	1.37 ± 0.07 ^{a}	0.16 ± 0.01 $^{c.d}$	72.22 ± 3.18 ^{a}
Linum usitatissium	1.34 ± 0.01 ^{a}	0.1 ± 0.02 $^{a.b}$	99.19 ± 19.54 ^{a}
Melilotus officinalis	1.36 ± 0.02 ^{a}	0.07 ± 0 ^{a}	116.55 ± 53.98 ^{a}
Pisum sativum	1.37 ± 0.04 ^{a}	0.13 ± 0.03 $^{b.c}$	104.62 ± 51.04 ^{a}
Raphanus sativus	1.37 ± 0.05 ^{a}	0.1 ± 0.01 $^{a.b}$	91.26 ± 46.2 ^{a}
Secale cereale	1.37 ± 0.07 ^{a}	0.1 ± 0.02 $^{a.b}$	85.37 ± 52.32 ^{a}
Trifolium incarnatum	1.34 ± 0.02 ^{a}	0.08 ± 0.01 $^{a.b}$	94.18 ± 49.98 ^{a}
Vicia faba	1.36 ± 0.09 ^{a}	0.12 ± 0.02 $^{b.c}$	72.31 ± 37.32 ^{a}

k_{as} = specific permeability, ρ_b = soil bulk density, θ = soil water content. Soil physical properties' values are the mean and standard error of three replicates. Means with the same letter within the same column were not significantly different at a 5% level based on the Pairwise Tukey test.

3.2. Root Traits Gradients and Comparison among Species

RLD values varied between 163.15 m.m^{-3} for *Lathyrus sativus* and 776.56 m.m^{-3} for *Linum usitatissium*. RMD values varied between 8.4 g.m^{-3} for *Lathyrus sativus* and 580 g.m^{-3} for *Melilotus officinalis*. SRL values varied between 204 cm.g^{-1} for *Raphanus sativus* and 2890 cm.g^{-1} for *Lathyrus sativus*. DMC values varied between 15.7 g.g^{-1} for *Pisum sativum* and 33.8 g.g^{-1} for *Linum usitatissium* (Table 3).

Table 3. Root traits–values per species.

	RLD (m.m^{-3}) **	RMD (g.m^{-3}) *	SRL (m.g^{-1}) ***	C/N (g.g^{-1})	DMC (g.g^{-1}) ***
Avena strigosa	454.9 ± 75.8 $^{c\,d}$	127.65 ± 17.7 $^{c\,d}$	3.91 ± 1.28 $^{a\,b}$	57.16	0.31 ± 0.03 $^{d\,e}$
Brassica juncea	540.56 ± 66.4 $^{b\,c\,d}$	70.11 ± 10.2 $^{b\,c\,d}$	7.77 ± 0.22 $^{a\,d}$	45.99	0.31 ± 0.03 $^{d\,e}$
Brassica napus	643.9 ± 67.1 $^{b\,c\,d}$	79.4 ± 10.1 $^{b\,c\,d}$	8.46 ± 1.71 $^{a\,d}$	30.59	0.19 ± 0.01 $^{a\,c}$
Brassica rapa	432.01 ± 69.4 $^{c\,d}$	250.82 ± 85.6 $^{c\,d}$	2.08 ± 0.54 ^{a}	19.84 ± 7.81	0.2 ± 0.02 $^{a\,c\,d}$
Lathyrus sativus	163.15 ± 57.3 ^{a}	8.41 ± 3.7 ^{a}	28.9 ± 10.72 ^{d}	21.16	0.17 ± 0.02 $^{a\,b}$
Linum usitatissium	776.57 ± 80.6 $^{a\,d}$	44.4 ± 3.7 $^{a\,d}$	17.46 ± 0.34 $^{b\,c\,d}$	39.89	0.34 ± 0.03 ^{e}
Melilotus officinalis	714.14 ± 173.7 ^{d}	580.86 ± 338.4 ^{d}	3.03 ± 1.95 ^{a}	23.43 ± 8.30	0.32 ± 0.01 $^{d\,e}$
Pisum sativum	302.82 ± 55.6 $^{a\,b}$	14.85 ± 0.6 $^{a\,b}$	20.18 ± 2.87 $^{c\,d}$	20.01	0.16 ± 0.02 ^{a}
Raphanus sativus	438.53 ± 162.8 $^{c\,d}$	209.21 ± 51.7 $^{c\,d}$	2.04 ± 0.55 ^{a}	47.17 ± 0.99	0.18 ± 0.01 $^{a\,c}$
Secale cereale	407.86 ± 79.6 $^{c\,d}$	183.49 ± 64.5 $^{c\,d}$	2.46 ± 0.4 ^{a}	22.83 ± 6.59	0.29 ± 0.01 $^{c\,e}$
Trifolium incarnatum	456.96 ± 41 $^{a\,c}$	32.9 ± 2.8 $^{a\,c}$	14.23 ± 2.13 $^{b\,c\,d}$	29.55	0.25 ± 0.01 $^{a\,d\,e}$
Vicia faba	289.15 ± 31 $^{b\,c\,d}$	57.92 ± 10.7 $^{b\,c\,d}$	5.6 ± 1.75 $^{a\,c}$	20.56	0.28 ± 0.04 $^{b\,c\,e}$

DMC = Dry Matter Content, RLD = Root Length Density, RMD = Root Mass Density, SRL = Specific Root Length, C/N = Carbon/Nitrogen ratio. Root trait values are the mean and standard error of three replicates except for the C/N value for some species determined by one measurement. The one-way ANOVA test showed significant effects of the species on the four traits measured: RLD $F_{11,23}$ = 3.575, ** $p < 0.01$, RMD $F_{11,23}$ = 9.542, * $p < 0.05$, SRL $F_{11,23}$ = 11.38, *** $p < 0.001$ and DMC $F_{11,23}$ = 8.008, *** $p < 0.001$. Means with the same letter within the same column were not significantly different at a 5% level based on the Pairwise Tukey test.

3.3. Relationship between Root Traits and Soil Properties

Root trait correlations with soil properties were reported in Table 4. Notably, θ was negatively correlated with both RLD ($r = -0.82$, *** $p < 0.001$) and RMD ($r = -0.62$, * $p < 0.05$), whereas no significant correlations were found with other root trait measurements. k_{as} was only positively correlated with RLD ($r = 0.61$, * $p < 0.05$) and ρ_b was only negatively correlated with C/N ($r = -0.70$, * $p < 0.05$) (Figure 2). Correlations between root traits were also found. RLD was positively correlated with RMD ($r = 0.61$, * $p < 0.05$) and DMC ($r = 0.58$, * $p < 0.05$), whereas SRL was negatively correlated with RMD ($r = -0.94$, *** $p < 0.001$).

Table 4. Pearson correlation matrix of soil physical properties and root traits. All traits and soil properties were log-transformed.

	ρ_b	θ	k_{as}	RLD	RMD	SRL	C/N
θ	0.19						
k_{as}	−0.32	−0.49					
RLD	−0.49	−0.82 ***	0.61 *				
RMD	−0.05	−0.62 *	0.11	0.61 *			
SRL	−0.15	0.38	0.15	−0.29	−0.94 ***		
C/N	−0.70 *	−0.17	0.27	0.40	0.19	−0.06	
DMC	−0.44	−0.34	0.14	0.58 *	0.40	−0.22	0.36

Correlation coefficients were shown using the significance of each correlation with p-value > 0.05 = NS, p-value < 0.05 = *, and p-value < 0.001 = ***. ρ_b= soil bulk density, θ= soil water content, k_{as}= specific air permeability, RMD = Root Mass Density, RLD = Root Length Density, SRL = Specific Root Length, C/N = Ratio Carbon/Nitrogen, DMC = Dry Matter Content.

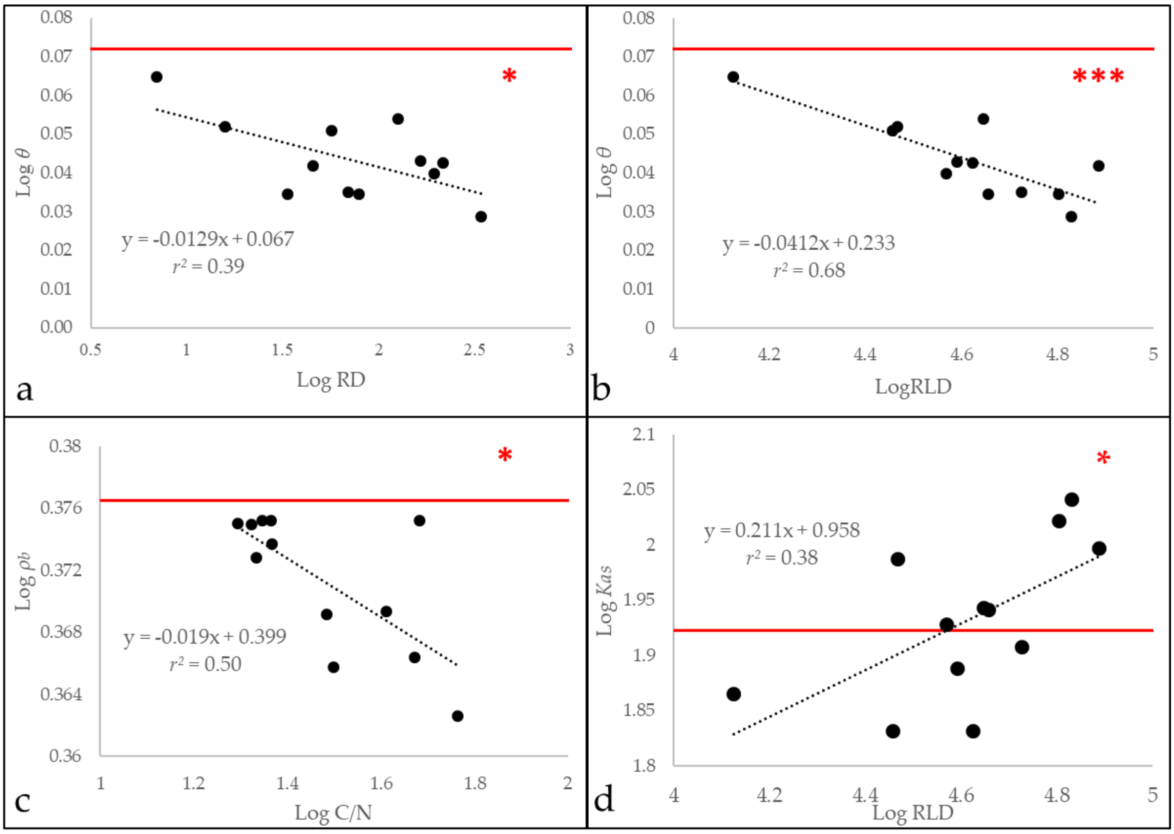

Figure 2. Relationships between root traits and soil properties. For each graph, the red line represents the mean value obtained in bare soil. Red stars represent the significance of each Pearson correlation with p-value > 0.05 = NS, p-value < 0.05 = *, and p-value < 0.001 = ***. ρ_b = soil bulk density, C/N = Carbon/Nitrogen ratio, k_{as} = specific air permeability, RMD = Root Mass Density, RLD = Root Length Density, θ = soil water content.

The comparison between GLM's AiCc for ρ_b and trait combinations is shown in Table 5. Only trait combinations related to the root density (RLD and RMD) in the soil and C/N were tested. C/N was the best predictor for ρ_b. None of the trait combinations between RMD, RLD and C/N were better.

Table 5. Selected models tested for bulk density predictors arranged from the smallest Akaike's Information Criterion (AICc) to the highest.

	Models	AICc
ρ_b	C/N	−96.0
	C/N + RLD	−92.5
	C/N + RMD	−91.4
	C/N × RMD	−88.3
	C/N × RLD	−87.6

ρ_b = soil bulk density, C/N = Carbon/Nitrogen, RMD = Root Mass Density, RLD = Root Length Density.

4. Discussion

Several roots' effects on soil physical properties could be involved in the mitigation of soil compaction during traffic. As hypothesised, we observed a positive correlation between RLD and k_{as} (Table 4) that indicated that soils containing plants with long roots were better at transporting air. Many effects could be involved in this relationship. RLD may directly reinforce the soil's shear strength, as observed in a previous study [29], which could reduce soil deformation during traffic and maintain the soil's ability to transport air. In addition, the negative relationship between RLD and θ suggests an indirect increase in the soil's shear strength through water uptake, which increases the soil's matric suction [30]. RMD and soil water content were also negatively correlated. However, RMD was not correlated to k_{as}, indicating no significant increase in the soil's shear strength. The second effect induced by the RLD could be due to the creation of new biopores during root growth that enhance the soil's ability to allow air to flow through it before being exposed to traffic. In this case, the differences observed could be explained by the soil's structure formed before the traffic and not by a conservation of soil properties during traffic. The relationship between RLD and the soil's ability to allow air to flow through it after traffic presents an interesting outcome in relation to reduced tillage practices. More generally, it is relevant to conservation agriculture, where the challenge is to conserve the hydro-physical properties without tillage and with a permanent soil cover. However, the results show that any species showed a k_{as} value significantly different than the bare soil. Thus, roots' effects on k_{as} might remain minor. The distinction between the effects before and during traffic should be the subject of future experimental studies and extensive work should study the importance of the roots' capacity to mitigate compaction.

Our results showed a negative correlation between the dry bulk density and the C/N ratio. We suppose that root C/N ratio is not directly related to the soil bulk density as it does not solely reflect the roots' ability to colonise soil porosity. We suggest that the effect of the root C/N ratio on soil porosity is part of a more complex process combining chemical and architectural traits (e.g., RLD and RMD). However, C/N was a better predictor for ρ_b than the root trait combinations (Table 5). Root density traits measured seem thus to not affect ρ_b as hypothesised. However, C/N, as a functional trait, relates to the plant growing strategy and is directly related to other root traits, such as root diameter and root volume [30]. Lower dry bulk density after traffic could be related to root traits not being quantified in the present study, such as root volume density (root volume relative to soil volume). Further investigations should consider the effects of root volume and root mean diameter on soil physical properties.

5. Conclusions

This study provides the first insight into root–soil relationships to mitigate soil compaction during traffic highlighting the correlation between the root length density and the specific air permeability after traffic. It encourages the investigations of the different potential effects involved to better understand the roots' ability to mitigate compaction during traffic. These investigations could complement existing solutions and new agroecological practices could be developed by designing cover crop selection that lessens soil compaction during specific farming operations.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4395/10/11/1697/s1, Figure S1: Climatic conditions between April and August 2018 at the experimental site, Table S1: Root traits and soil properties raw data.

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