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# Rôle des traits racinaires dans la conservation des propriétés du sol lors du tassement induit par le passage d'engins agricoles

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# Thèse de Doctorat

*Mention Sciences Ecologiques*  
*Spécialité Agroécologie et Ecophysiologie*

présentée à l'*Ecole Doctorale en Sciences Technologie et Santé (ED 585)*

**de l'Université de Picardie Jules Verne**

par

**Matthieu Forster**

pour obtenir le grade de Docteur de l'Université de Picardie Jules Verne

***Rôle des traits racinaires dans la conservation des propriétés  
du sol lors du tassement induit par le passage d'engins  
agricoles***

Soutenue le 20 Novembre 2020 après avis des rapporteurs, devant le jury d'examen :

<b>M. Frédéric DUBOIS – Professeur UPJV HDR</b>	<b>Président</b>
M <sup>me</sup> Isabelle COUSIN – Directrice de recherche INRAE HDR	Rapporteur
M. Freddy REY – Directeur de recherche INRAE HDR	Rapporteur
M <sup>me</sup> Pauline DEFOSSEZ – Chargée de recherche INRAE HDR	Examinatrice
M <sup>me</sup> Alexia STOKES – Directrice de recherche INRAE HDR	Examinatrice
M. Mathieu LAMANDE – Senior scientist Aarhus University – Professeur associé Norwegian University of Life Sciences	Examineur
M. Michel-Pierre FAUCON – Directeur à la recherche Unilasalle HDR	Directeur de thèse
M <sup>me</sup> Carolina UGARTE- Enseignante-Chercheure Unilasalle	Co-encadrante
M. François PINET – OHT Test Manager Michelin	Membre invité

# **Rôle des traits racinaires dans la conservation des propriétés du sol lors du tassement induit par le passage d'engins agricoles**

Le tassement du sol est reconnu comme une menace pour l'agrosystème. Les racines pourraient permettre une meilleure conservation des propriétés du sol, limitant les conséquences néfastes du tassement. Cette thèse vise à examiner:

- (1) les effets des traits racinaires sur la conservation des sols en utilisant de larges gradients de traits racinaires
- (2) le rôle de la structure du sol sur la réponse et l'effet des traits racinaires dans la conservation du sol
- (3) les effets des traits racinaires des cultures annuelles sur la résistance du sol au cisaillement

Des expériences in situ ont été mises en place pour répondre aux deux premiers objectifs. Pour répondre au troisième objectif, une expérience en laboratoire a été mise en place.

L'identification des effets des traits racinaires sur la conservation des propriétés du sol et l'examen de la relation racines-sol ont mis en évidence le rôle des racines dans la conservation des propriétés physiques du sol. La comparaison de la résistance au cisaillement du sol contenant des racines a mis en évidence la capacité des espèces annuelles à augmenter la résistance du sol au cisaillement. La conservation des propriétés physiques du sol peut-être dû à l'augmentation de la résistance du sol au cisaillement. Cependant, la conservation du sol ou l'augmentation de la résistance au cisaillement n'est pas systématique et dépend des traits racinaires, des propriétés du sol et de la déformation induite. Cette thèse constitue la première étape vers une compréhension plus profonde du rôle des racines dans la conservation des sols lors du passage d'engins agricoles.

## **Mots-clés :**

Conservation des sols, Tassement, Mécanique des sols, Physique des sols, Ecologie fonctionnelle ; Cisaillement ; Agrosystème ; Agriculture de conservation



## Doctoral thesis

*Honours Ecological Sciences*  
*Speciality Agroecology and Ecophysiology*

presented to the *Doctoral school in Sciences, Technology and Health (ED 585)*

**of the University of Picardie Jules Verne**

by

**Matthieu Forster**

To obtain the degree of Doctor from the University of Picardie Jules Verne

***Role of root traits in the conservation of soil properties during compaction induced by traffic in agrosystem for new services of cover crops***

Defended on the 20<sup>th</sup> November 2020 after the reviewers' opinion, in front of the examination jury:

<b>M. Frédéric DUBOIS – Professor UPJV HDR</b>	<b>President</b>
M. Freddy REY – Head of Research INRAE HDR	Reviewer
Ms. Isabelle COUSIN – Head of Research INRAE HDR	Reviewer
Ms. Alexia STOKES – Head of Research INRAE HDR	Examiner
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M. François PINET – OHT Test Manager Michelin	Guest member

# **Role of root traits in the conservation of soil properties during compaction induced by traffic for new services of cover crops**

Soil compaction is recognized as a major threat in agrosystem. Roots were considered to alleviate soil compaction but never as a possible solution to conserve soil properties during traffic. The thesis objectives are:

- (1) the root traits effects on soil conservation by using wide gradients of root traits
- (2) the role of soil structure on response and effect of root traits in the soil conservation
- (3) understand how roots could conserve soil properties by studying the effects of cover crop root traits on soil shear strength.

In-situ experiments were set up to answer first and second objectives. To answer the third objective, a laboratory experiment was implemented. A direct shear box was built during the thesis to measure the soil shear strength.

The identification of root traits effects on conservation of soil properties and the examination of the root-soil relationship highlighted key evidences of the role of roots in the soil conservation properties during traffic. The comparison of soil shear strength highlighted that annual species are able to increase soil shear strength. The conservation of soil properties during compaction could thus be due to the soils shear strength increase. However, all the experiments also highlighted that soil conservation or increase of soil shear strength is not systematic on a rooted soil and depend on root traits, soil properties and on the type and scale of deformation induced by traffic. This PhD work constitutes the first step for a deepest understanding of the role of roots in the soil conservation during traffic. Besides, it emphasizes the potential use of crops services to complement the existing solutions to cope with soil compaction.

## **Keywords:**

Soil conservation, compaction, soil mechanic, soil physics, Functional ecology, Shear, Agrosystem, Conservation agriculture

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# RESUME ETENDU

## **Rôle des traits racinaires dans la conservation des propriétés du sol lors du tassement induit par le passage d'engins agricoles**

L'agriculture de conservation semble être adaptée pour relever le défi de cette décennie : nourrir une population grandissante tout en limitant l'impact écologique de la production de nourriture. L'agriculture de conservation suit trois principes: (1) perturbation minimale du sol, (2) couverture permanente du sol et (3) diversification des espèces grâce à des rotations diversifiées. L'agriculture de conservation offre de nombreux avantages tels que la réduction de l'érosion des sols, l'augmentation de la biodiversité des sols, l'optimisation de l'acquisition du phosphore ou la réduction du lessivage des nitrates mais aussi de nombreux inconvénients tels que l'infestation de mauvaises herbes ou la perte de rendement. L'absence de travail du sol conduit également à un tassement du sol en surface qui était classiquement atténué par cette pratique. Les solutions existantes sont principalement conçues pour un système conventionnel et pourraient ne pas être adaptables à l'agriculture de conservation

Le tassement du sol est en effet reconnu comme une menace majeure pour la qualité des sols en Europe. Le compactage dans les agroécosystèmes résulte de la propagation tridimensionnelle des contraintes dans le sol, qui est principalement causée par le trafic lors des opérations agricoles sur le terrain. Le tassement peut être défini comme la somme de deux processus: la compression et le cisaillement (Horn, 2003). Les deux processus ont un impact négatif sur le système de pores du sol. En effet, la compression réduit le volume des pores, tandis que le cisaillement réduit la continuité des pores (Berisso et al. 2013). Ces modifications du système poreux réduisent les échanges d'air et d'eau entre la surface du sol et le profil du sol et ralentissent le transport de l'air et de l'eau à travers le profil du sol. Pour combler le manque de travail du sol, l'agriculture de conservation se repose sur la capacité de la faune et de la flore à atténuer le tassement en créant de nouveaux biopores à travers les zones compactées. Néanmoins, la bio-résilience des sols vis-à-vis du tassement prend du temps pour être efficace et des solutions complémentaires pouvant atténué directement le tassement pendant le passage d'engins agricoles

seraient les bienvenues. Malgré la vaste gamme de solutions disponibles, le tassement reste un problème. En effet, même si de plus en plus de solutions sont proposées pour faire face au tassement, l'agriculture évolue vers une intensification qui s'accompagne d'une augmentation constante du poids des machines et donc de la contrainte appliquée au sol (Keller et al., 2019).

### **L'augmentation de la résistance du sol par les racines pourrait-elle être considérée comme une solution pour mitiger le tassement de sol dans les agrosystèmes ?**

Les effets des plantes dans les agrosystèmes n'ont jusqu'à présent été examinés que comme une solution pour remédier au tassement via la création de nouveaux pores mais jamais étudiés pour leur potentiel effet sur la résistance du sol au tassement. Des effets de racines sur la résistance du sol au cisaillement ont toutefois été observés dans d'autres contextes comme la protection des pentes contre le glissement de terrain ou la protection des berges de rivières (e.g. Pollen-Bankhead and Simon, 2010; Stokes et al., 2009). Seules quelques-unes de ces études traitent des effets de racines d'espèces annuelles sur la résistance au cisaillement du sol et suggèrent qu'elles pourraient jouer un rôle dans la résistance du sol au cisaillement. Néanmoins, des différences fondamentales existent entre le tassement en agrosystèmes et le cisaillement en contexte de prévention de glissements de terrain ou de stabilité des berges. Les différences se trouvent notamment dans les propriétés du sol, les racines rencontrées et les types et gradient de stress appliqués au sol durant le passage d'engins agricoles. Tout d'abord, la contrainte de cisaillement est mineure par rapport à la contrainte de compression pour le tassement induit par le passage d'engins agricoles. De plus: (1) la fréquence élevée et l'abondance des espèces annuelles présentant un gradient de traits racinaires, (2) les contraintes verticales et horizontales très courtes mais intenses appliquées et propagées progressivement dans l'ensemble du profil du sol, (3) la contrainte de compression induite par les engins agricoles est beaucoup plus importante que celle induite par le sol dans les autres contextes, (4) le cisaillement peu profond (<30 cm de profondeur) qui se produit principalement (Figure 1) où le sol n'est pas nécessairement saturé en eau et où les racines des espèces annuelles sont les plus densément présentes. Les effets des racines sur le tassement des sols dans les agrosystèmes pourraient ainsi être différents, impliquant d'autres mécanismes et produisant ainsi des résultats différents. Malgré cela, ces précédentes études montrent que les racines pourraient augmenter

la résistance du sol mais que cette relation doit être étudiée dans les agrosystèmes. Les racines pourraient donc être capables d'augmenter la résistance du sol et ainsi permettre la conservation des propriétés et services du sol durant le passage d'engins agricoles.

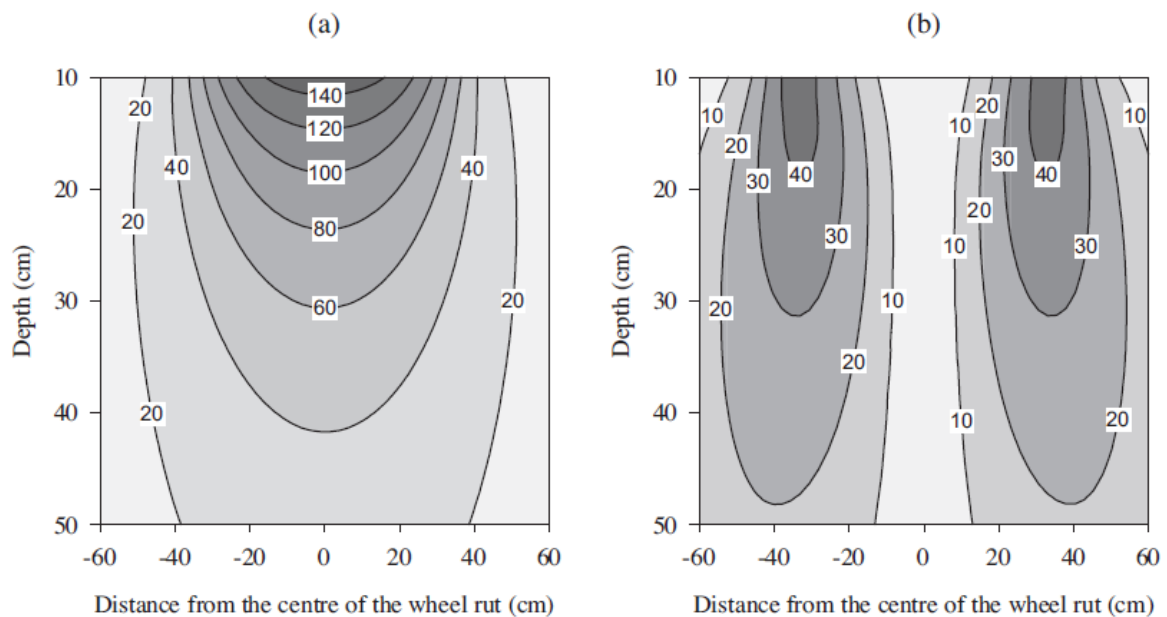


Figure 1: Moyenne prédite de (a) la force de compression et (b) la force de cisaillement en fonction de la distance horizontale au centre du pneu et de la profondeur. Les nombres placés sur les isolines sont donnés en kPa pour la force normale et la force de cisaillement (Berisso et al., 2013)

### **Approche de l'écologie fonctionnelle : réponses et effets des traits racinaires sur les propriétés et services du sol afin d'atténuer le compactage du sol**

Les plantes sont très sensibles à leur environnement car il définit en partie leur morphologie, leur architecture ou leur composition chimique en affectant leur capacité à acquérir de l'eau, de l'air ou des nutriments. D'un autre côté, les caractéristiques des plantes affectent leur environnement et modifient les processus écosystémiques. L'écologie fonctionnelle fournit des outils et des concepts afin de comprendre les relations entre plantes et services écosystémiques. Comparée à l'approche taxonomique qui compare et classe les espèces, l'approche fonctionnelle décrit les plantes par leurs traits ou traits et les utilise pour caractériser et classer les plantes ou communautés végétales. Un trait fonctionnel est un trait morphologique -physiologique-chimique ou phénologique quantifiable d'un organisme individuel qui présente une réponse vis-à-vis de son environnement et qui a un impact sur la croissance,

la reproduction, la survie ou sur les processus écosystémiques des plantes (Faucon et al., 2017). L'approche fonctionnelle permet ainsi de caractériser les traits des plantes et d'étudier leurs effets sur les processus écosystémiques tel que la résistance du sol ou la conservation des propriétés du sol.

### **Objectifs**

Ce projet de doctorat vise à étudier la relation entre les traits fonctionnels des racines et les propriétés physiques du sol dans les agrosystèmes afin d'évaluer la capacité des racines de couverts à atténuer le tassement du sol pendant le passage d'engins agricoles. Cette thèse comprend trois chapitres correspondant aux trois principaux objectifs visés.

Le premier chapitre étudie les effets des traits racinaires sur les conséquences du tassement sur les propriétés physiques du sol. Les objectifs de ce chapitre étaient (1) de caractériser la capacité des racines à conserver les propriétés du sol durant le passage d'engins et (2) d'identifier les traits racinaires impliqués dans le processus. De larges gradients de traits racinaires ont été obtenus en cultivant douze espèces de plantes de couverts issues de familles phylogénétiques contrastées. Répondre à ces objectifs permettrait une meilleure compréhension de la relation entre les traits racinaires et la conservation des propriétés du sol pendant le passage d'engins agricoles.

Le deuxième chapitre étudie l'influence des conditions initiales du sol, telles celles modulées par le travail du sol, sur les réponses et les effets des racines impliquées dans l'atténuation du tassement du sol. Le but de ce chapitre était d'identifier les effets de deux structures de sol contrastées sur l'expression des traits racinaires et la rétroaction sur l'effet des racines sur la conservation des propriétés du sol pendant le passage d'engins agricoles. L'hypothèse principale était que les racines jouent un rôle dans l'atténuation du tassement du sol en conservant les propriétés physiques du sol après la circulation, mais que les propriétés initiales du sol résultant de différentes techniques de travail du sol modifieront à la fois l'expression des traits racinaires et leurs effets sur la conservation des propriétés du sol. Les résultats de ce chapitre pourraient conduire à une meilleure compréhension de la relation entre les traits racinaires et les propriétés du sol avant et après passage de l'engin.

Le troisième chapitre se concentre sur les effets des racines sur la résistance du sol au cisaillement mesurée en laboratoire à l'aide d'une boîte de cisaillement. Le but de ce chapitre était de mettre en évidence les traits racinaires impliqués dans la résistance au cisaillement du sol. L'hypothèse principale était que les racines des cultures de couverts augmentent la résistance au cisaillement du sol, ce qui pourrait expliquer le rôle des racines dans la conservation des propriétés du sol lors du tassement identifié dans les expériences précédentes. Cet objectif pourrait nous aider à mieux comprendre l'un des principaux processus impliqués dans la conservation des propriétés du sol par les racines lors du passage des engins agricoles.

### **Approche méthodologique**

Cette thèse vise à étudier le rôle des racines dans l'atténuation du tassement du sol lors du passage d'engins agricoles. L'hypothèse principale était que les racines sont capables de limiter le tassement du sol en conservant les propriétés du sol pendant le passage de l'engin et cela est dû, au moins partiellement, à une augmentation de la résistance du sol au cisaillement. Nous avons examiné cette hypothèse en (1) comparant les propriétés physiques du sol avant et après le passage d'un engin agricole avec différentes espèces végétales mises en place, fournissant des traits racinaires contrastés (2) comparant la résistance du sol pour différents systèmes sol-plante avec des traits racinaires également contrastés.

Les propriétés du sol sélectionnées étaient la densité apparente et la perméabilité à l'air, car nous prévoyons que ces propriétés seront modifiées négativement par le tassement. Les mesures des propriétés du sol et des caractères racinaires fournissent des indicateurs clés de la capacité des racines à atténuer le tassement du sol et relient les traits racinaires à la conservation des propriétés du sol pendant le passage avec une expérimentation in situ. Dans une seconde expérimentation in-situ, nous avons ensuite étudié la relation entre les traits racinaires et la conservation des propriétés du sol dans deux sols différents pour caractériser l'effet de rétroaction potentiel des propriétés du sol sur l'effet des traits racinaires. Enfin, la dernière expérimentation en conditions contrôlées nous a permis d'explorer et d'identifier si les effets des racines sur la conservation des sols lors de la circulation pouvaient être dus à un renforcement du sol par des racines au cisaillement. Les mesures directes de la résistance du sol

nécessitent un équipement spécialisé adapté à des échantillons de sol contenant un système racinaire complet. L'équipement n'était pas disponible au début de la thèse et donc une boîte de cisaillement directe a été construite pendant la thèse. La construction était basée sur les plans de boîtes de cisaillement trouvés au sein d'études précédentes.

### **Évaluation des conséquences in situ du tassement du sol sur les propriétés physiques du sol**

Les échantillons de sol ont été prélevés sur la partie roulée à 0 et 0,3 m du centre du passage du pneu. La densité apparente du sol et la teneur en eau du sol a été déterminée à l'aide de la méthode gravimétrique et la perméabilité à l'air ( $k_a$ ,  $\mu\text{m}^2$ ) a été déterminée à l'aide de la méthode décrite par Iversen (2001). Dans chaque champ, la densité des particules du sol a également été estimée avec la teneur en argile et la teneur en matière organique en utilisant l'équation décrite par Schjønning et al. (2017). La porosité remplie d'air a ensuite été estimée ( $\epsilon_a$ ,  $\text{m}^3 \text{ m}^{-3}$ ) en utilisant la densité des particules du sol,  $\rho_b$  et  $\theta$ . Enfin, la perméabilité à l'air spécifique ( $k_{as}$ ,  $\mu\text{m}^2$ ) a été calculée en divisant  $k_a$  par  $\epsilon_a$ , comme suggéré par Groenevelt et al. (1984).

### **Mesure de la résistance au cisaillement du sol et des effets potentiels des racines à l'aide d'une boîte de cisaillement directe**

L'expérience en laboratoire s'est concentrée sur les effets des racines sur la résistance du sol au cisaillement. Pour ce faire, des tests de cisaillement ont été réalisés à l'aide d'une boîte de cisaillement construite lors de la thèse. La boîte de cisaillement était composée de quatre parties: (1) la vérin hydraulique actionné par un servomoteur rotatif, (2) la partie électronique contenant un servo-variateur qui contrôle le système de positionnement linéaire, une alimentation à découpage à sortie unique de 150W, un switch Ethernet reliant l'ordinateur au servo variateur, une cellule de force H3-C3 de 500 kg et un Arduino pour relier la cellule de force à l'ordinateur; (3) la partie de réception du cylindre pour immobiliser le cylindre de sol inférieur; (4) la partie faite pour appliquer le poids sur le sol. La boîte de cisaillement a d'abord été modélisée en 3D à l'aide de Tinkercad pour définir les dimensions des pièces en acier utilisées dans l'assemblage.

Les essais de cisaillement consistent à immobiliser le cylindre inférieur et à pousser le cylindre supérieur à l'aide du vérin. Le cisaillement a été appliqué à une vitesse constante de  $3 \text{ mm} \cdot \text{min}^{-1}$  jusqu'à ce qu'un déplacement horizontal de 25 mm soit atteint. Durant le test, la force requise pour déplacer le cylindre a été enregistrée en utilisant la cellule de force.

## **Chapitre 1 : La relation entre les traits racinaires et la conservation des propriétés physiques du sol pendant le trafic**

Le tassement induit par le passage d'engins agricoles représente une menace majeure pour la qualité du sol et les services fournis par celui-ci car il diminue à la fois le volume et la continuité des pores. Les conséquences sont nombreuses, en effet le tassement touche plusieurs processus majeurs : l'infiltration d'eau dans le sol, la disponibilité de l'air et le développement des racines. Les effets des racines sur le renforcement du sol ont été étudiés dans des contextes de glissements de terrain ou de stabilité des berges. L'effet des traits racinaires sur le renforcement du sol vis-à-vis du tassement du sol induit par le passage d'engin peut être différent de celui observé dans des contextes différents de celui de l'agrosystème et n'est actuellement pas étudié. Le renforcement du sol par les racines pourrait conduire à une meilleure conservation des propriétés physiques du sol et des services associés durant le passage d'engins agricoles. L'objectif de cette étude était d'étudier la relation entre les traits racinaires et les propriétés du sol directement après le trafic. Douze espèces de cultures ont été sélectionnées pour fournir de larges gradients de traits racinaires. Le tassement a été provoqué à l'aide d'une combinaison tracteur-remorque sur des plantes matures. La densité apparente du sol, la teneur en eau et la perméabilité à l'air spécifique ont été mesurées dans la zone de tassement et ont été comparées aux traits racinaires. Les résultats ont montré une corrélation positive entre la perméabilité à l'air spécifique et la densité de longueur de racines dans le sol. De plus, une corrélation négative a été trouvée entre la densité apparente et le rapport carbone/azote des racines. Cette enquête in situ a mis en évidence la relation entre les traits racinaires et la fonctionnalité du système poral directement après le passage d'engins agricoles. Cette première expérimentation est la preuve que la conservation des services et propriétés du sol en utilisant des racines afin d'atténuer le tassement est ainsi possible. Les perspectives seront d'examiner les effets

des traits racinaires sur la résistance à la compression du sol et la résistance au cisaillement du sol dans des conditions contrôlées pour mettre en évidence les principaux processus et traits racinaires impliqués et par conséquent les espèces végétales les plus efficaces à potentiellement utiliser pour gérer l'atténuation du tassement du sol.

## **Chapitre 2 : Les conditions de travail du sol entraînent des effets contrastés des espèces cultivées sur la conservation des propriétés du sol pendant le tassement du sol**

Le tassement du sol induit par le passage d'engins agricoles est un problème bien connu depuis des décennies en agrosystème. Les causes et conséquences sur les propriétés et la productivité du sol ont été largement rapportées dans des études antérieures. Le tassement du sol est issu de deux processus: la compression et le cisaillement. La compression est l'effort vertical soumis par le passage d'engins et cause une diminution du volume des pores du sol, tandis que le cisaillement est l'effort horizontal et cause une modification de la forme du système poral du sol affectant notamment la continuité des pores. La compression et le cisaillement sont inégalement répartis sous le pneu en contact avec le sol. Berisso et all. (2013) ont identifié un cisaillement croissant du centre vers le bord du pneu flexible remorqué, tandis que la compression diminuait du centre vers le bord sous le même pneu. Lorsque la traction est appliquée au pneu, la répartition de la compression et du cisaillement peut changer, mais aucune preuve expérimentale n'est rapportée à ce jour pour des pneus flexibles sur matériaux tendres. La relation entre un meilleur maintien de la continuité des pores lors du tassement et la densité de longueur racinaire par volume de sol a été soulignée lors d'une expérience précédente (chapitre 1). La capacité des racines à maintenir les propriétés du sol pendant le passage d'engins agricoles peut être liée à la capacité des racines à augmenter la résistance mécanique du sol à la déformation (c'est-à-dire la résistance du sol). Cependant, la résistance mécanique du sol est connue pour jouer un rôle dans la croissance des racines et modifiera ainsi les réponses des traits racinaires en affectant la pénétration racinaire, modifiant donc les traits racinaires morphologiques et architecturaux. Le but de cette étude était d'étudier la capacité des racines à conserver les propriétés physiques du système sol-racine et la rétroaction potentielle des conditions initiales du sol sur l'expression et les effets des traits racinaires. Quatre espèces de cultures ont été sélectionnées fournissant chacune une morphologie et une architecture différentes. Les cultures



ont poussés sur un sol travaillé de deux manières différentes : le premier a été labouré tandis que le second a seulement subi un déchaumage de surface provoquant deux structures de sol distinctes. Le tassement a été provoqué à l'aide d'une combinaison tracteur-remorque sur des plantes matures. La densité apparente du sol, la teneur en eau et la perméabilité à l'air ont été mesurées avant et après tassement et ont été comparées aux traits racinaires. Nos résultats ont mis en évidence l'effet positif des racines sur la conservation des propriétés du sol durant le passage d'engins agricole, confirmant les premiers résultats de l'expérimentation précédente (Chapitre 1). Cependant, l'effet des racines a été influencé par les conditions initiales du sol et par le gradient et le type de stress appliqué. La relation entre les traits racinaires, les conditions initiales du sol et le stress appliqué doit donc être prise en compte afin de déterminer au mieux la capacité de la matrice sol-racines à conserver efficacement les propriétés physiques du sol et les services associés pendant le passage d'engins agricoles.

Les perspectives seront d'essayer d'étudier le ou les mécanismes impliqués dans cette capacité des racines à conserver les propriétés du sol. L'hypothèse actuelle pointe le doigt vers une augmentation de la résistance du sol au cisaillement par les racines permettant ainsi de limiter la déformation et de conserver les propriétés du sol pendant le passage d'engins agricoles. D'autres études devraient ainsi inclure une mesure directe de la résistance du sol et déterminer l'effet des racines d'espèces annuelles sur la résistance du sol au cisaillement.

### **Chapitre 3 : Traits racinaires d'espèces annuelles cultivées contribuant à la résistance du sol**

La capacité des racines d'augmenter la résistance du sol au cisaillement a été démontré dans différents contextes comme celui des glissements de terrains ou de stabilité des berges. Néanmoins, les espèces utilisées, souvent des espèces pérennes d'arbres et d'arbustes, sont différentes de celles rencontrées en agrosystème, souvent des espèces annuelles herbacées. Les expérimentations précédentes ont montré que les racines d'espèces annuelles sont capables de conserver les propriétés du sol pendant le tassement du sol induit par le passage d'engins agricoles (Chapitre 1 et 2). L'effet des racines sur la résistance du sol au cisaillement observé dans d'autres contextes pourrait être le processus responsable de cette conservation des propriétés du sol en agrosystème. L'objectif de cette étude était de déterminer et de comparer les traits racinaires et la résistance du sol au cisaillement parmi trois espèces de cultures

intermédiaires fournissant des traits racinaires morphologiques contrastés afin de voir si les racines des espèces annuelles sont capables d'augmenter la résistance du sol au cisaillement et ainsi expliquer la conservation des propriétés du sol. L'expérience a été réalisée dans des conditions contrôlées en utilisant des cylindres contenant un sol remanié. La résistance au cisaillement du sol a été déterminée à l'aide d'une boîte de cisaillement permettant de déterminer la cohésion du sol et l'angle de friction interne à l'aide de l'équation de Mohr – Coulomb. Les résultats ont montré que seul la densité de volume de racines par volume de sol et le diamètre moyen des racines étaient associés à une augmentation de la cohésion et de l'angle de friction interne du sol. La différence entre le type de racine (racine pivotante et fasciculée), la densité de longueur de racines par volume de sol, la densité de poids sec de racine par volume de sol, la longueur spécifique des racines et la teneur en matière sèche des racines n'étaient pas liées à une différence de résistance du sol au cisaillement. Cette étude a permis de mettre en évidence le rôle des racines d'espèces de cultures annuelles dans la résistance du sol du sol. La densité de volume de racines par volume de sol peut être le principal trait impliqué à la fois dans l'augmentation de la cohésion du sol et de l'angle de friction interne. Cette expérimentation constitue une première étape vers l'amélioration de la compréhension des effets des plantes sur la résistance du sol au cisaillement en agrosystème, la sélection des espèces et la conception de nouveaux systèmes de culture visant la conservation des sols.

### **Discussion générale et perspectives**

#### **Premiers indices démontrant de l'effet des racines sur la conservation des propriétés physiques du sol pendant le passage d'un engin agricole et leur implication dans l'atténuation du tassement**

Nos résultats ont montré un lien clair entre la longueur de racines par volume de sol et une meilleure conservation de la capacité du sol à laisser passer l'air et l'eau (Chapitre 1). Notre deuxième expérience a également soutenu ce résultat en démontrant la capacité des racines à conserver les propriétés physiques du sol pendant le passage d'engins agricoles (Chapitre 2). Néanmoins, dans les deux cas un des principaux résultats était que les racines ne permettaient pas systématiquement de conserver les propriétés du sol pendant le passage d'un engin agricole. En effet, les racines semblent pouvoir

empêcher le tassement du sol et conserver les propriétés physiques du sol lors du passage d'engin mais cette capacité est liée à des traits racinaires spécifiques.

Notre hypothèse est que la conservation des propriétés physiques du sol par les racines est due, au moins partiellement, à un renforcement du sol par les racines. Cette hypothèse est basée sur la preuve de la capacité des racines à augmenter la résistance au cisaillement du sol dans d'autres contextes. Par contre, des différences existent et l'effet de racines de plantes annuelles peut-être différents de l'effet de racines de plantes pérennes. De plus, par rapport au contexte de glissement de terrain où l'objectif est d'augmenter la résistance du sol au cisaillement du sol des couches vulnérables spécifiques, en agrosystème l'objectif devrait être de renforcer l'entière du profil du sol de manière homogène pour éviter des zones plus faibles, vulnérables à la déformation. Les traits liés à une répartition homogène des racines dans le sol pourraient ainsi jouer un rôle central dans l'atténuation du tassement en agrosystème. Les traits racinaires liés à la densité de racines par volume de sol pourraient donc présenter un intérêt particulier. Trois traits racinaires reflètent la densité des racines dans le sol: la densité de longueur racinaires, la densité poids racinaires et la densité de volume racinaire par volume de sol. Cependant, les plantes à racines pivotantes, peuvent avoir la majeure partie de leur volume ou de leur poids racinaire concentré dans le pivot, et ainsi la densité de poids et de volume racinaire ne représente plus une répartition homogène des racines dans le sol. La meilleure façon d'évaluer la capacité des racines à occuper le sol pourrait être de ne mesurer que la densité de poids de volume du système fibreux. Cela permettrait de prendre en compte la longueur mais aussi l'épaisseur du système fibreux qui pourrait jouer un rôle complémentaire dans la conservation des propriétés physiques du sol lors du passage d'engins agricoles. Les traits architecturaux des racines pourraient également être intéressants comme l'angle d'insertion des racines dans le sol ou la typologie des racines. La morphologie du système porale et l'architecture racinaire pourraient être étudiés à l'aide de la tomographie aux rayons X couplée à la mesure de la perméabilité à l'air dans le but de mieux comprendre les effets racinaires et leur capacité à conserver les propriétés physiques du sol.

**Relations entre les traits racinaires, les propriétés physiques du sol et le stress appliqué et leur application à la conservation des propriétés physiques du sol**

La deuxième expérimentation a mis en évidence que des plantes présentant des traits racinaires identiques n'avaient pas le même effet sur la conservation des propriétés physiques du sol en fonction des propriétés du sol ou du type ou du gradient de contraintes appliquées. La capacité des racines à conserver les propriétés physiques du sol n'est donc pas seulement liée à l'expression des traits racinaires, mais dépend de processus complexes impliquant les traits racinaires, les propriétés du sol et leur réponse au stress appliqué. Le stress induit par le passage de l'engin dans les agrosystèmes se propage à travers tout le profil du sol dans toutes les directions et la déformation se produira principalement là où le stress est le plus élevé (près des pneus) et/ou là où le sol est le plus faible. La résistance du sol peut être hétérogène, principalement entre les différentes couches horizontales, car seule la surface peut être labourée et certaines couches plus profondes peuvent être compactées (la semelle de labour par exemple). Dans notre expérience, nous avons mis en évidence des espèces capables de (1) conserver les propriétés physiques du sol quel que soit le stress appliqué et les propriétés physiques initiales du sol (2) conserver les propriétés physiques du sol uniquement lorsque le stress appliqué est plus faible ou (3) conserver les propriétés physiques du sol uniquement lorsque le sol n'est pas labouré (c'est-à-dire lorsque la résistance initiale du sol est plus élevée). De plus, aucun trait racinaire mesuré n'a différencié les effets des espèces sélectionnées sur la conservation des propriétés du sol. Même la densité de longueur racinaire par volume de sol ne discriminait pas les espèces les unes des autres. Notre expérience confirme cependant que les racines peuvent jouer un rôle majeur dans la conservation des propriétés physiques du sol pendant le passage d'un engin agricole. L'effet des racines sur la conservation des propriétés du sol dépend des traits racinaires, pas encore entièrement identifiés, ainsi que des propriétés du sol et du type et de la gamme de stress appliqués. Il est donc nécessaire d'étudier plus profondément les différents processus qui pourraient être impliqués dans la conservation des propriétés du sol par les racines lors du passage d'un engin agricole dans l'agrosystème.

### **Le rôle des racines dans l'augmentation de la résistance du sol au cisaillement : un processus majeur**

Nos expériences in-situ ont produit de solides preuves démontrant du rôle des racines dans la conservation des propriétés physiques du sol pendant le passage d'un engin agricole. La prochaine étape

consiste maintenant à comprendre les processus par lesquels les racines conservent les propriétés physiques du sol. Comme décrit précédemment, le tassement peut être divisé en deux sous-processus: la contrainte horizontale et la contrainte verticale qui sont respectivement appelées cisaillement et compression. Ces deux processus sont préjudiciables au système poreux du sol car la compression diminuera son volume tandis que le cisaillement rompra la continuité des pores. Dans les expériences in situ, la conservation des propriétés physiques du sol a été observée à 0,1 m de profondeur directement après le passage de l'engin agricole. Par conséquent, la conservation observée est certainement liée à la réaction du sol au cisaillement qui doit être observée dans de telles circonstances.

Les rôles des racines dans la résistance du sol au cisaillement ont déjà été largement décrits dans le contexte des glissements de terrain ou de la stabilité des berges. Cependant, la plupart des études des espèces d'arbres et d'arbustes ou des espèces herbacées pérennes qui produisent un gradient de traits racinaires différent des traits racinaires des espèces annuelles rencontrées en agrosystème. Nous avons donc décidé d'évaluer le renforcement de la résistance du sol au cisaillement par les racines des espèces annuelles. La comparaison entre un sol nu et trois espèces a mis en évidence que les racines annuelles pouvaient augmenter considérablement la résistance au cisaillement du sol (chapitre 3). Les racines pourraient donc avoir augmenté la résistance du sol au cisaillement dans les expériences in-situ d'une manière similaire, ce qui pourrait expliquer, au moins partiellement, la conservation des propriétés physiques du sol. Parmi les trois espèces cultivées étudiées, une seule espèce présentait une résistance au cisaillement du sol significativement plus élevée que le sol nu. La présence de racines n'augmente donc pas systématiquement la résistance du sol au cisaillement. Comme observé pour la conservation des propriétés physiques du sol, la capacité des racines à augmenter la résistance au cisaillement du sol dépend donc d'un certain nombre de traits racinaires spécifiques. Dans notre expérience, les principaux traits racinaires qui distinguent l'impact de l'espèce sur le renforcement de la résistance du sol au cisaillement n'étaient pas la densité de longueur racinaire par volume de sol, mais la densité de volume racinaire par volume de sol et le diamètre moyen des racines qui étaient significativement plus élevés chez la Féverole. Cela confirme l'hypothèse selon laquelle la densité de longueur racinaire n'est peut-être pas le seul trait racinaire impliqué dans la conservation des propriétés physiques du sol et que

l'épaisseur du système fibreux doit jouer un rôle complémentaire. Cependant, nous avons observé une différence entre la capacité des racines à conserver les propriétés physiques du sol et la capacité des racines à augmenter la résistance du sol au cisaillement. En effet, il semble que les racines sont plus souvent capables de conserver, au moins certaines propriétés physiques du sol, que d'augmenter la résistance du sol au cisaillement. Cela soulève ainsi l'hypothèse que la capacité des racines à conserver les propriétés physiques du sol pendant le passage d'engin agricole pourrait ne pas être uniquement due à un renforcement du sol au cisaillement. Le premier processus complémentaire possible est le renforcement du sol à la compression par les racines. Les preuves d'un effet des racines sur la résistance à la compression du sol sont rares, mais Kleinfelder et al. (1992) ont montré que les racines sont capables d'augmenter la résistance à la compression du sol. Cependant, le contexte est une fois de plus différent de notre système d'intérêt et les études concluent que la force acquise par les racines vivaces n'était pas assez grande pour résister au stress induit par le déplacement du bétail. En agrosystème, le renforcement potentiel du sol à la compression par les racines des plantes annuelles pourrait être insignifiant par rapport à la forte contrainte de compression induite par le passage d'engin agricole

Le deuxième processus complémentaire possible pourrait être que les racines empêchent la rupture des pores sans augmenter systématiquement la résistance du sol au cisaillement. Pollen (2007) a déclaré que «le sol est résistant à la compression mais faible vis-à-vis de la tension. A l'inverse, les racines sont faibles en compression mais résistantes à la tension ». L'hypothèse est que les racines n'augmentent pas suffisamment la résistance du sol au cisaillement et ne permettent donc pas d'éviter la déformation pendant le passage de l'engin agricole. Cependant, les racines à l'intérieur des pores résisteront à la tension et ne se briseront pas pendant le cisaillement, ce qui gardera le pore plus tortueux mais continu (Figure 2).

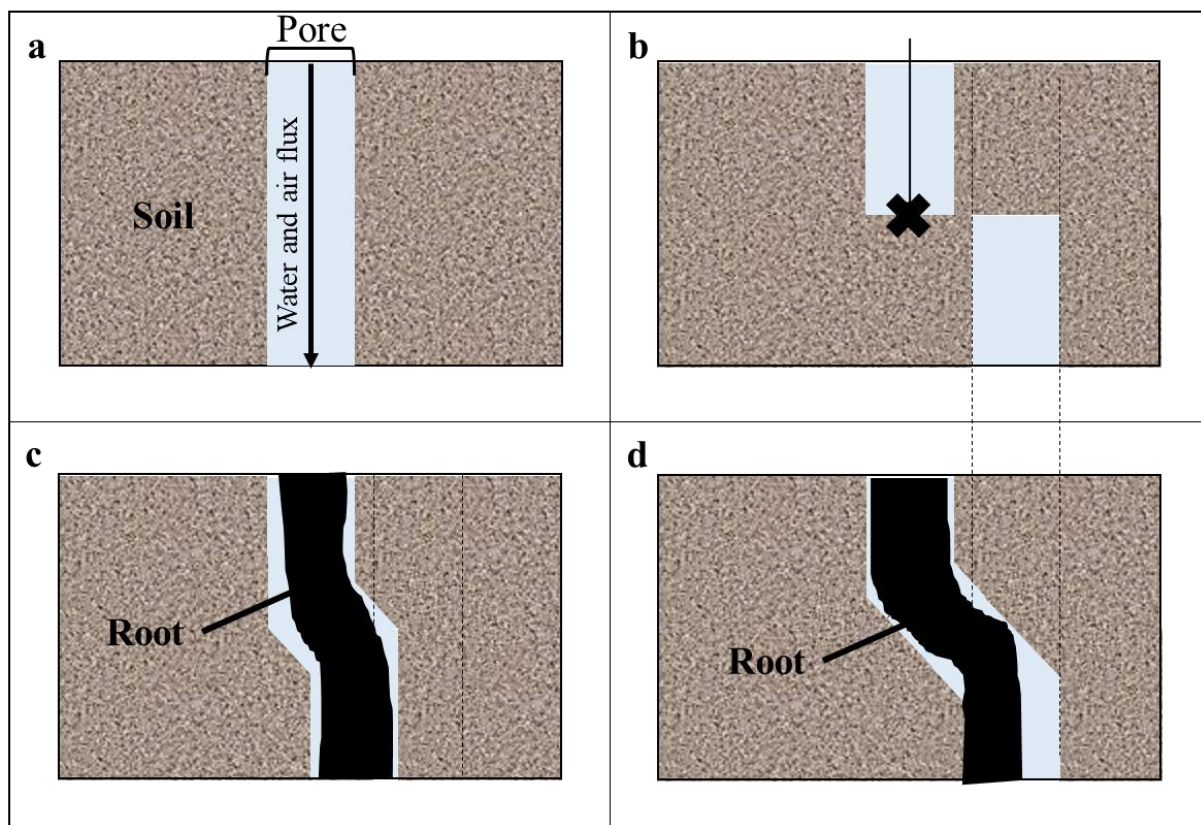


Figure 2: Représentation hypothétique de la déformation d'un sol induit par des forces de cisaillement. Les lignes en pointillés indiquent la déformation du sol nu. a : Le sol avant déformation ; b : Le sol nu après cisaillement, la continuité du pore est brisée, l'air et l'eau ne peuvent plus circuler librement ; c : Sol avec racine après cisaillement. Ici, la racine a renforcé le sol et a limité la déformation, l'eau et l'air peuvent encore circuler au sein du pore ; d : Sol avec racine après cisaillement. Ici, la racine n'a pas limité la déformation mais la racine n'a pas cassé permettant au pore de garder une certaine continuité. L'air et l'eau peuvent encore circuler

### **Mélanges fonctionnels diversifiés pour optimiser l'atténuation du tassement pendant le passage d'engins agricoles**

Les racines sont capables de limiter la déformation du sol et leur capacité à coloniser le sol et à remplir les pores semble être un facteur clé pour conserver les propriétés physiques du sol pendant le passage d'engins agricoles. Néanmoins, la distribution des racines dans le sol est très hétérogène étant donné la forte variation des traits architecturaux des racines entre les espèces et les variétés et la forte plasticité racinaire en réponse à l'hétérogénéité du sol chez la même espèce (Figure 3). Le renforcement du sol en surface est très important car c'est là que le stress sera le plus élevé. Cependant, même si la couche supérieure renforcée est moins déformée, elle ne limitera pas la propagation des contraintes et la déformation peut se produire plus en profondeur si le sol est plus faible. Des effets de complémentarité

pourraient ainsi être attendus pour les associations végétales avec des traits racinaires architecturaux renforçant à la fois la surface du sol ainsi que les couches plus profondes et limitant ainsi totalement la déformation. Diverses espèces aux traits racinaires architecturaux et morphologiques contrastés dans les mélanges seraient la solution la mieux adaptée pour coloniser et renforcer de manière homogène les différentes parties du sol. Une perspective consiste alors à étudier la complémentarité plausible entre les traits racinaires architecturaux en comparant les cultures monospécifiques et multispécifiques présentant une grande diversité fonctionnelle et leurs effets sur la conservation des propriétés des sols. Nos expériences ont seulement mis en évidence le rôle des traits morphologiques et de la distribution des racines dans le sol, mais d'autres traits racinaires pourraient être impliqués, y compris des traits racinaires liés à la capacité des racines à augmenter la résistance au cisaillement du sol indépendamment de la densité comme par exemple la résistance à la tension des racines. Les espèces sélectionnées doivent donc présenter des traits racinaires influant sur deux propriétés: (1) la capacité des racines à augmenter la résistance du sol au cisaillement et (2) la façon dont la racine se disperse dans le sol ce qui définira l'horizon de croissance préférentiel. Nous avons souligné que la capacité des racines à augmenter la résistance du sol au cisaillement est un processus impliqué dans la conservation des propriétés physiques du sol pendant le passage d'engins agricoles, mais que d'autres processus pourraient également jouer un rôle. Une fois que les processus sont bien identifiés, des cultures multispécifiques pourraient également être sélectionnées pour offrir une conservation des propriétés du sol optimisée via la fourniture de plusieurs services liés à plusieurs processus simultanés.



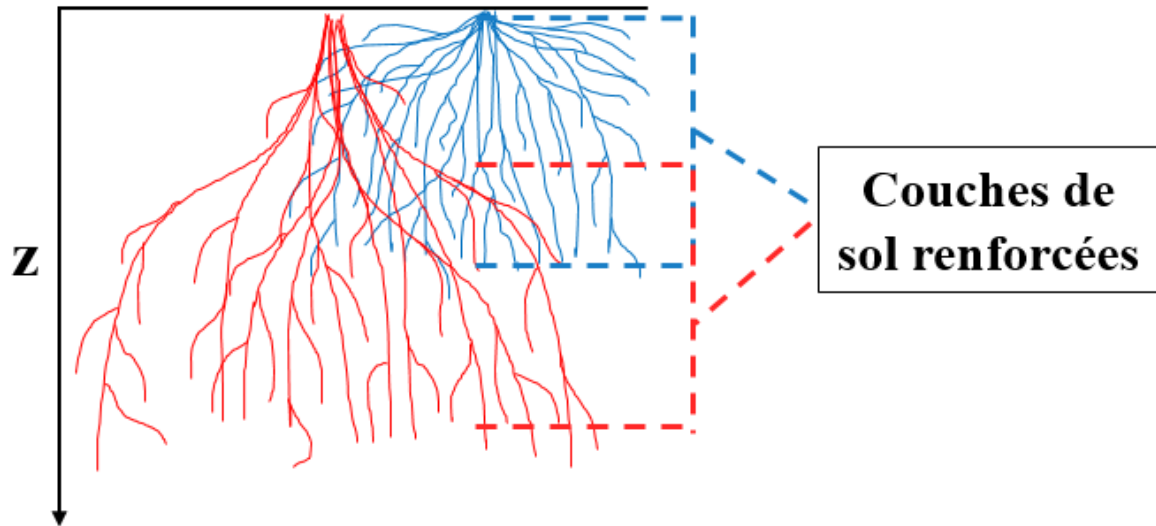


Figure 3: Représentation schématique d'une diversité architecturale au sein d'un mélange et ses conséquences sur le renforcement du sol.

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# **INTRODUCTION**

# **1. INTRODUCTION**

## **1.1. The challenge of mitigating soil compaction in conservation agriculture**

### **1.1.1. The context**

One of the main challenges of this decade and the future is to feed an ever growing population with limited environmental and societal impacts. Conservation agriculture seem to be well-suited to address this challenge. It follows three principles: (1) minimum soil disturbance, (2) permanent soil cover and (3) species diversification through diversified rotations. These practices help addressing some of the main challenges as for example soil erosion by water or nitrate leaching (Alliaume et al., 2014; Aronsson et al., 2016). As tillage is abandoned or very limited, the impacts of soil compaction in the soil surface (i.e. the usually tilled surface) are no longer compensated and could become very problematic (Lahmar, 2010). To bridge the lack of soil disturbance, conservation agriculture relies on the capacity of fauna and flora to alleviate compaction by creating new biopores through compacted areas (Capowiez et al., 2012; Williams and Weil, 2004). Compaction bio-alleviation take time to be efficient (Radford et al., 2007) and complementary solutions that can directly mitigate compaction during traffic would be welcome.

### **1.1.2. Soil compaction**

Soil compaction occurs when soil internal strength is lower than the stress transmitted onto it and results on soil deformation (Horn et al., 1995; Soane et al., 1980). Soil compaction is derived from two processes: compression and shearing. Stress applied in agrosystems depend on machinery factors such as the weight of the machine, its weight repartition or its tyres properties (Lamandé and Schjønning, 2011a; ten Damme et al., 2019). The machinery weight induce both compression and shear. Shear is also induced by the traction required to move the machinery. Vertical and horizontal deformation thus happens when compressive stress or shearing stress applied exceed the vertical and horizontal soil

strength, respectively called the precompression stress (or preconsolidation stress) and the soil shear strength. Soil precompression stress and soil shear strength are usually both measured in the laboratory using undisturbed soil samples collected from the field. Soil precompression stress characterises the soil resistance to compression and depends on soil clay content, bulk density and matric potential (Schjønning and Lamandé, 2018a). The soil shear strength depends on clay content, organic matter content, bulk density and soil matric potential (Amiri et al., 2018; Schjønning et al., 2020a) and is the result of two physical properties: soil cohesion and soil internal friction. The Mohr-Coulomb equation [Eq. 1] is commonly used to summarize the soil shear strength:

$$\tau = C + \sigma \tan\phi \quad [\text{Eq. 1}]$$

Where  $\tau$  is the soil shear strength  $C$  is the soil cohesion,  $\sigma$  is the normal force applied (i.e. horizontal stress), and  $\phi$  is the internal angle of friction.

### **1.1.3. Consequences of soil compaction on soil properties and functions**

Soil vertical and horizontal deformation caused by compression and shear affect soil pore system as it remoulds the soil structure. The main consequence induced by compression is the loss of pore volume which also results in an increase of bulk density while shear will mainly modify the pore structure which usually affect the pore continuity (Figure 1) (Berisso et al., 2013). In agrosystems shear induced by traffic will mainly impact the soil surface (<0.3 m). One of the main consequences of shear in agrosystems is the loss of air and water flow in the soil which is caused by the breaking of the vertical pore continuity (Figure 1 and 2). As showed by Williams and Weil (2004), young roots use pores already established to grow rather than creating new pores. The breaking of pore continuity thus also negatively impact the growth of young plants.



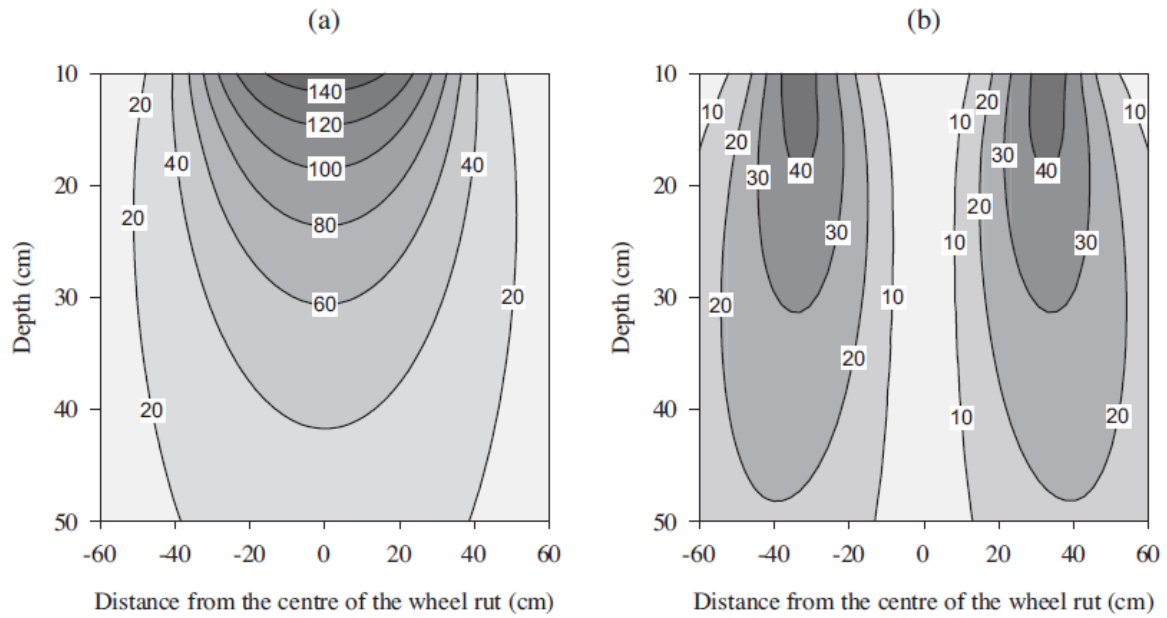


Figure 1: Predicted (a) mean compressive stress and (b) shear stress as a function of horizontal distance from the centre of the wheel rut and depth. The numbers placed along the isolines are given in kPa for the mean normal stress and the shear stress). (Berisso et al., 2013)

Compaction thus induce many problems such as surface erosion due to the loss of water infiltrability in the topsoil, or denitrification due to anaerobic conditions. The increase of bulk density and the creation of dense block of soil will increase soil resistance to penetration and thus, conjointly with the lack of air and water, disturb root growth and development. Compaction thus impacts the physical, chemical and biological functions of the soil which will at terms negatively affect crops yield (Batey, 2009).

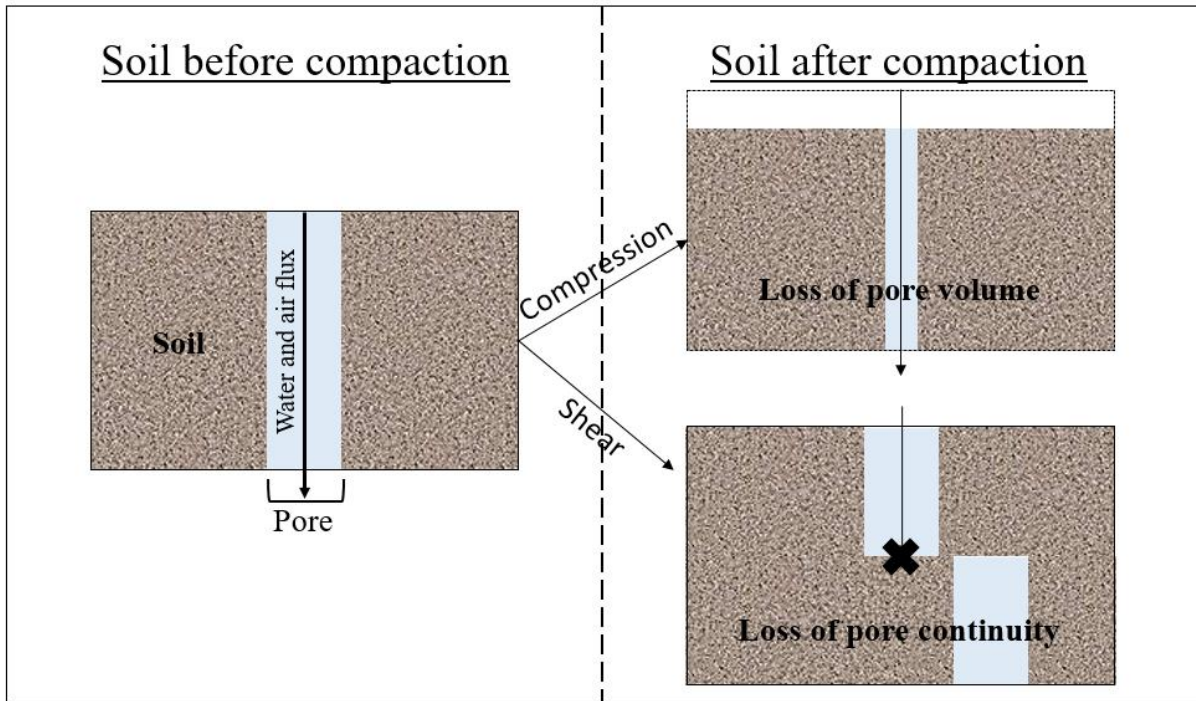


Figure 2: Schematic representation of compaction consequences on soil pore system

## 1.2. Existing solutions to prevent soil compaction and its adverse effects in agrosystem

### 1.2.1. Technological solutions to traffic induced compaction

#### 1.2.1.1. Controlled traffic farming

To prevent the adverse effects of compaction, Controlled Traffic Farming (CTF) propose to restrict traffic in the fields to permanent traffic lanes (Bluett et al., 2019). The advantages of CTF is to limit compaction to a reduced area of the field and protect the most of the area from the adverse effects of traffic. This practice could be really promising in systems with reduced or zero-tillage so that only a reduced fraction of the cropped area will be affected by compaction (Tullberg et al., 2007). However, this concept could be difficult to adopt for farmers as all or most of the machinery needs to have similar working width (Bluett et al., 2019). Concentrated water flow could also appear as water will not be able to infiltrate in the highly compacted traffic lanes and thus cause soil erosion or flooding problems (Figure 3).



Figure 3 : Soil erosion in a field of linseed in Scotland. A storm caused water runoff down the compacted wheel tracks (Batey, 2009)

#### ***1.2.1.2. Tyres innovation***

Several tyres design have been developed by scientist and manufacturer to decrease the stress applied and prevent compaction consequences on the soil. As the stress induced is defined by the force applied per soil area (Warrick, 2001), these innovations often rely on increasing the contact area between the machinery and the soil. Chain-track tractor for example have a wider area and could limit soil compaction (Mударисов et al., 2020) but they may result in an uneven stress distribution affecting soil aeration (Lamandé et al., 2018). Tyres remain the main intermediates between the machinery and the soil. Tyres properties could then be manipulated to increase the contact area such as modifying the tyres dimensions or the tyres design. Tyres inflation pressure is one of the main factors as the lower the pressure is, the higher the contact area will be. Ten Damme et al. (2020) proposed that in order to reduce soil stress, tyres design that allow low inflation pressure and large contact area should be used. Tyres design could also decrease the stress applied on the soil as observed in Ten Damme et al. (2019) (Figure 4). To increase contact area, dual or tandem wheels could also be used (Keller and Arvidsson, 2004). However, despite these innovations, modern heavy machinery will still induce a reduced but significant amount of stress. Additional and complementary solutions are thus needed.

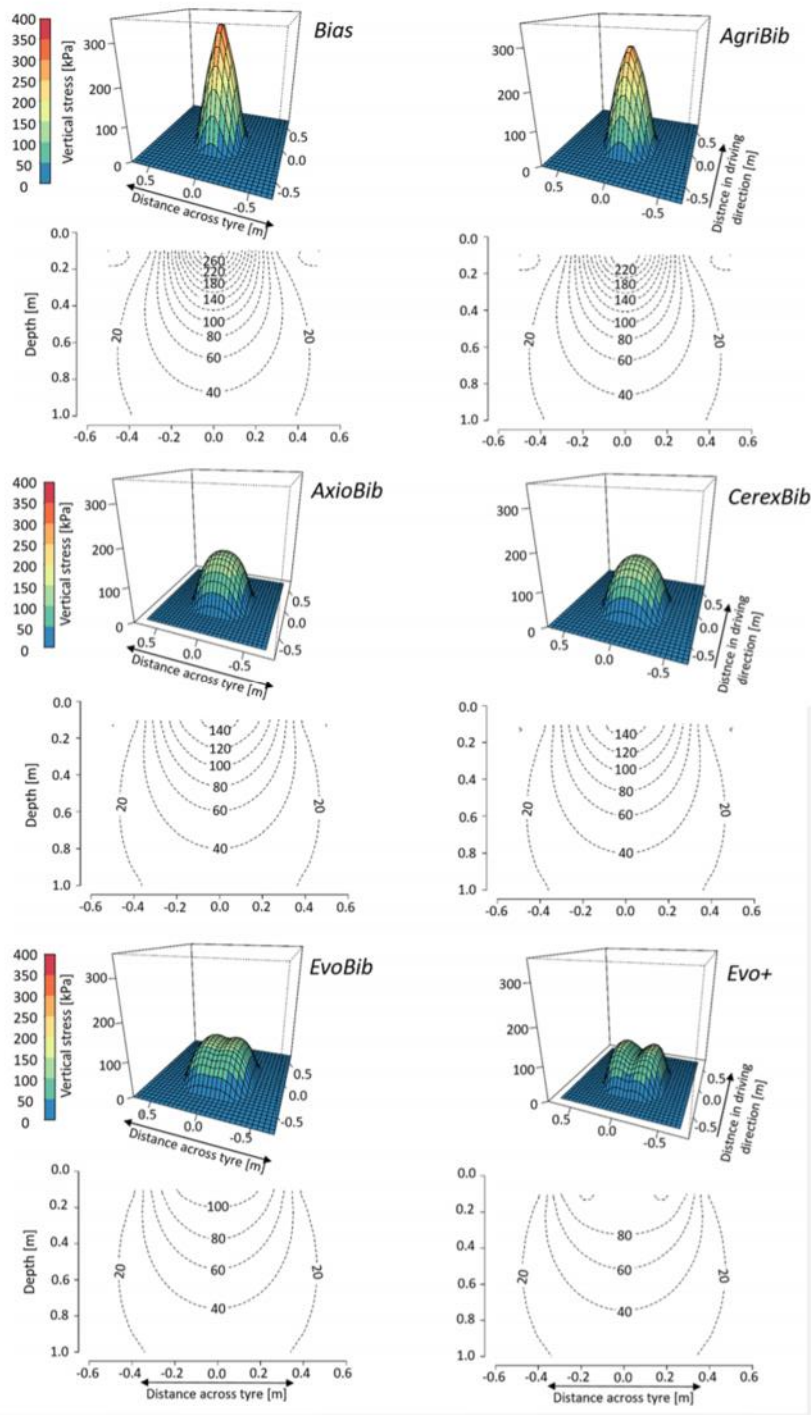


Figure 4 : FRIDA calculations of the vertical stress distribution in the contact area (3D) and calculated vertical soil stress (2D) for the tyres at the rear position as used in the field experiment and the theoretical tyre Evo+ (ten Damme et al., 2019)

## **1.2.2. Agronomic solutions**

### ***1.2.2.1. Tillage***

Tillage is the most common way to “erase” compaction consequences in agrosystems as soil structure is completely remoulded. However, tillage only affect soil surface (<0.3 m approx.) and do not deal with subsoil compaction. Subsoil decompaction thus can be required to deal with deeper layers and can deal with compaction up to 1m depth. However, special equipment and powerful tractor are required for this practice. Tillage is an efficient solution to cope with surface compaction but it can also induce other problems such as erosion (Lindstrom et al., 1992) or biodiversity loss (Brito et al., 2012; House and Parmelee, 1985). Reduced tillage or zero-tillage system are also gaining increased attention and adoption, thus requiring substitute solutions to alleviate compaction are needed.

### ***1.2.2.2. Predicting field readiness for field operations***

Another solution to prevent compaction is to decide field operation date based by taking into account soil workability and trafficability which are respectively the soil capacity to withstand traffic and tillage without soil degradation or structural damage (Edwards et al., 2016; Obour et al., 2017). Each operation as tillage or sowing has specific optimal conditions. Obour et al. (2017) define a range of water content where tillage can produce a desirable seedbed without structural damage. Other operations that do not require specific soil conditions can also be concerned such as manure spreading or harvest. In this case, to prevent compaction, traffic should occur when the soil trafficability is the highest (i.e. when the soil is the most resistant). The time frame for each operations vary widely from a few days to one month and soil water content is generally the main factor influencing the soil resistance during this time frame. Prediction models exist to estimate the optimal dates but their use could be limited to specific soil and climate conditions (Edwards et al., 2016; Obour et al., 2019, 2017; Rounsevell, 1993). Concentrating traffic during the time frames when the soil workability or trafficability is maximal could thus prevent compaction and its adverse consequences. In some case, no “ideal date” match and compaction is thus unavoidable (Figure 5).



Figure 5 : Tractor stuck in the mud during cover crop shredding in winter. Photo: Quentin Sarter

### **1.2.2.3. Bio-alleviation of soil compaction**

Alleviation of soil compaction using roots or soil fauna is increasingly used to substitute tillage in reduced or zero tillage system. When tillage is reduced, soil fauna diversity and density often increase (e.g. House and Parmelee, 1985; Metzke et al., 2007). In the temperate area, the main actors of the alleviation of soil compaction are the earthworms. Their capacity to create vertical and horizontal biopores regenerate soil structure and functions and slowly limit compaction consequences (Figure 6) (Capowiez et al., 2012). Roots are also capable of creating biopores and alleviating soil compaction (Büchi et al., 2018; Williams and Weil, 2004). However, soil restoration takes time and hard compacted layer might remain unaltered for years (Radford et al., 2007).

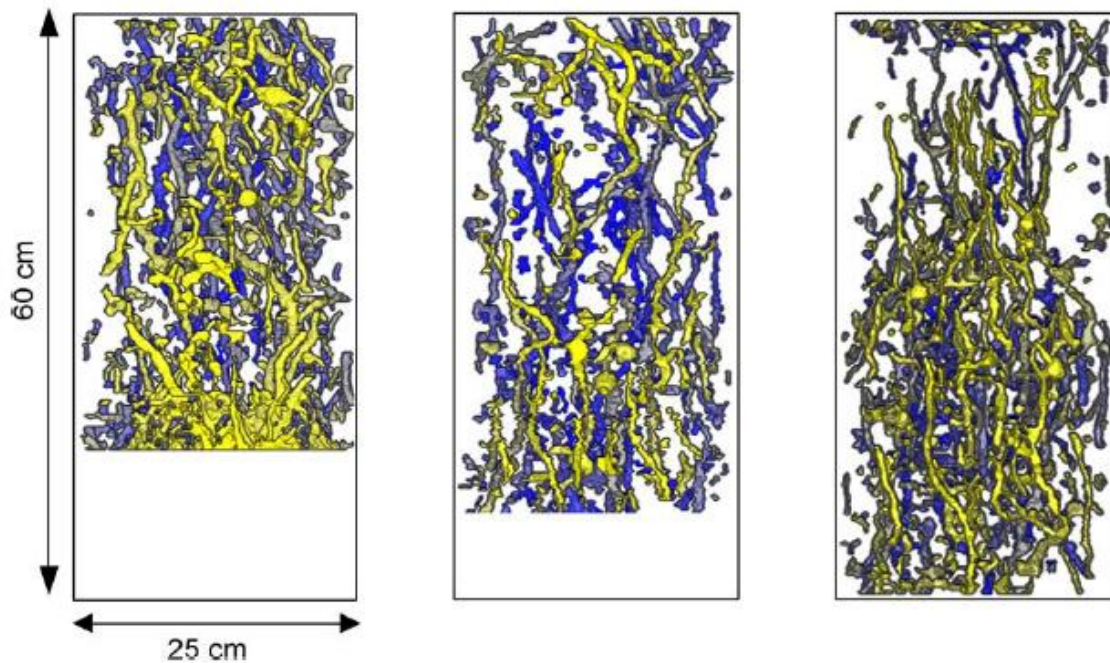


Figure 6 : Illustration of the 3D volumetric reconstruction of natural earthworm burrow systems in three different samples. The shading ranges from light grey for the nearest to dark grey for the farthest burrows. (Bastardie et al., 2005)

### 1.3. Could roots effects on soil strength be considered as a solution to cope with soil compaction in agrosystems?

Despite the vast array of solutions available, compaction is still a contemporary problem. Indeed, as more and more solutions are proposed to cope with compaction, agriculture evolve toward intensification which go along with a constant increase of the machinery weight and thus of the stress applied on the soil (Keller et al., 2019). Agricultural practices also evolve towards an increased adoption of conservation agriculture, avoiding soil disturbance by tillage and thus not producing the mechanical remediation of traffic-induced compaction it can provide (Friedrich et al., 2012). New complementary solutions are thus needed to cope with compaction in agrosystems either in the case of highly mechanised agricultural systems or in the case of conservation agriculture.

The effects of plants in the agrosystems were so far only examined as a solution to alleviate compaction and never studied for their potential to cope with compaction during traffic. Roots effects on soil shear

strength were however observed in studies examining the role of vegetation in the protection of slopes or river bank from landslides, or erosion (i.e. Stokes et al., 2009, Pollen-Bankhead and Simon, 2010). Only few of these studies deals with the effects of roots of annual species on soil shear strength but they suggest that they might play a role in the soil shear strength (Hubble et al., 2013). Fundamental differences in soil properties, root, and the rates and ranges of deformation however exist between the contexts of landslide prevention or riverbank stability and traffic-induced compaction of agricultural soils. First of all, shear stress is minor compared to the compressive stress for compaction induced by traffic and the role of roots in the soil compressive strength been sparsely addressed (Kleinfelder,1992). The other particularities are: (1) the high frequency and abundance of annual species presenting a gradient of root traits, (2) the very short yet intense vertical and horizontal stress applied and propagated gradually in the whole soil profile (Keller and Lamandé 2010), (3) the compressive stress induced is much greater than overburden stress (e.g. Lamandé and Schjøning, 2011b), (4) the shallow shearing (<30 cm in depth) which mainly occurs (Figure 1; Berisso et al., 2013) where soil is not necessarily saturated with water and where roots of annual species are the most densely present (Osman and Barakbah 2006). Roots effects on soil compaction in agrosystems could thus be different from their role in landslide prevention or riverbank stability, implicating different mechanisms and thus producing different results. For example the increased soil compressive strength when roots are present shown by Kleinfelder (1992) (Figure 7) might be insignificant compared to the compressive stress induced by the machinery in agrosystems. Despite this, previous studies in other context show evidences that roots could increase soil strength and this relation should be studied in the agrosystems



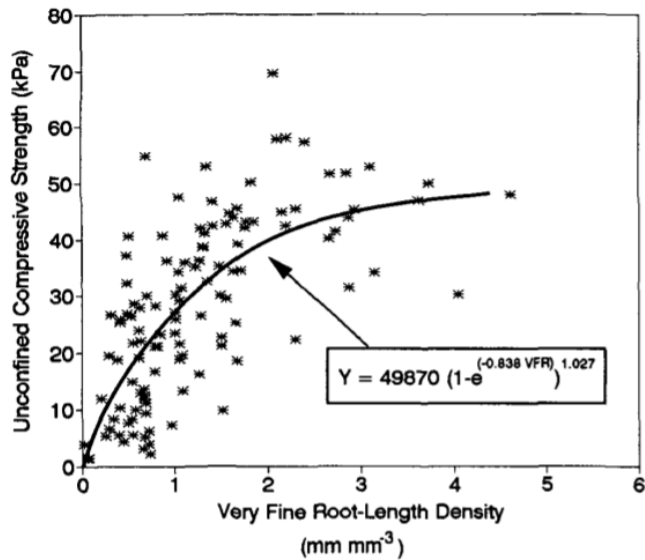


Figure 7: Scatter plot of very-fine root-length density vs unconfined compressive strength at 40% deformation (Kleinfelder et al., 1992)

## 1.4. Functional approach to the responses and effects of roots traits on soil properties and services to mitigate soil compaction

Plants have are highly responsive to their environment as it in part defines their morphology, architecture or the plant chemical composition via impacting their capacity to acquire water, air and nutrients. On the other hand, plants traits affect their environment and modify ecosystem processes (Diaz et al., 2004). Functional ecology provides tools and concepts to understand the relationships between plants and ecosystem services. Compared to the taxonomical approach which compares and classify species, the functional approach describes plants by their characteristics or **traits** and use them to characterise and classify plants or plants communities (Figure 8). A functional trait is “a quantifiable morphological - physiological-chemical or phenological traits of an individual organisms that present a response to the variation of environment and impacts plant growth, reproduction, survival, and ecosystem processes.” (Faucon et al., 2017). The functional approach thus allow to characterise plants traits and investigate their effects on ecosystem processes (Figure 9)

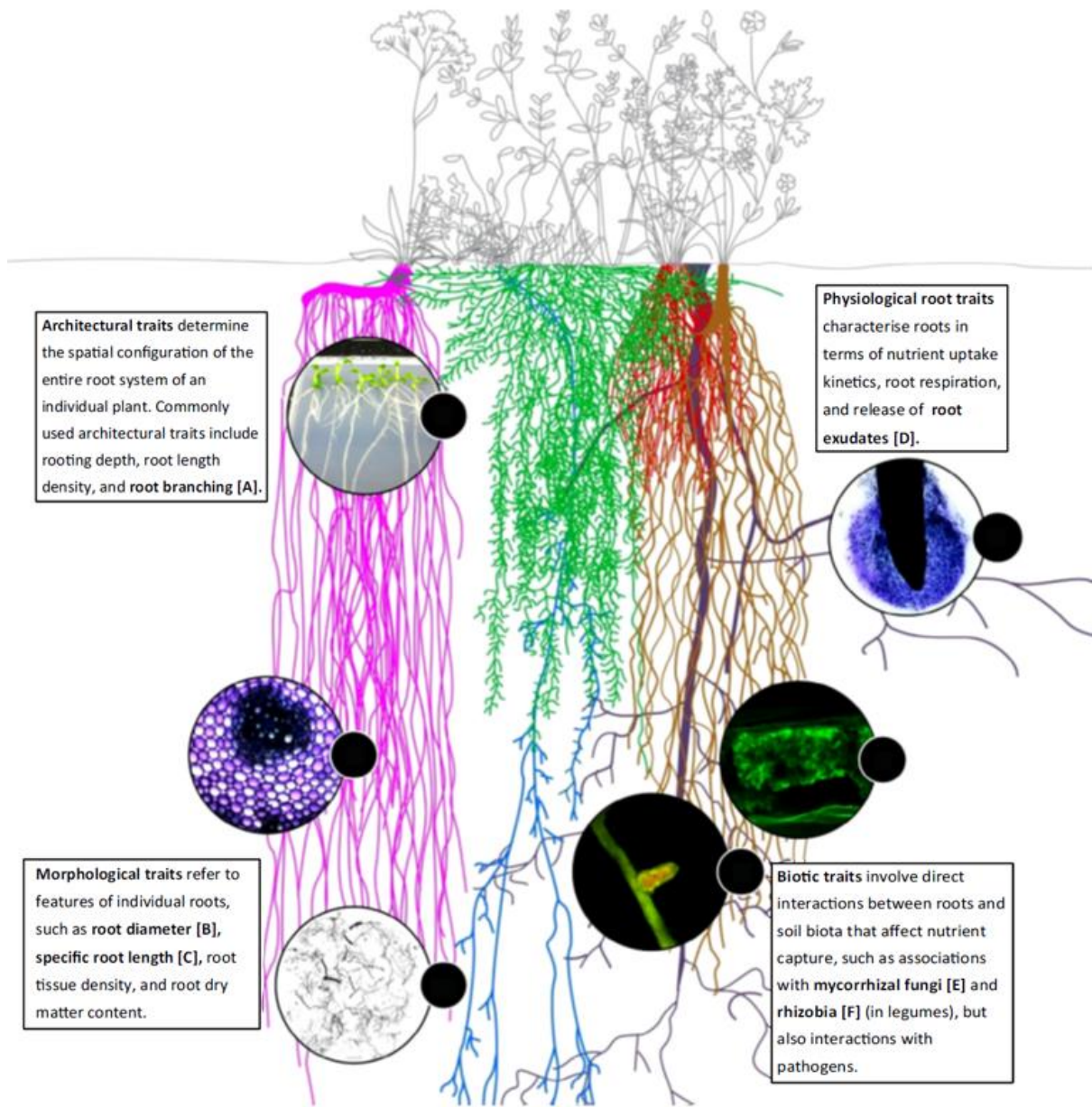


Figure 8: Categories of root traits that have the potential to impact ecosystem processes, including architectural, morphological, physiological, and biotic traits. (Bardgett et al., 2014)

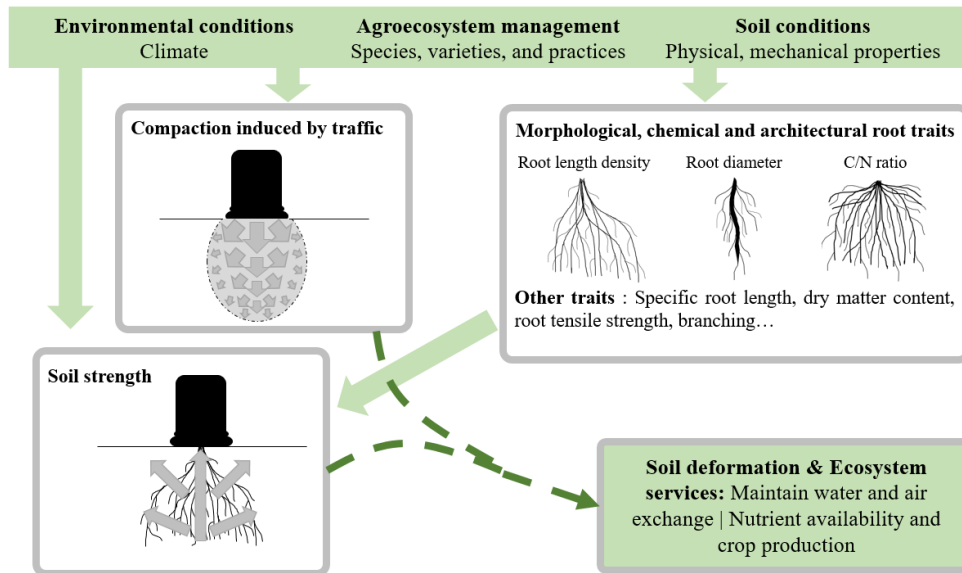


Figure 9: Relationships between root traits, environment properties, traffic induced compaction, soil strength and ecosystem services.

### 1.4.1. Putative root traits playing a role in soil strength

Very few studies investigated roots effect on soil compressive strength and only the root length density was observed to be positively related to the soil compressive strength (Kleinfelder et al., 1992). The functional approach was however extensively used to quantify the roots effects on soil shear strength (Stokes et al., 2009). Many root traits were highlighted for their role in soil shear strength such as the root tensile strength (the root's capacity to resist tension), the root area ratio (the proportion of a plane surface occupied by roots) (Operstein and Frydman 2000); the root density (the dry weight of roots per volume of soil) (Ali and Osman 2008; Tengbeh 1989); or the root length density (the length of roots per volume of soil) (Osman and Barakbah 2006). Effects of the root architecture or type (i.e. taproot or fibrous) have also been highlighted (Ghestem et al. 2014; Li et al. 2017). In most cases, root effect on soil shear strength is due to their effects on soil cohesion (Gyssels et al., 2005) while only scarce evidence of root effects on soil internal friction exist (Graf et al., 2009). However in our context, traits increasing soil friction, even hardly so, could be the most impactful due to the high normal force applied during compaction by traffic which will amplified 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.

# **PhD OBJECTIVES**

## 2. PhD OBJECTIVES

This PhD project aims to investigate the relationship between root functional traits and soil physical properties in agrosystems in order to evaluate the capacity of crop and cover crops roots to mitigate soil compaction during traffic. This thesis comprise three chapters corresponding to the three main objectives addressed (Figure 10)

**The first chapter investigates the effects of root traits on the consequences of compaction on soil physical properties.** The aims of this chapter were (1) to characterise the root capacity to conserve soil properties during traffic (2) to identify the roots traits involved in the process. Wide gradients of root traits were obtained by cultivating twelve cover crop species from contrasted phylogenetic families. Addressing these objectives would lead to an improved understanding of the relationship between root traits and soil properties conservation during traffic.

**The second chapter studies the influence of soil initial conditions, as modulated by soil tillage, on the responses and effects of roots involved in the mitigation of soil compaction.** The aim of this chapter was to identify the effects of two contrasted soil structures on root trait expression and its feedback on the root effects on soil properties conservation during traffic. The main hypothesis was that roots are able to play a role in the mitigation of soil compaction by conserving the soil physical properties after traffic, but that the initial soil mechanical properties resulting from different tillage techniques will modify both root traits expression and root traits effects (i.e. conservation of physical properties). The findings of this chapter could lead to an improved comprehension of the relationship between roots traits and soil properties before and after traffic.

**The third chapter focuses on the root effects on soil shear strength** measured in laboratory using a shear box. The aim of this chapter was to highlight root traits involved the soil shear strength. The main hypothesis was that cover crop roots can increase soil shear strength which could explain the role of roots in the conservation of soil properties during compaction identified in previous experimentation. This objective could help us gain a better understanding of one of the main process involved in the soil properties conservation by roots during traffic.

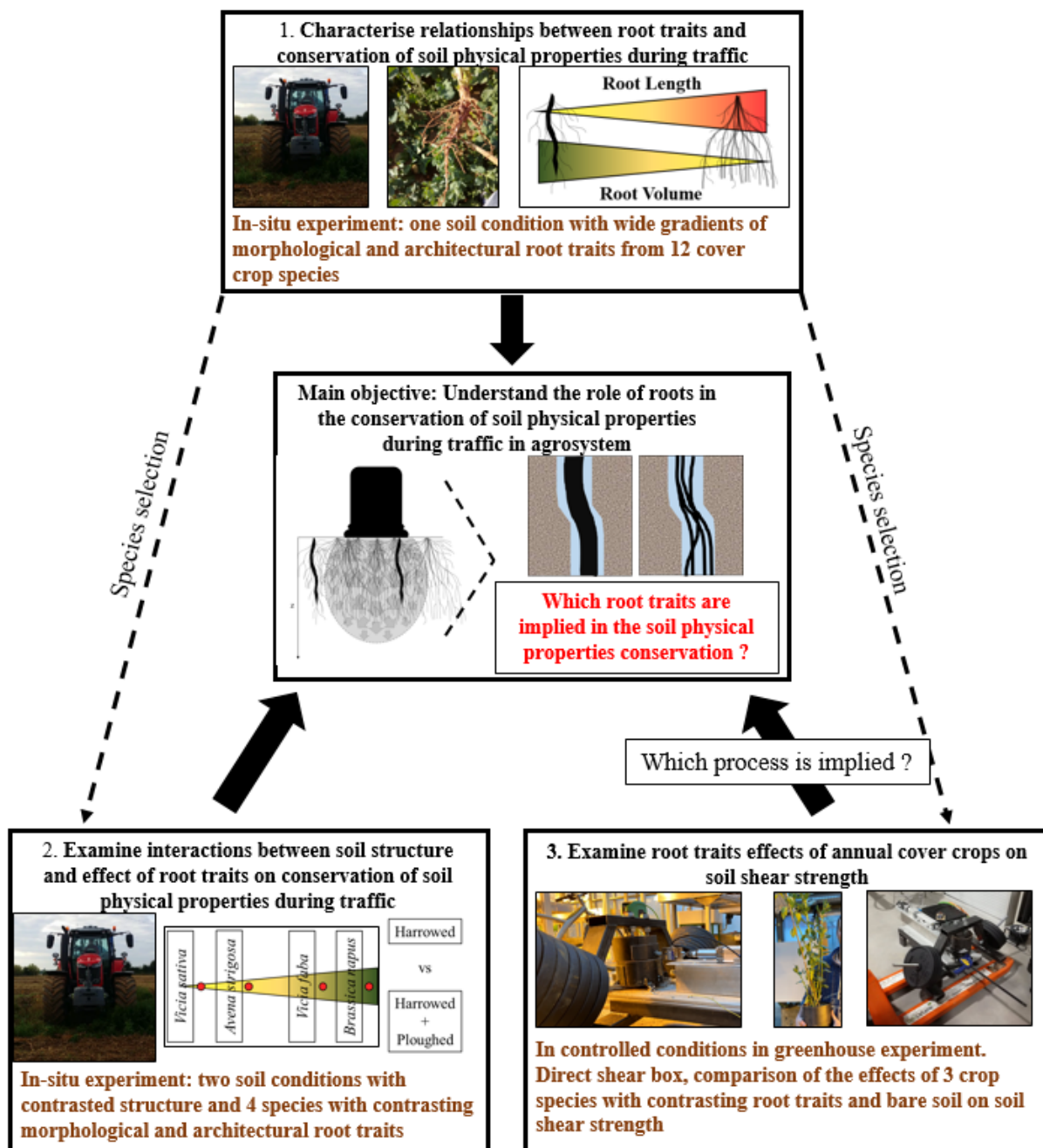


Figure 10: Objectives of the PhD research



# PhD METHODS



## **3. PhD METHODS**

This PhD aim to investigate the role of roots in the soil compaction mitigation during traffic. The main hypothesis was that roots are able to prevent soil compaction by conserving soil properties during traffic and it is due, at least partially, to an increase of soil shear strength. We examine this hypothesis by (1) comparing soil physical properties before and after a traffic event for different plant species with contrasted root traits (2) comparing soil strength for different soil-plant systems with similarly contrasted root traits. To explore the roles of roots, root traits were characterised on a wide gradients of species.

The soil properties selected were the bulk density and the air permeability as we expect that these properties will be negatively modified by compaction. The soil properties and root traits measurements provide key indicators of the root capacity to mitigate soil compaction and relate root traits to soil properties conservation during traffic with an in-situ experimentation. In another in-situ experimentation, we then investigated the relationship between root traits and soil properties conservation in two different soils to characterise the potential feedback effect of soil properties on root traits effect. Finally, the last experimentation in controlled conditions allowed us to explore and identify whether root effects on soil conservation during traffic could be due to a soil reinforcement by roots to shear. Direct measures of soil strength require specialised equipment adapted for samples containing a soil with a complete root system. The equipment was not available at the beginning of the PhD and thus a direct shear box was built during the PhD. The construction was based on previous shear box blueprint found on previous studies (Ali and Osman, 2008; Ghestem et al., 2014; Giadrossich et al., 2017).

### **3.1. Assessment of the in-situ soil consequences of soil compaction on soil physical properties**

Undisturbed soil cores of 100 cm<sup>3</sup> were used in-situ to measure soil properties. The soil cores were sampled across the wheeled part at 0 and 0.3m from the centre of the track. The soil cores were collected and transported to the laboratory for the measurements. Soil dry bulk density ( $\rho_b$ , Mg m<sup>-3</sup>) and soil water

content ( $\theta$ ,  $\text{m}^3 \text{m}^{-3}$ ) were determined using the gravimetric method and air permeability ( $k_a$ ,  $\mu\text{m}^2$ ) was determined using the method described by Iversen (2001) (Figure 10). Before the air permeability measurement, soil was pressed on the edge to limit air leakage between the soil and the cylinders' edges. On each field, the soil particle density was also estimated with the clay content and organic matter content using the equation described by Schjønning et al. (2017). Air filled porosity was then estimated ( $\epsilon_a$ ,  $\text{m}^3 \text{m}^{-3}$ ) using the soil particle density,  $\rho_b$  and  $\theta$ . Finally, specific air permeability ( $k_{as}$ ,  $\mu\text{m}^2$ ) was calculated by dividing  $k_a$  by  $\epsilon_a$ , as suggested by Groenevelt et al. (1984).

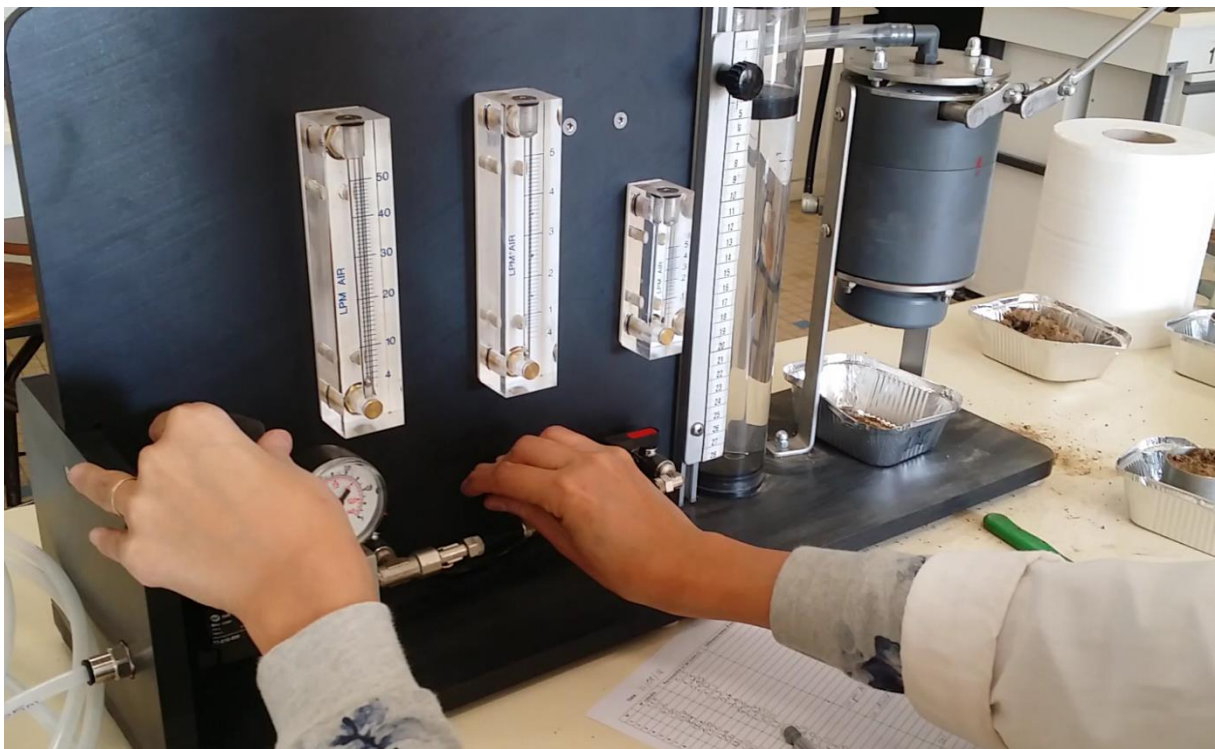


Figure 11 : Air permeator used to measure the air volumetric flow rate with an air pressure of 5hPa applied to the top of the core

### **3.2. Investigating soil shear strength and the potential effects of roots using a direct shear box**

The laboratory experiment focused on the root effects on soil shear strength. To do so, shear tests were performed using a direct shear box that was built during the thesis. The shear box was made of four part:

(1) the hydraulic actuator power by a rotary servo motor, (2) the electronic part which contain a servo drive that control the linear positioning system, a 150W single output switching power supply, an Ethernet switch that link the computer to the servo drive, a H3-C3 500kg Load cell and an Arduino to link the load cell to the computer; (3) the cylinder reception part to immobilize the bottom soil cylinder; (4) the weight part made to apply the weight on the soil. The shear box was firstly modelled in 3D using Tinkercad to define the dimensions of the steel parts used in the assembly (Figure 11).

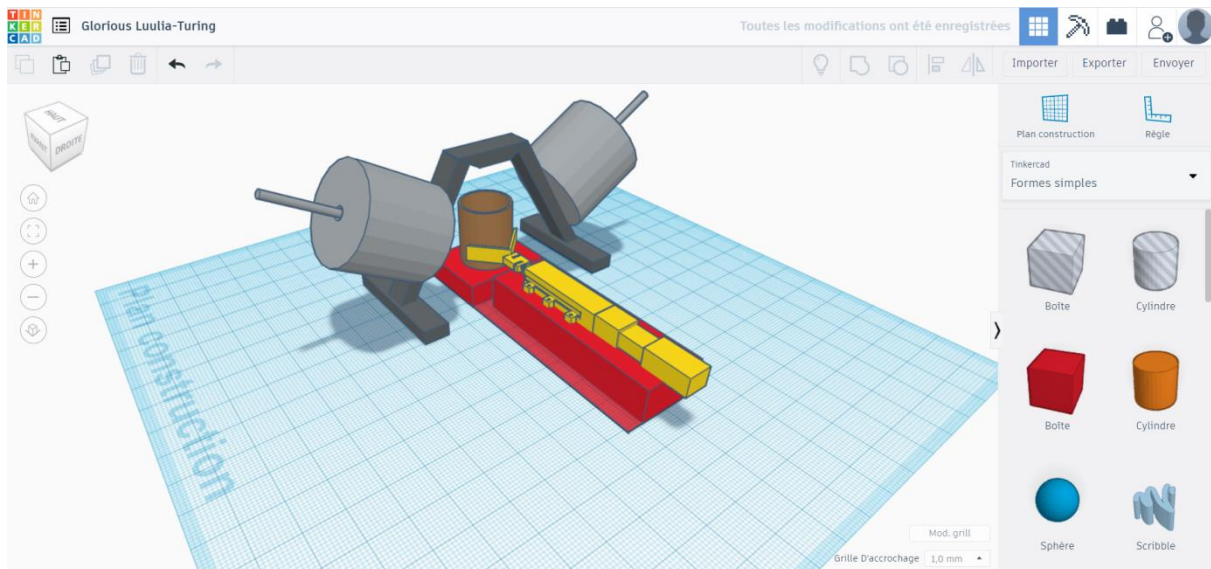


Figure 12 : 3D modelling of the shear box using Tinkercad. The yellow part is the actuator and the motor part. The red part is the structure which was adapted latter. The brown part are the cylinders used and the grey part is the system created to apply normal load on the soil.

The shear box construction follow two specific objectives (1) the cylinder sheared has to contain an entire and representative root morphology, (2) the normal stress applied should be fairly high as the normal stress induced by the machinery could exceed 400 kPa. The limit of the construction was that the normal stress has to be applied using dead weights. The cylinder selected should thus not be too small to not disturb the plant growth and also not too large to limit the dead weights used to reach a high normal stress. Finally, the dimension selected were a 0.16m diameter and 0.1m height. The highest normal stress reachable was 93kPa with nearly 200kg (Figure 12).

Shear tests consist in immobilizing the bottom cylinder and pushing the top cylinder using the actuator. Shear was applied at a constant rate of 3 mm.min<sup>-1</sup> until a horizontal displacement of 25 mm was achieved and the force required to shear was recorded using the load cell.



Figure 13 : The constructed shear box. The structure was adapted for the use of a forklift. The forklift was used to lift the dead weight between each test and bring the weight down before the test. The structure permit to manipulate the weight without lifting the whole shear box and also permit to bring down the weight on the soil without being support by the forklift

### 3.3. Species and root traits selection

The species used in the first experiment were selected based on four major criteria: (1) the species should be used as a cover crop in the pedoclimatic context of North-West Europe, (2) the species or the varieties used should be frost resistant as one experiment took place in winter, (3) the species should be easily destructible and should not create adventitious problem for the farmer, (4) the species selected should show wide gradients of root traits. Twelve species were selected for the first experiment among four botanical 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 usitatissimum* L.). Four species were then selected for the second experiment: *Avena strigosa*, *Brassica*

*napus*, *Vicia faba* and *Vicia sativa*, and three for the last experiment: *Avena strigosa*, *Brassica napus* and *Vicia faba*.

The root traits measured were selected amongst the highlighted root traits in previous studies that impact the effect of roots on soil strength: the root density (dry weight of roots per volume of soil) (Ali and Osman, 2008; Tengbeh, 1989), the root length density (length of roots per volume of soil) (Osman and Barakbah, 2006) or the specific root length (root length divide by root dry mass) (Stokes et al., 2009). We did not measure two of the main root traits highlighted in previous studies, the root tensile strength and the root area ratio. The measure of the root tensile strength indeed require a specific equipment which was not available in the laboratory. However, the measurement of the root tensile strength was substituted by the measurement of the average root diameter which is directly correlated to the root tensile strength (Baets et al., 2008; Bischetti et al., 2005; Gyssels et al., 2005; Operstein and Frydman, 2000; Wu et al., 1979). The root area ratio, which is the surface proportion of a plane occupied by roots was not measured due to the context specificity as the deformation will not occur on a single plane as in the landslide context but in the whole soil profile. The root area ratio of a plane is thus not relevant in this context. This root trait were thus replaced by the root volume ratio which is the root volume per unit area volume. The C/N ratio was also measured to examine the effects of the chemical composition of the root.

### **3.4. Root traits measurement**

Root trait measurements were performed following the method described by Ristova and Barbez (2018). All roots pot were weighed and scanned while submerged in water using the Epson Perfection V850 Pro at a resolution of 600 dpi (Figure 13). The software WinRhizo 2016 (Regent Instrument Inc., Instruments, Québec, Canada) was used to quantify the root length, root average diameter and root volume. Roots were then dried at 105°C during 24h and weight. Carbon and nitrogen concentrations were determined on ground material using an elemental analyser (AFNOR, 2013, 2012).



*Figure 14 : Scans of Brassica napus roots grow in pots. The whole roots has to be divide in smaller parts to not overload the tray and loose analyse accuracy. The taproot was not include in the scan analysis*



# CHAPTER 1



# 4. THE RELATIONSHIP BETWEEN ROOT TRAITS AND SOIL PHYSICAL PROPERTIES CONSERVATION DURING TRAFFIC

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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

## 4.1. Introduction

Soil compaction is known as one of the three major threats to soil quality in Europe (Stolte et al., 2015, Berge et al. 2017). It occurs when mechanical resistance (soil strength) is lower than the force transmitted onto it (soil stress) (Soane et al., 1980). 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 (Nawaz et al., 2013; Schjønning et al., 2016; Soane et al., 1980).

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 (Keller et al., 2019). Technological solutions, such as tyre innovation, cannot cope alone with this increase (Schjønning et al., 2015). 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 (Büchi et al., 2018). 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 (Ghestem et al. 2014), water erosion (Gyssels et al., 2005), and increase streambank stability (Pollen, 2007). Other effects could be involved in reducing soil compaction during traffic. These include strengthening the soil through the uptake of water by the plants (Fredlund, 2006); roots increasing soil strength to compression, which was demonstrated on streambank soil (Kleinfelder, 1992); the effect of plant–soil microorganisms on soil aggregation (Rillig et al., 2002). The functional trait approach characterises the morphological, architectural, physiological and chemical root trait responses to soil properties and functions (Faucon et al., 2017). Traditionally used in semi-natural ecosystems, the functional trait approach may apply to address key issues in agrosystems (Damour et al, 2018), 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 (Keller and Lamandé, 2010) ; (3) the compressive stresses beneath the tyres or tracks are much greater than the overburden stress (Lamandé and Schjønning, 2011) ; (4) the shallow shearing (<30 cm in depth) (Berisso et al., 2013) of often unsaturated soils where the roots of annual species are most dense (Ali and Osman, 2008); (5) the

distribution of principal stresses beneath a tyre is uneven and changes during loading (De Pue et al, 2020).

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.

## **4.2. 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 . 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<sub>3</sub> with a pH of 7.1. The soil particle density was calculated using the clay and organic matter content (Schjønning et al., 2017). The soil particle density was 2.54 g.cm<sup>-3</sup>. 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 15; Appendix 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 ( $1.24 \pm 0.046$  g.cm<sup>-3</sup>) after a shallow tillage ( $\leq 5$  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<sup>-1</sup>. 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 15). 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.

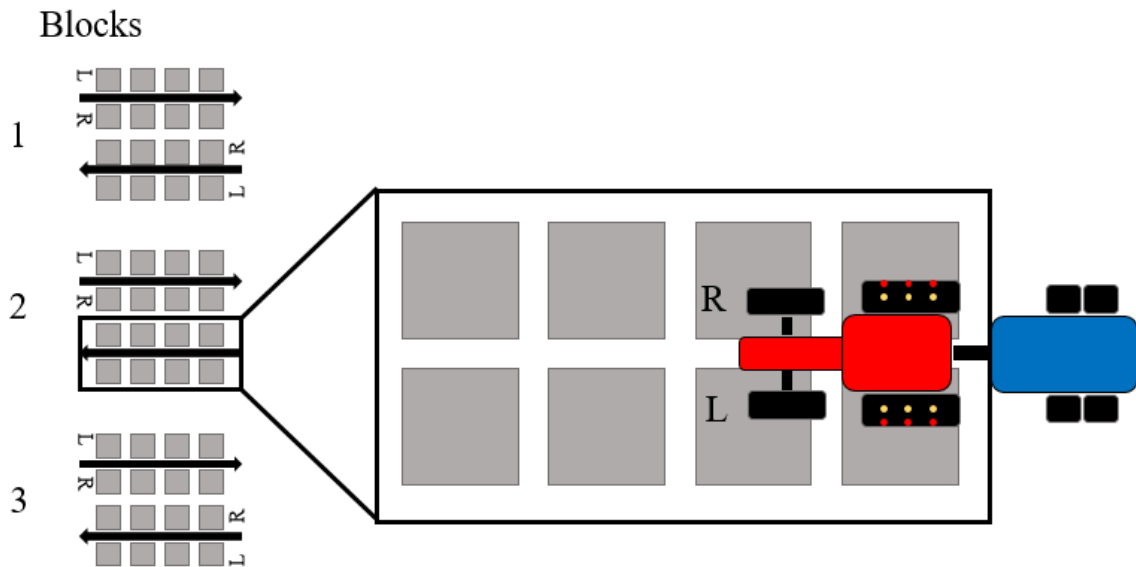


Figure 15: The experiment design included three blocks of 16 square plots with a side length of 2.5 m; four plots of bare soil; one plot per species for the twelve selected species. Each plot was driven over by four wheels of the right side of the combination (R) or the left side (L). The yellow dots 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.

#### 4.2.1. 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 usitatissimum* L.). The objective was to create gradients of architectural, morphological and chemical root traits.

#### 4.2.1.1. *Root traits characterisation*

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 (2018). Soil cylinders of  $2 \times 10^{-3} \text{ m}^3$  (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. 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 (AFNOR 2012, AFNOR 2013).

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

Root traits studied	Abbreviation	Unit	Formula
Root Length Density	RLD	$\text{m} \cdot \text{m}^{-3}$	RLD = root length/soil volume
Root Mass Density	RMD	$\text{g} \cdot \text{m}^{-3}$	RD = root dry mass/soil volume

Specific Root Length	SRL	m.g <sup>-1</sup>	SRL = root length/root dry mass
C/N	C/N	g.g <sup>-1</sup>	C/N = g of carbon/g of nitrogen
Dry Matter Content	DMC	g.g <sup>-1</sup>	DMC = root dry mass/root fresh mass

#### 4.2.2. Characterisation of soil physical properties

As the stress induced could be heterogeneous in type and in range under the tyre (Berisso et al, 2013), 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<sup>3</sup> 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 15). Air permeability ( $k_a$ ,  $\mu\text{m}^2$ ) was measured for each soil core using the method described by Iversen et al. (2001) with a pressure gradient of 5 hPa. Bulk density ( $\rho_b$ ,  $\text{g.cm}^{-3}$ ) and soil water content ( $\theta$ ,  $\text{g.g}^{-1}$ ) were then calculated using the gravimetric method. Air filled porosity ( $\varepsilon_a$ ,  $\text{m}^3.\text{m}^{-3}$ ) was then calculated as follows:

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

where  $W_s$  is the dry weight of the soil (g),  $\rho_s$  is the soil particle density ( $\text{g.cm}^{-3}$ ),  $W_w$  is the weight of the soil water (g), and  $\rho_w$  is the water density ( $\text{g.cm}^{-3}$ ). Finally, specific air permeability ( $k_{as}$ ,  $\mu\text{m}^2$ ) was calculated by dividing  $k_a$  by  $\varepsilon_a$ , as suggested by Groenevelt et al. (1984), which provided an indicator of air-filled pore continuity.

### 4.2.3. 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  $p_b$ . 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 (Burnham et al., 2002).

## 4.3. Results

### 4.3.1. 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.  $k_{as}$  = specific permeability,  $p_b$  = soil bulk density,  $\theta$  = soil water content

	$p_b$ (g.cm <sup>-3</sup> )	$\theta$ (g.g <sup>-1</sup> )	$k_{as}$ (μm <sup>2</sup> )
Bare soil	1.38 ± 0.02 <sup>a</sup>	0.18 ± 0.02 <sup>d</sup>	83.24 ± 12.66 <sup>a</sup>
<i>Avena strigosa</i>	1.3 ± 0.06 <sup>a</sup>	0.13 ± 0.03 <sup>bd</sup>	99.3 ± 60.61 <sup>a</sup>
<i>Brassica juncea</i>	1.32 ± 0.06 <sup>a</sup>	0.08 ± 0.01 <sup>ab</sup>	80.44 ± 13.26 <sup>a</sup>

<i>Brassica napus</i>	1.32 ± 0.05 <sup>a</sup>	0.08 ± 0.01 <sup>ab</sup>	106.51 ± 26.43 <sup>a</sup>
<i>Brassica rapa</i>	1.37 ± 0.1 <sup>a</sup>	0.1 ± 0.02 <sup>ab</sup>	68.14 ± 16.34 <sup>a</sup>
<i>Lathyrus sativus</i>	1.37 ± 0.07 <sup>a</sup>	0.16 ± 0.01 <sup>cd</sup>	72.22 ± 3.18 <sup>a</sup>
<i>Linum usitatissimum</i>	1.34 ± 0.01 <sup>a</sup>	0.1 ± 0.02 <sup>ab</sup>	99.19 ± 19.54 <sup>a</sup>
<i>Melilotus officinalis</i>	1.36 ± 0.02 <sup>a</sup>	0.07 ± 0 <sup>a</sup>	116.55 ± 53.98 <sup>a</sup>
<i>Pisum sativum</i>	1.37 ± 0.04 <sup>a</sup>	0.13 ± 0.03 <sup>bc</sup>	104.62 ± 51.04 <sup>a</sup>
<i>Raphanus sativus</i>	1.37 ± 0.05 <sup>a</sup>	0.1 ± 0.01 <sup>ab</sup>	91.26 ± 46.2 <sup>a</sup>
<i>Secale cereale</i>	1.37 ± 0.07 <sup>a</sup>	0.1 ± 0.02 <sup>ab</sup>	85.37 ± 52.32 <sup>a</sup>
<i>Trifolium incarnatum</i>	1.34 ± 0.02 <sup>a</sup>	0.08 ± 0.01 <sup>ab</sup>	94.18 ± 49.98 <sup>a</sup>
<i>Vicia faba</i>	1.36 ± 0.09 <sup>a</sup>	0.12 ± 0.02 <sup>bc</sup>	72.31 ± 37.32 <sup>a</sup>

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.

### 4.3.2. Root traits gradients and comparison among species

RLD values varied between 163.15 m.m<sup>-3</sup> for *Lathyrus sativus* and 776.56 m.m<sup>-3</sup> for *Linum usitatissimum*.

RMD values varied between 8.4 g.m<sup>-3</sup> for *Lathyrus sativus* and 580 g.m<sup>-3</sup> for *Melilotus officinalis*.

SRL values varied between 204 cm.g<sup>-1</sup> for *Raphanus sativus* and 2890 cm.g<sup>-1</sup> for *Lathyrus sativus*.

DMC values varied between 15.7 g.g<sup>-1</sup> for *Pisum sativum* and 33.8 g.g<sup>-1</sup> for *Linum usitatissimum* (Table 3).

Table 2 : Root traits-value per species CN = Ratio Carbon/Nitrogen, DMC = Dry Matter Content, SRL = Specific Root Length, RD = Root Density, RLD = Root Length Density

	RLD (m.m <sup>-3</sup> )**	RMD (g.m <sup>-3</sup> )*	SRL (m.g <sup>-1</sup> ***)	CN (g.g <sup>-1</sup> )	DMC (g.g <sup>-1</sup> ***)
<i>Avena strigosa</i>	454,9 ± 75,8 <sup>cd</sup>	127,65 ± 17,7 <sup>cd</sup>	3,91 ± 1,3 <sup>ab</sup>	57,16	0,31 ± 0,03 <sup>de</sup>
<i>Brassica juncea</i>	540,56 ± 66,4 <sup>bc</sup>	70,11 ± 10,2 <sup>bcd</sup>	7,77 ± 0,2 <sup>ad</sup>	45,99	0,31 ± 0,03 <sup>de</sup>
<i>Brassica napus</i>	643,9 ± 67,1 <sup>bc</sup>	79,4 ± 10,1 <sup>bcd</sup>	8,46 ± 1,7 <sup>ad</sup>	30,59	0,19 ± 0,01 <sup>ac</sup>
<i>Brassica rapa</i>	432,01 ± 69,4 <sup>cd</sup>	250,82 ± 85,6 <sup>cd</sup>	2,08 ± 0,5 <sup>a</sup>	19,84	0,2 ± 0,02 <sup>acd</sup>
<i>Lathyrus sativus</i>	163,15 ± 57,3 <sup>a</sup>	8,41 ± 3,7 <sup>a</sup>	28,9 ± 10,7 <sup>d</sup>	21,16	0,17 ± 0,02 <sup>ab</sup>
<i>Linum usitatissimum</i>	776,57 ± 80,6 <sup>ad</sup>	44,4 ± 3,7 <sup>ad</sup>	17,46 ± 0,3 <sup>bcd</sup>	39,89	0,34 ± 0,03 <sup>e</sup>



<i>Melilotus officinalis</i>	714,14 ± 173,7 <sup>d</sup>	580,86 ± 338,4 <sup>d</sup>	3,03 ± 1,95 <sup>a</sup>	23,43	0,32 ± 0,01 <sup>de</sup>
<i>Pisum sativum</i>	302,82 ± 55,6 <sup>ab</sup>	14,85 ± 0,6 <sup>ab</sup>	20,18 ± 2,9 <sup>cd</sup>	20,01	0,16 ± 0,02 <sup>a</sup>
<i>Raphanus sativus</i>	438,53 ± 162,8 <sup>c</sup>	209,21 ± 51,7 <sup>cd</sup>	2,04 ± 0,6 <sup>a</sup>	47,17	0,18 ± 0,01 <sup>ac</sup>
<i>Secale cereale</i>	407,86 ± 79,6 <sup>cd</sup>	183,49 ± 64,5 <sup>cd</sup>	2,46 ± 0,4 <sup>a</sup>	22,83	0,29 ± 0,01 <sup>ce</sup>
<i>Trifolium incarnatum</i>	456,96 ± 41 <sup>ac</sup>	32,9 ± 2,8 <sup>ac</sup>	14,23 ± 2,1 <sup>bcd</sup>	29,55	0,25 ± 0,01 <sup>ad</sup>
<i>Vicia faba</i>	289,15 ± 31 <sup>bcd</sup>	57,92 ± 10,7 <sup>bcd</sup>	5,6 ± 1,8 <sup>ac</sup>	20,56	0,28 ± 0,04 <sup>bc</sup>

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.

### 4.3.3. Relationships between root traits and soil properties

Root trait correlations with soil properties were reported in Table 4. Notably,  $\theta$  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. kas was only positively correlated with RLD ( $r = 0.61$ ,  $* p < 0.05$ ) and pb was only negatively correlated with C/N ( $r = -0.70$ ,  $* p < 0.05$ ) (Figure 16). 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 ( $r = -0.94$ ,  $*** p < 0.001$ ).

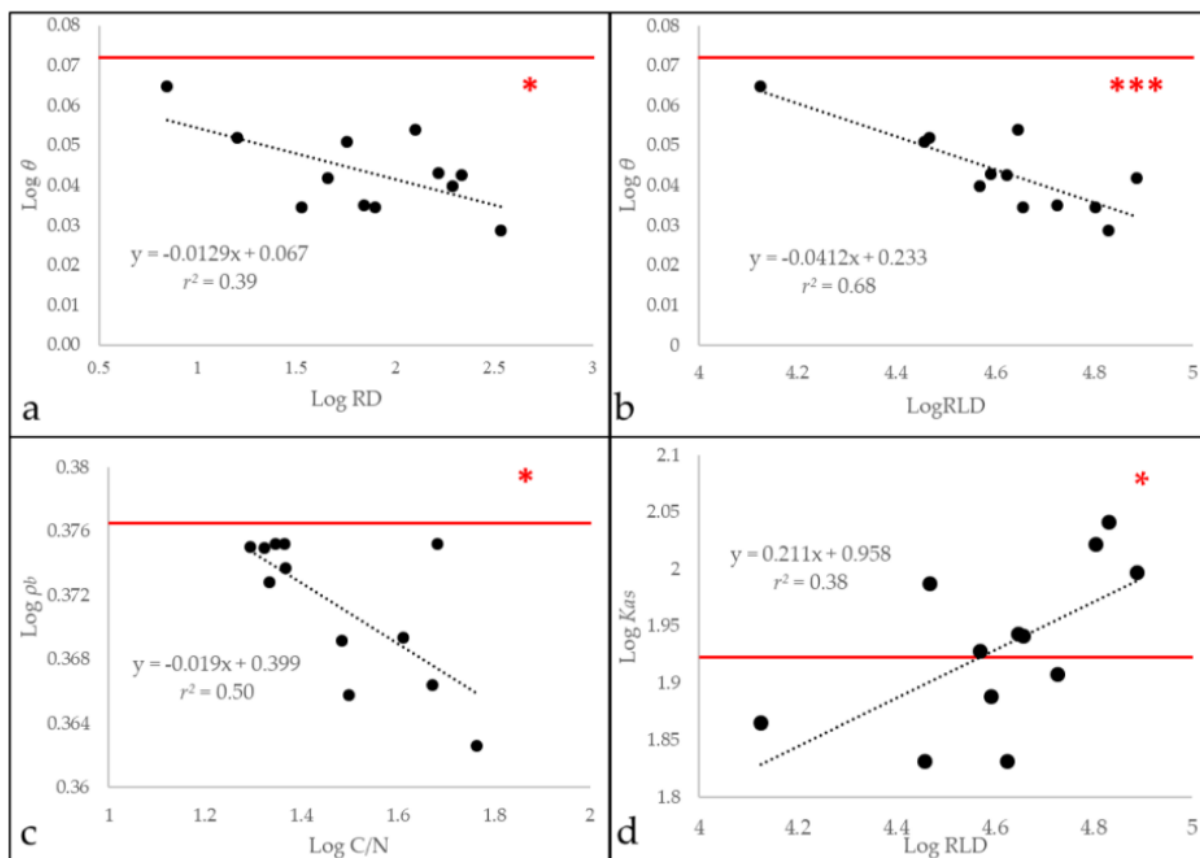


Figure 16 : Relationships between root traits and soil properties. For each graph, the red line represents the mean value obtained in bare soil. Red stars represent the significance of each Pearson correlation with  $p$ -value  $> 0.05 = NS$ ,  $p$ -value  $< 0.05 = *$ , and  $p$ -value  $< 0.001 = ***$ .  $\rho_b$  = soil bulk density,  $C/N$  = Carbon/Nitrogen ratio,  $k_{as}$  = specific air permeability,  $RMD$  = Root Mass Density,  $RLD$  = Root Length Density,  $\theta$  = soil water content

The comparison between GLM's AiCc for  $\rho_b$  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  $\rho_b$ . None of the trait combinations between RMD, RLD and C/N were better.

Table 3 : Pearson correlation matrix of soil physical properties and root traits. All traits and soil properties were log-transformed. Multiplier factors were shown using the significance of each correlation with  $p$ -value  $> 0.05 = NS$ ,  $p$ -value  $< 0.05 = *$ ,  $p$ -value  $< 0.01 = **$  and  $p$ -value  $< 0.001 = ***$ .  $\rho_b$  = Bulk Density,  $C/N$  = Ratio Carbon/Nitrogen,  $DMC$  = Dry Matter Content,  $k_{as}$  = Specific Air Permeability,  $SRL$  = Specific Root Length,  $RD$  = Root Density,  $RLD$  = Root Length Density,  $\theta$  = Soil Water Content.

	$\rho_b$	$\theta$	$k_{as}$	RMD	RLD	SRL	C/N
$\theta$	0.19						
$K_{as}$	-0.32	-0.49					
RMD	-0.05	-0.62*	0.11				

<i>RLD</i>	-0.49	-0.82***	0.61*	0.61*			
<i>SRL</i>	-0.15	0.38	0.15	-0.94***	-0.29		
<i>C/N</i>	-0.70*	-0.17	0.27	0.19	0.40	-0.06	
<i>DMC</i>	-0.44	-0.34	0.14	0.40	0.58*	-0.22	0.36

Table 4 : Selected models tested for bulk density predictors arranged from the smallest AICc to the highest.  $\rho_b$  = Bulk Density, CN = Carbon/Nitrogen, RD = Root Density, RLD = Root Length Density

	Models	AICc
	CN	-96.0
	CN + RLD	-92.5
$\rho_b \sim$	CN + RD	-91.4
	CN * RD	-88.3
	CN * RLD	-87.6

#### 4.4. 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 (Osman and Barakbah, 2006), which could reduce soil deformation during traffic and maintain the soil's ability to transport air. In addition, the negative relationship between RLD and  $\theta$  suggests an indirect increase in the soil's shear strength through water uptake, which increases the soil's

matric suction (Roumet et al., 2016). 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  $p_b$  than the root trait combinations (Table 5). Root density traits measured seem thus to not affect  $p_b$  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 (Roumet et al., 2016). 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.

## 4.5. 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.

## Acknowledgments

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# CHAPTER 2

# 5. TILLAGE CONDITIONS DRIVES CONTRASTING CROP SPECIES EFFECTS ON SOIL PROPERTIES CONSERVATION DURING TRAFFIC

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## 5.1. Introduction

Traffic induced soil compaction is a well-known problem since decades (Batey, 2009; Nawaz et al., 2013; Raper, 2005). Causes and consequences on soil properties and productivity have been largely reported in previous studies (e.g. Soane et al., 1980; Nawaz et al., 2013; Schjønning et al., 2016). Soil compaction derived from two processes: compression and shearing. Compression refers to a decrease of soil pore volume, while pure shearing refers to a modification of the shape of soil pore system affecting pore continuity. In the context of traffic induced soil compaction, compression is the vertical deformation due to vertical stresses beneath tyres and tracks, and shearing is the deformation due to shear stresses beneath tyres and tracks. Compression and shearing are unevenly distributed on the tyre or track contact with the soil. Berisso et al. (2013) reported an increasing shearing from the centre to the edge beneath a towed flexible tyre, while compression was decreasing from the centre to the edge beneath the same tyre. When traction is applied to the tyre, distribution of compression and shearing might change (De Pue et al., 2020), but no experimental evidences are reported so far for flexible tyres on soft materials.

Present solutions to reduce soil compaction mainly focus on agricultural techniques as in the case of controlled traffic (Bluett et al., 2019), agricultural equipment innovations such as new tyres' (ten Damme et al., 2019), or on the execution of agricultural interventions only during workable days (Obour et al., 2017). Traffic induced compaction mitigation is still a contemporary challenge since the existing solutions sometimes can't be implemented or might not be enough because of the constant increase of

the machinery weight (Keller et al., 2019). New solutions including plants, as a main part of an agricultural system, should be considered as a potential contributor to soil compaction mitigation.

Existing studies highlighted the effects of roots on the alleviation of compaction (e.g. Chen, 2009; Williams and Weil, 2004). , but the roots effects on soil deformation during traffic is still poorly known. Some studies showed that roots were able to increase soil shear strength in other contexts as landslide (Schmidt et al., 2001; Schwarz et al., 2010; Wu et al., 1979) or riverbank stability (Adhikari et al., 2013; Pollen-Bankhead and Simon, 2010; Thorne, 1990). Fundamental differences in soil properties, root traits, and the rates and ranges of deformation exist between the contexts of landslide prevention or riverbank stability and traffic-induced compaction of agricultural soils. However, these studies highlighted the potential role of roots in the mitigation of soil deformation.

The relationship between a better maintain of the pore continuity during compaction and specific root traits on an agricultural soil was emphasized on a previous experiment (Chapter 1). A larger root length density (root length per soil volume) was related to a better maintain of pore continuity directly after traffic. The roots ability to maintain soil properties during traffic can be related to the roots ability to increase the soil mechanical resistance to deformation (i.e. soil strength). However, the soil mechanical strength is known as playing a role in the root growth and will thus modify trait responses (Faucon et al., 2017; Nawaz et al., 2013; Sinnott et al., 2008) by affecting root penetration and thus morphological and architectural root traits.

The aim of this study was to investigate the roots ability to maintain soil-root system physical properties and the potential feedback of the soil initial conditions on the root traits expression and effects. The main hypothesis was that roots are able to play a role in the mitigation of soil compaction by conserving the soil-root system physical properties after traffic, but that the different initial soil conditions resulting from tillage techniques will modify both root traits expression and root traits effects (i.e. conservation of physical properties). Specific objectives are to examine the effects of crop species and soil initial conditions on the expression of root traits and on the physical properties of the soil-root system before traffic, and to compare the root-soil system physical properties before and after a traffic event

considering the impact of crop species, initial soil conditions and location under the tyre (i.e. centre and edge).

## 5.2. Materials and methods

### 5.2.1. Experimental design and plant materials

The experiment took place in a farm belonging to the Institute Polytechnic UniLaSalle in Beauvais (France, 49°27'54.39"N, 2°4'21.36"E). The experiment lasted seven months and took place between August 2018 and February 2019. The total rainfall recorded was 308.4mm during this period. The temperature and the rainfall per month are reported in Figure 17. The soil, defined as Luvisol (IUSS Working Group WRB, 2015), was characterised by 20.5% clay, 69.4% silt, 10.1% sand and 1.8% organic matter content. The soil particle density was calculated using the clay and the organic matter content (Schjønning et al., 2017). The soil particle density was 2.54 Mg.m<sup>-3</sup>.

Four species and two tillage treatments were considered on the experimentation. Tillage treatments were "harrowed" and "ploughed+harrowed". The harrowed treatment was tilled at less than 0.1m depth and the ploughed+harrowed treatment was tilled at 0.3 m depth. The two tillage treatments were chosen with the objective of having different soil strength as a result of tillage. Each tillage treatment included 3 plots of 60 m<sup>2</sup> (3 m by 20 m) per species, for a total of 24 plots. The four species selected were: *Avena strigosa* Schreb., *Brassica napus* L., *Vicia faba* L. and *Vicia sativa* L.. The sowing density were respectively: 35 kg.ha<sup>-1</sup>, 8 kg.ha<sup>-1</sup>, 100 kg.ha<sup>-1</sup> and 40 kg.ha<sup>-1</sup>. For both treatments, the harrow was used to prepare the seedbed.

Traffic stress was applied to the soil on each plot by driving a tractor-trailer combination for slurry application over the field at a constant speed of 1.1 m.s<sup>-1</sup>. The traffic event was organised perpendicular to the sowing direction (Figure 18). The front wheels of the tractor were AXIOBIB IF600/70 A30 159D and the rear wheels were AXIOBIB IF710/70 A42 179D. The trailer wheels were XBIB IF600/55 R26.5. The wheel load of the tractor's front wheel was 2.86 Mg and the rear wheel was 3.8 Mg. The wheel load of the front and rear trailer wheel was respectively 4.7 Mg and 4.9 Mg. Tyre inflation of the tractor front

wheels was 110 kPa and 90 kPa for the rear wheels. Tyre inflation of the trailer wheels was 340 kPa. The maximum wheel slip registered by the tractor was 5% wheel slip on the LR condition and 10% on the HR condition.

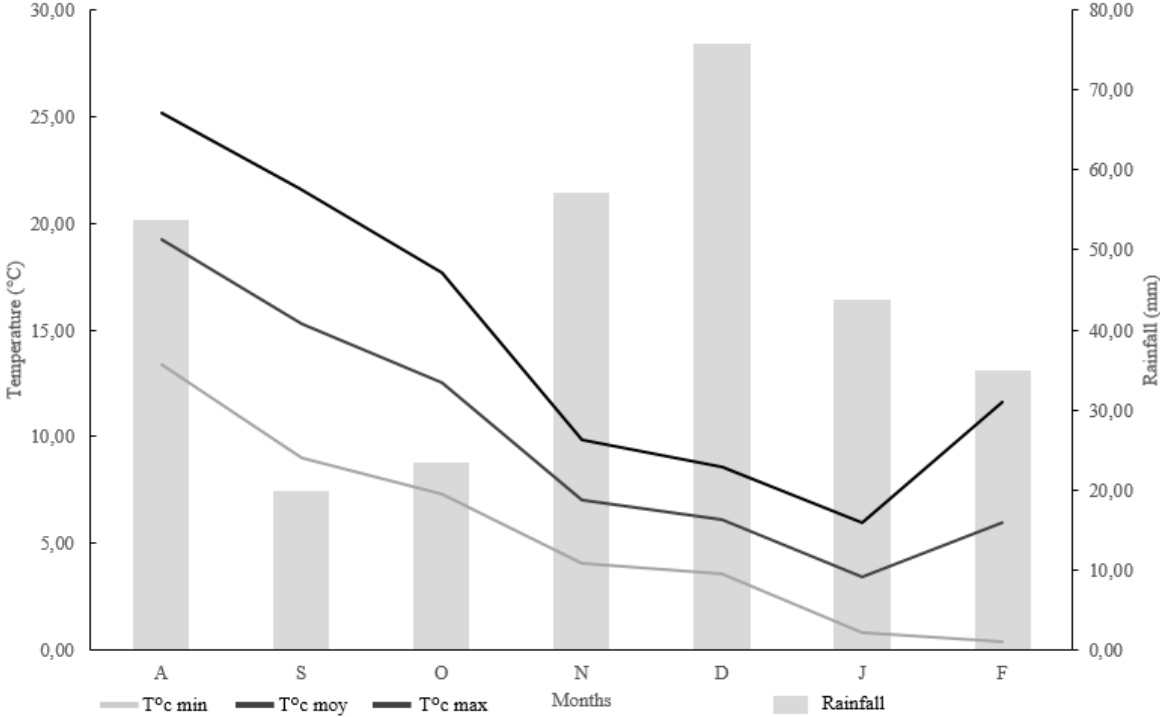


Figure 17 : Climatic conditions between August 2018 and February 2019. The line represents the lowest, the mean and the highest temperature of the month. Columns represent the rainfall during the experiment over the months.

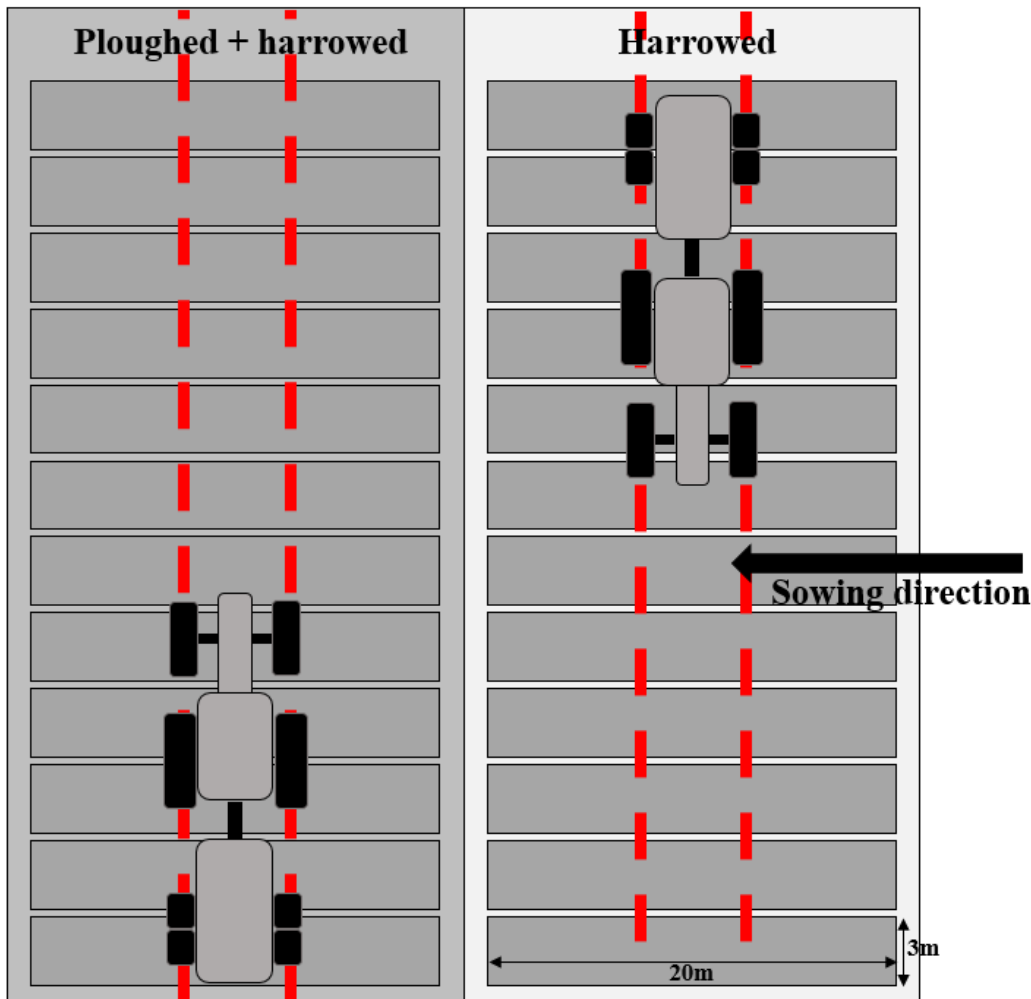


Figure 18 : The experiment design included the ploughed+harrowed part and the only harrowed part with 12 plots on each. The plots dimensions were 3m by 20m. Each plot was randomly sowed with the 4 selected species. Each plot contain two tracks driven over by four wheels perpendicular to the sowing direction.

## 5.2.2. Root trait characterisation

Two days before compaction, roots of two plants were collected on each plot. To do so, two plants were selected as representative of the plot (average size) and not in the middle of the plot to avoid future wheel paths. A cube of 0.005 m<sup>3</sup> of soil was then extract around the plant. The size width was determined as the width of the spade (0.15m) and depth was the length of the spade (0.21m). Roots were then manually separated from the soil. 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 of the fibrous system. Fresh roots were weighed and then dried at 105°C for 24 h and then weighed again. Two root traits were then measured on the fibrous system: the average root diameter (ARD, mm) and the root length density (RLD, cm.cm<sup>-3</sup>), which is the root length divided by the soil volume. Four others root traits were measured on the whole root system; the root volume density (RVD, cm<sup>3</sup>.cm<sup>-3</sup>), which is the roots' volume divided by the soil volume, the root density (RD, g.m<sup>-3</sup>), which is the roots' dry weight divided by the soil volume; the specific root length (SRL, m.g<sup>-1</sup>), 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. The taproot volume (TRV) was determined separately using the ImageJ freeware (Schneider et al. 2012). TRV was calculated using the sum of homogeneous volume sections in terms of diameter. Each volume section was determined by its length and mean diameter. Total root volume used to measure RVD was the sum of the TRV and the volume measure on the fibrous system. Trait measurements were performed following the method described by Ristova and Barbez (2018).

### **5.2.3. Soil precompression stress measurements**

The mechanical soil resistance to compression for each tillage treatment was represented by the soil precompression stress (kPa) determined from uniaxial confined compression (UCC) tests. Six undisturbed 100 cm<sup>3</sup> soil cores (0.056 m inner diameter, 0.041 m height) were collected per tillage treatment at the field-sampled water content equivalent to field capacity. UCC tests with strain-controlled stress application (Koolen, 1974) were done using a triaxial machine TRI-SCAN 50 (Vj technology, Berkshire, UK) in which soil samples were directly placed under a customized piston (diameter 0.054 m) connected to a 5 kN load cell and by applying a constant piston speed of 1 mm min<sup>-1</sup>. Soil displacement (mm) over load (N) was recorded with a frequency of 1 s until water was expelled from the sample, corresponding to an applied stress between 530 kN and 1200 kN and at least 300 load-displacement measured points. Stress-strain data was then determined for each UCC test after making data 5 N equidistant on load scale. Soil precompression stress (kPa) was derived for each data set using the numerical method proposed by (Lamandé et al., 2017).

#### **5.2.4. Soil physical properties**

At each plot, undisturbed 100 cm<sup>3</sup> soil cores (inner diameter 0.05m, height 0.051m) were sampled at ~0.1 m depth (measured from the top of the cylinder). Three cores per plot containing soil and roots (soil-root system) were sampled two days before the traffic event and used as a t<sub>0</sub>. After the traffic event, three soil-roots cores per plot were sampled at two different locations on the track: at the centre and at 0.3 m from the centre. Air permeability ( $k_a$ ,  $\mu\text{m}^2$ ) was measured for each soil core using the method described by Iversen et al. (2001) with a pressure gradient of 5 hPa. Bulk density ( $\rho_b$ ,  $\text{Mg m}^{-3}$ ) and soil water content ( $\theta$ ,  $\text{m}^3 \text{m}^{-3}$ ) were then estimated using the gravimetric method.

Each property were then defined using the mean of the three cylinder sampled for each plot at t<sub>0</sub> and after the traffic event for the two locations.

#### **5.2.5. Statistics**

A Pairwise Wilcoxon test was used to compare the soil mechanical resistance between the two tillage conditions.

Linear models using generalized least squares (GLS) were used to determine the effects of species, tillage conditions and their interactions on root traits and soil properties before the traffic event (t<sub>0</sub>). A pairwise Wilcoxon test was used to discriminate root traits between each species except for RLD. GLS was used to determine RLD differences between HR and LR.

GLS models were used to determine the effects of species, tillage conditions and the effects of the initial value on soil properties after traffic under the tyres' centre and at 0.3m from the tyres' centre. GLS were then used to determine differences on soil properties between t<sub>0</sub> and t<sub>1</sub> for the two locations for each species.



## 5.3. Results

### 5.3.1. Soil strength between tillage treatments

Differences in soil strength between tillage treatments were verified by comparing soil precompression stress values. The precompression stress of the two soils were significantly different (Chi square = 4.05, p-value = 0.044, df = 1) with a mean of 85 kPa for the ploughed soil and 140 kPa for the other section. Thus, each tillage treatment is denoted following its resistance to compression: the ploughed+harrowed treatment become the Lower Resistance treatment (LR) and the harrowed treatment is the Higher Resistance treatment (HR).

### 5.3.2. Root traits comparison among crop species and soil initial conditions before traffic

Table 6 presents the effects of crop species and soil initial conditions on the expression of root traits before the traffic event. Differences between species were found for ARD, DMC, RD, RVD and SRL. RLD was the only trait affected by the soil initial conditions and its interaction with the species. Table 7 presents the comparison between species for all traits. For RLD, species were also compared considering the two soil initial conditions HR and LR. ARD value decrease between species in the order *Vicia faba* >= *Brassica napus* >= *Avena strigosa* = *Vicia sativa*. DMC value decreases between species in the order *Brassica napus* > *Avena strigosa* > *Vicia faba* > *Vicia sativa*. RD value decrease between species in the order *Vicia faba* = *Brassica napus* > *Avena strigosa* > *Vicia sativa*. RVD value decrease between species in the order *Vicia faba* = *Brassica napus* > *Vicia sativa* = *Avena strigosa*. SRL value decrease between species in the order *Vicia sativa* > *Avena strigosa* > *Vicia faba* = *Brassica napus*. As expected, RLD show no differences between species for both soil initial conditions. *Avena strigosa*, *Brassica napus* and *Vicia sativa* showed no differences of RLD between HR and LR. Only *Vicia faba* show a significantly lower RLD on the HR condition.

Table 5 : Results of GLS model testing the effect of species, soil initial conditions and their interaction on root traits. The table shows p-values of each variable. Significant p-values ( $P < 0.05$ ) are highlighted in bold

Traits	Species	Soil initial conditions	Soil initial conditions *Species
ARD	<b>&lt;0.001</b>	0.1	0.84
DMC	<b>&lt;0.001</b>	0.28	0.44
RD	<b>&lt;0.001</b>	0.33	0.63
RLD	0.37	<b>0.05</b>	<b>0.03</b>
RVD	<b>&lt;0.001</b>	0.80	0.28
SRL	<b>&lt;0.001</b>	0.41	0.14

Table 6 : Root traits' mean and standard error per species. ARD = Average root diameter, DMC = Dry Matter Content, RD = Root Density, RLD = Root Length Density, RVD = Root Volume Density, SRL = Specific Root Length.. RLD mean and standard error is defined per species/soil resistance combination. Letters indicate significant differences between species. Stars indicate significant differences of RLD between the two soil initial conditions for each specie according to the GLS model: \*\*\* = p-value < 0.001, \*\* = p-value < 0.01, \* = p-value < 0.05.

Species	ARD (mm)	DMC (g g <sup>-1</sup> )	RD (g cm <sup>-3</sup> )	RVD (cm <sup>3</sup> cm <sup>-3</sup> )	SRL (cm g <sup>-1</sup> )	RLD(cm cm <sup>-3</sup> )	
						HR	LR
<i>Avena strigosa</i>	0,7 ± 0,24 <sup>a</sup>	0,2 ± 0,02 <sup>a</sup>	40,35 ± 13,3 <sup>a</sup>	28,47 ± 18 <sup>a</sup>	611,32 ± 175,1 <sup>a</sup>	259,21 ± 18,15 <sup>a</sup>	194,21 ± 39,73 <sup>a</sup>
<i>Brassica napus</i>	0,74 ± 0,24 <sup>ab</sup>	0,25 ± 0,03 <sup>b</sup>	105,88 ± 27,43 <sup>b</sup>	425,94 ± 212,16 <sup>b</sup>	238,8 ± 57,17 <sup>b</sup>	184,17 ± 26,82 <sup>a</sup>	268,99 ± 117,93 <sup>a</sup>
<i>Vicia faba</i>	1,46 ± 0,35 <sup>b</sup>	0,15 ± 0,02 <sup>c</sup>	122,42 ± 35,7 <sup>b</sup>	638,83 ± 183,53 <sup>b</sup>	242,82 ± 97,86 <sup>b</sup>	176,53 ± 52,35 <sup>a*</sup>	358,98 ± 90,96 <sup>a*</sup>
<i>Vicia sativa</i>	0,47 ± 0,11 <sup>a</sup>	0,12 ± 0,02 <sup>d</sup>	11,48 ± 2,03 <sup>c</sup>	61,22 ± 33,28 <sup>a</sup>	1754,7 ± 375,96 <sup>c</sup>	187,23 ± 16,31 <sup>a</sup>	210,91 ± 78,58 <sup>a</sup>

Values are the mean and standard deviation of 3 replicates for the RLD

Values are the mean and standard deviation of 6 replicates for the others traits

### 5.3.3. Effects of crop species and soil initial conditions on soil-root system physical properties before traffic

The only effect found on soil-root system physical properties before the traffic event is the soil initial conditions on  $\rho_b$  (Table 8).  $k_a$  and  $k_{as}$  was not different among the four species and soil initial conditions, and were not affected by species\*soil initial conditions interaction before the traffic event (Table 8). Only *Vicia faba* show a difference of  $\rho_b$  with a significantly lower  $\rho_b$  on the HR condition (Table 9).

Table 7 : Results of GLS model testing the effect of species, soil initial condition and their interaction on initial soil properties. The table shows p-values of each variable. Significant p-values ( $P < 0.05$ ) are highlighted in bold

Soil initial properties	Soil initial condition	Species	Soil strength level*Species
$\rho_b$	<b>0.01</b>	0.50	0.09
$k_a$	0.80	0.19	0.66
$k_{as}$	0.62	0.23	0.58

Table 8 : Mean and SE of  $k_{as}$  and  $k_a$  before traffic for each specie. Mean and SE of  $\rho_b$  before traffic for each specie  $k_{as}$ = Specific air permeability,  $k_a$  = Air permeability,  $\rho_b$ = Dry bulk density. Stars indicate significant differences between the two soil strength level for each specie according to the GLS model: \*\*\* = p-value < 0.001, \*\* = p-value < 0.01, \* = p-value < 0.05.

Species	$\rho_b$ (Mg m <sup>-3</sup> )		$k_a$ ( $\mu\text{m}^2$ )	$k_{as}$ ( $\mu\text{m}^2$ )
	HR	LR		
<i>Avena strigosa</i>	1,55 ± 0,05	1,49 ± 0,03	7,45 ± 2,19	18,12 ± 5,42
<i>Brassica napus</i>	1,53 ± 0,07	1,47 ± 0,08	7,62 ± 1,7	18,63 ± 4,41
<i>Vicia faba</i>	<b>1,57 ± 0,07*</b>	<b>1,41 ± 0,02*</b>	7,06 ± 7,14	17,14 ± 17,22
<i>Vicia sativa</i>	1,46 ± 0,06	1,48 ± 0,07	13,08 ± 1,25	30,61 ± 3,14

Values are the mean and standard deviation of 3 replicates for  $\rho_b$

Values are the mean and standard deviation of 6 replicates for  $k_{as}$  and  $k_a$

### 5.3.4. Soil-root system physical properties after traffic

Effects of crop species, soil initial conditions and soil-root system initial properties ( $t_0$ ) on the physical properties of the soil-root system after traffic for the two locations under the track (i.e. centre and 0.3 m edge) are presented in Table 10. No effects of the crop species, the soil initial conditions or  $t_0$  including their interactions were found on  $\rho_b$  for both locations under the tyres. For both locations,  $k_a$  and  $k_{as}$

showed an effect of the species, the soil initial conditions, the interaction between the values at t0 and the species, and the interactions between the species and soil initial conditions.  $k_a$  and  $k_{as}$  also showed an effect of the t0 for the 0.3m location.

### **5.3.5. Comparison between soil-root system physical properties before and after traffic**

The soil-root system physical properties before and after the traffic event are compared for soil initial conditions and location under the track of each crop specie (Table 11). In the HR condition,  $\rho_b$  did not significantly increase for all the conditions while  $k_a$  and  $k_{as}$  only decreased significantly under the tyres' centre for *Avena strigosa*.

In the LR condition,  $\rho_b$  did significantly increase under the tyres' centre and at 0.3m from the tyres' centre for *Avena strigosa* and *Vicia faba*.  $k_a$  decreased at the two location for *Avena strigosa* while  $k_{as}$  only decrease at 0.3m from the tyres' centre.  $k_a$  and  $k_{as}$  also decreased under the tyres centre for *Brassica napus*.

Table 9 : Results of GLS model testing the effect of the value at t0, species, soil initial conditions and their interaction on soil properties after compaction under the tyres' centre and at 0.3m from the tyres' centre. The table shows p-values of each variable. Significant p-values ( $P < 0.05$ ) are highlighted in bold

Soil properties	t0	Soil initial conditions	Species	t0* Soil initial conditions	t0*Species	Soil initial conditions *Species	t0* Soil initial conditions *Species
<b>pb0</b>	0.61	0.59	0.45	0.79	0.91	0.49	0.77
<b>ka0</b>	0.3	<b>0.003</b>	<b>0.005</b>	0.22	<b>0.003</b>	<b>0.0002</b>	0.23
<b>kas0</b>	0.40	<b>0.007</b>	<b>0.009</b>	0.37	<b>0.006</b>	<b>0.0005</b>	0.35
<b>pb30</b>	0.33	0.75	0.81	0.92	0.79	0.77	0.69
<b>ka30</b>	<b>0.03</b>	<b>&lt;.0001</b>	<b>&lt;.0001</b>	0.20	<b>0.0001</b>	<b>0.0005</b>	0.41
<b>kas30</b>	<b>0.007</b>	<b>&lt;.0001</b>	<b>&lt;.0001</b>	0.13	<b>0.0001</b>	<b>0.002</b>	0.24

Values are the mean and standard deviation of 3 replicates

Table 10 : Mean of each properties and standard error per species and the two soil initial conditions before compaction (t0) and after compaction at two distance from the tyres' centre.  $\rho_b$  = Dry bulk density,  $k_{as}$  = Specific air permeability,  $k_a$  = Air permeability. Stars indicate if the mean is significantly different than the t0 mean according to the ANOVA on the GLS model: \*\*\* = p-value < 0.001, \*\* = p-value < 0.01, \* = p-value < 0.05.

HR	t0	$\rho_b$ (Mg m <sup>-3</sup> )		t0	$k_a$ ( $\mu\text{m}^2$ )		t0	$k_{as}$ ( $\mu\text{m}^2$ )	
		0	30		0	30		0	30
<i>Avena strigosa</i>	1,55 ± 0,05	1,55 ± 0 <sup>NS</sup>	1,51 ± 0,06 <sup>NS</sup>	5,58 ± 1,51	<b>1,5 ± 1,31*</b>	4,22 ± 0,97 <sup>NS</sup>	14,21 ± 3,12	<b>3,84 ± 3,33*</b>	10,39 ± 2,69 <sup>NS</sup>
<i>Brassica napus</i>	1,53 ± 0,07	1,59 ± 0,06 <sup>NS</sup>	1,55 ± 0,01 <sup>NS</sup>	8,48 ± 3,53	12,25 ± 3,19 <sup>NS</sup>	5,2 ± 1,27 <sup>NS</sup>	21,77 ± 10,38	33,16 ± 9,43 <sup>NS</sup>	13,33 ± 3,09 <sup>NS</sup>
<i>Vicia faba</i>	1,57 ± 0,07	1,52 ± 0,04 <sup>NS</sup>	1,51 ± 0,05 <sup>NS</sup>	8,92 ± 7,48	1,61 ± 0,72 <sup>NS</sup>	13,57 ± 5,58 <sup>NS</sup>	22,82 ± 17,17	3,99 ± 1,84 <sup>NS</sup>	32,81 ± 13,71 <sup>NS</sup>
<i>Vicia sativa</i>	1,46 ± 0,06	1,52 ± 0,05 <sup>NS</sup>	1,56 ± 0,03 <sup>NS</sup>	13,35 ± 6,43	9,04 ± 0,66 <sup>NS</sup>	3,21 ± 0,31 <sup>NS</sup>	30,81 ± 14,51	22,37 ± 1,75 <sup>NS</sup>	8,3 ± 0,79 <sup>NS</sup>
LR	t0	$\rho_b$		t0	$k_a$		t0	$k_{as}$	
		0	30		0	30		0	30
<i>Avena strigosa</i>	1,49 ± 0,03	<b>1,57 ± 0,03*</b>	<b>1,56 ± 0,02*</b>	9,32 ± 2,06	<b>4,96 ± 1,72*</b>	<b>0,46 ± 0,63**</b>	22,03 ± 4,7	12,88 ± 4,57 <sup>NS</sup>	<b>1,18 ± 1,58**</b>
<i>Brassica napus</i>	1,47 ± 0,08	1,56 ± 0,01 <sup>NS</sup>	1,54 ± 0,05 <sup>NS</sup>	6,77 ± 2,91	<b>1,38 ± 1,14*</b>	3,3 ± 1,71 <sup>NS</sup>	15,48 ± 6,05	<b>3,59 ± 2,98*</b>	8,5 ± 4,64 <sup>NS</sup>
<i>Vicia faba</i>	1,41 ± 0,02	<b>1,55 ± 0,03**</b>	<b>1,55 ± 0,05*</b>	5,2 ± 4,11	4,8 ± 2,07 <sup>NS</sup>	2,46 ± 1,89 <sup>NS</sup>	11,46 ± 8,62	12,26 ± 5,7 <sup>NS</sup>	6,14 ± 4,47 <sup>NS</sup>
<i>Vicia sativa</i>	1,48 ± 0,07	1,56 ± 0,02 <sup>NS</sup>	1,55 ± 0,02 <sup>NS</sup>	12,81 ± 8,91	3,09 ± 1,2 <sup>NS</sup>	2,09 ± 1,7 <sup>NS</sup>	30,4 ± 21,19	8,09 ± 3,25 <sup>NS</sup>	5,34 ± 4,17 <sup>NS</sup>

Values are the mean and standard deviation of 3 replicates

## 5.4. Discussion

### 5.4.1. Mechanical soil strength effect on root traits expression and physical properties

Before analysing the role of roots on the conservation of the physical properties of the soil-root system it is essential to consider the impact of the soil strength level on the expression of traits and on the soil-root system physical properties before the traffic event. As roots and soil interact, it implies a feedback between the soil capacity to let the root growth and the root capacity to modify the soil. In this study, the mechanical strength differences between the two soil initial conditions (HR and LR) did not significantly modify the root expression except for *Vicia faba* which present in average a RLD almost two times higher in the LR condition than in the HR condition. Thus the root traits values were mainly driven by the selected species and not by the soil initial conditions.

The  $\rho_b$  differences before traffic between the two conditions is mainly explain by the fact that soil cores were sampled under 0.1 m where the soil was tilled in the LR condition but not in the HR condition. However, the tillage nor the species had no effect on  $k_a$  and  $k_{as}$ . The latest tillage on the HR condition was only one year before the experiment and might explain why, even if the soil is not till, no significant differences of  $k_a$  and  $k_{as}$  were observed between the two conditions.

### 5.4.2. Role of roots on soil properties conservation during traffic

The main objective of this study is to investigate the capacity of roots to conserve soil-root system physical properties such as bulk density  $\rho_b$ , air permeability  $k_a$  and specific air permeability  $k_{as}$  after a traffic event for four crop species under two levels/conditions of soil strength. *Brassica napus* and *Vicia sativa* showed non-significant differences of  $\rho_b$  before and after traffic in the LR condition. However, the  $\rho_b$  seem to increase in the same way than *Avena strigosa* and *Vicia faba*. The difference is that the  $\rho_b$  value before traffic has a high standard error which encourage the model to not differentiate  $\rho_b$  before and after the traffic event. Moreover,  $\rho_b$  did not depend on any factor after traffic (Table 10) which might indicate that  $\rho_b$  values are identical under the tyres' centre for every condition after traffic and identical



at 0.3 m from the tyres' centre for every condition after traffic. Plough manage to reduce temporarily  $\rho_b$  but it also reduced the soil resistance and thus  $\rho_b$  is more susceptible to increase during traffic. In our case traffic bring  $\rho_b$  value in the LR condition at the same range than those found on the HR condition which were not significantly modified by traffic. It highlighted that tillage is in some case only a temporary solution to cope with compaction as traffic directly increase  $\rho_b$  back to its value before tillage. Moreover, no evidence of the role of roots in the conservation of  $\rho_b$  was found.  $\rho_b$  is mainly increase by the compression induced by traffic (Berisso et al., 2013), the hypothesis is that roots of annual plants species have no potential or a limited potential to play a role in the mitigation of compression and thus in a potential conservation of  $\rho_b$  during traffic.

Before traffic  $k_a$  and  $k_{as}$  were not driven by any effect of species nor soil initial conditions. However, after traffic  $k_a$  and  $k_{as}$  were driven by the effect of the species, soil initial conditions and their interaction (Table 10). Thus the deformation induced by traffic modify differently  $k_a$  and  $k_{as}$  according to the species/soil initial conditions combination.  $k_a$  and  $k_{as}$  will mainly be affected by the shear induced during traffic (Berisso et al., 2013). Tillage is known as decreasing soil cohesion and aggregate stability (Bullock et al., 1988) and thus decreased soil shear strength in the LR condition explaining the tillage effects on  $k_{as}$  and  $k_{as}$  only after traffic. Following this reasoning, the presence of significant differences of  $k_{as}$  and  $k_{as}$  only after traffic should indicate that the species selected modified differently the soil shear strength or at least conserve differently  $k_a$  and  $k_{as}$  during conservation.  $k_a$  significantly decrease for *Avena strigosa* in three out of four conditions with only a conservation of  $k_a$  at 0.3m from the tyres' centre in the HR condition.  $k_a$  also decrease for *Brassica napus* but only under the tyres' centre in the LR condition. However, traffic did not significantly decrease  $k_a$  and  $k_{as}$  in any condition for *Vicia sativa* and *Vicia faba*. In both cases, roots were thus able to better conserve  $k_a$  and  $k_{as}$  during traffic. However, none of the root traits measured can discriminate *Vicia sativa* and *Vicia faba* from *Brassica napus* and *Avena strigosa* nor discriminate *Avena strigosa* from the 3 other species. The potential effect on the conservation of  $k_a$  and  $k_{as}$  during traffic should thus be due to another trait not measured here. As showed earlier, a loss of  $k_a$  and  $k_{as}$  is a direct consequence of shear induced by traffic (Berisso et al., 2013). Root capacity to increase soil shear strength is well-known in other context (Stokes et al., 2009; Yildiz et al.,

2018, and others) and might explain the capacity to conserve  $k_a$  and  $k_{as}$  during traffic. In the literature, one of the main root traits involved in soil shear strength is the root tensile strength which is the root capacity to sustain tension without breaking. Here, this root traits might be the one, or one of the root traits involved in the capacity to conserve  $k_a$  and  $k_{as}$  during traffic. *Brassica napus* and *Avena strigosa* were able to conserve  $k_a$  and  $k_{as}$  only in certain condition. The hypothesis is that shear stress induced at 0.3 m from the tyres' centre is lower than the shear stress induced under the tyres' centre. As said above, we also expect the HR condition to have the higher shear strength. It could explain why  $k_a$  and  $k_{as}$  were only conserve at 0.3m in the HR condition for *Avena strigosa* and not conserve for *Brassica napus* only under the tyres' centre in the LR condition. The capacity to conserve  $k_a$  and  $k_{as}$  do not depends only on roots but will also depend on the soil own properties and on the type of deformation induced.

## **5.5. Conclusion**

In this study, root traits attributes was hardly modified by the initial soil conditions. Our results highlight new evidences of the roots effects on soil properties conservation during traffic. However, the root effects was mediated by the initial soil conditions and by the scale and type of stress applied. The relationship between root traits, soil initial conditions and stress applied thus need to be taken into account to determine the soil-roots matrix capacity to conserve effectively soil properties during traffic. Further studies should try to investigate the mechanism involved in the roots capacity to conserve soil properties during traffic. Current hypothesis point the roots effect on soil shear strength which could be directly related to the soil properties conservation. Further studies should include direct measurement of soil shear strength and identify if roots of annual species are able to increase soil shear strength.

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# CHAPTER 3

## 6. ROOT TRAITS OF CROP SPECIES CONTRIBUTING TO SOIL SHEAR STRENGTH

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### Abstract

#### Aims

Roots of annual species are 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 cover 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.

#### Methods

The experiment was performed under controlled conditions in steel cylinders containing a repacked loamy sand. Soil shear strength parameters, i.e. cohesion and angle of internal friction, were determined from direct shear tests using the Coulomb equation.

#### Results

Two root traits, root volume density and average root diameter could be related to an increase in soil shear strength. The difference of root type (taproot versus fibrous), 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.

#### Conclusion

This study highlights the effect of roots of annual crop species on soil shear strength. The root volume density was the main trait involved in both soil cohesion and the angle of internal friction. 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

### **6.1. Introduction**

Soil compaction is known as a major threat to soil quality in Europe (Berge et al. 2017; Stolte et al. 2015). 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 agro systems 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). 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.

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.

Soil shear strength parameters, cohesion and angle of internal friction, are classically determined from the Coulomb equation

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

where  $\tau$  is the shear strength (kPa),  $\sigma$  is the normal stress acting on the failure surface (kPa),  $C$  is the cohesion (kPa) and  $\varphi$  is the angle of internal friction ( $^{\circ}$ ).

Plant roots could potentially influence both of these two shear strength parameters. Several studies examining the effects of roots on soil shear strength have highlighted the effects of a range of root properties on cohesion: root tensile strength (the root's capacity to resist tension) and 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) (Ali and Osman 2008; Tengbeh 1989); and root length density (the length of roots per volume of soil) (Osman and Barakbah 2006).

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). It has also been demonstrated that root traits could improve the angle of internal friction (Graf et al. 2009; Yildiz et al. 2018). However, more research is needed to identify the specific root traits involved in the increase of soil friction (Stokes et al. 2009). Roots increase soil shear strength directly through their mechanical resistance, and their anchoring in the soil, and indirectly through water removal by absorption (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).

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. 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. The hypothesis stated that crop roots would increase only soil cohesion and the angle of internal friction will not be modified.

## **6.2. Materials and methods**

### **6.2.1. 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; soil with *Brassica napus* L., which provides a taproot; soil with *Secale cereale* L., which provides a fibrous root; and soil with *Vicia faba* L., which provides a taproot system with larger fine roots than *Brassica napus*. The soil consisted of a 2:1 ratio mix of Luvisol (IUSS Working Group WRB, 2015: 20.5 g 100g<sup>-1</sup> of clay, 69.4 g 100g<sup>-1</sup> of silt and 10.1 g 100g<sup>-1</sup> of sand) and of river sand previously sieved at 5 mm.

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 (Fig. 1.b). Pots were packed with soil to reach a dry bulk density of 1.2 g cm<sup>-3</sup>. To do so, pots were

filled and compact three consecutive times. Soil was added and compact at 7cm, 14cm and 20cm. 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 100kPa 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 closer to the light, each replacing its neighbouring pot, while the pot closest to the light was moved to the farthest space. Each pot was irrigated once a week during the first month and then twice a week until the end of the experiment.

### **6.2.2. Soil shear strength**

A direct shear apparatus was built especially for this study to perform shear tests directly on the pots, thus avoiding unnecessary manipulation of the repacked soil cores (Fig. 1). Two pots per treatment were subjected to a direct shear test at six external normal stress levels (25, 34, 44, 63, 83 and 93 kPa), resulting in twelve shear tests per treatment. The external normal stress was applied using a dead weight system. The direct shear tests were performed two and a half months after sowing. Few days before the tests, each pots were saturated with tap water. Two times per day, soil matric suction was measured at 0.08m depth for each treatment using tensiometers placed in three pots chosen randomly for each treatment. Shear tests were performed when the soil matric suction reached approximately -10 kPa which correspond to a water content at field capacity, i.e. where most of macro- and mesopores are air-filled (Table 1). The upper part of the soil core was moved horizontally at a constant rate of 3 mm.min<sup>-1</sup>, and the test was stopped when a total horizontal displacement of 25 mm was reached. Horizontal displacement rate was controlled using an actuator monitored by a software called “Kollmorgen WorkBench”. During the test, the force required to displace the upper part of the soil core was recorded by a H3-C3 500kg load cell every 0.095 seconds. Shear strength was calculated from the load cell readings (kg) and the contact area between the upper and the lower part of the soil core. This contact

area was considered as a lens formed by the 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 ( $\text{mm}\cdot\text{s}^{-1}$ ).

The maximum shear strength was determined graphically on each shear strength-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 strength was defined as the inflexion point of the curve. For unsaturated soils, the negative pore water pressure will participate 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. 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”,  $c_{\text{app}}$  (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  $\phi_{\text{app}}$  ( $^{\circ}$ ):

$$\tau = c_{\text{app}} + \sigma \tan \phi_{\text{app}}$$

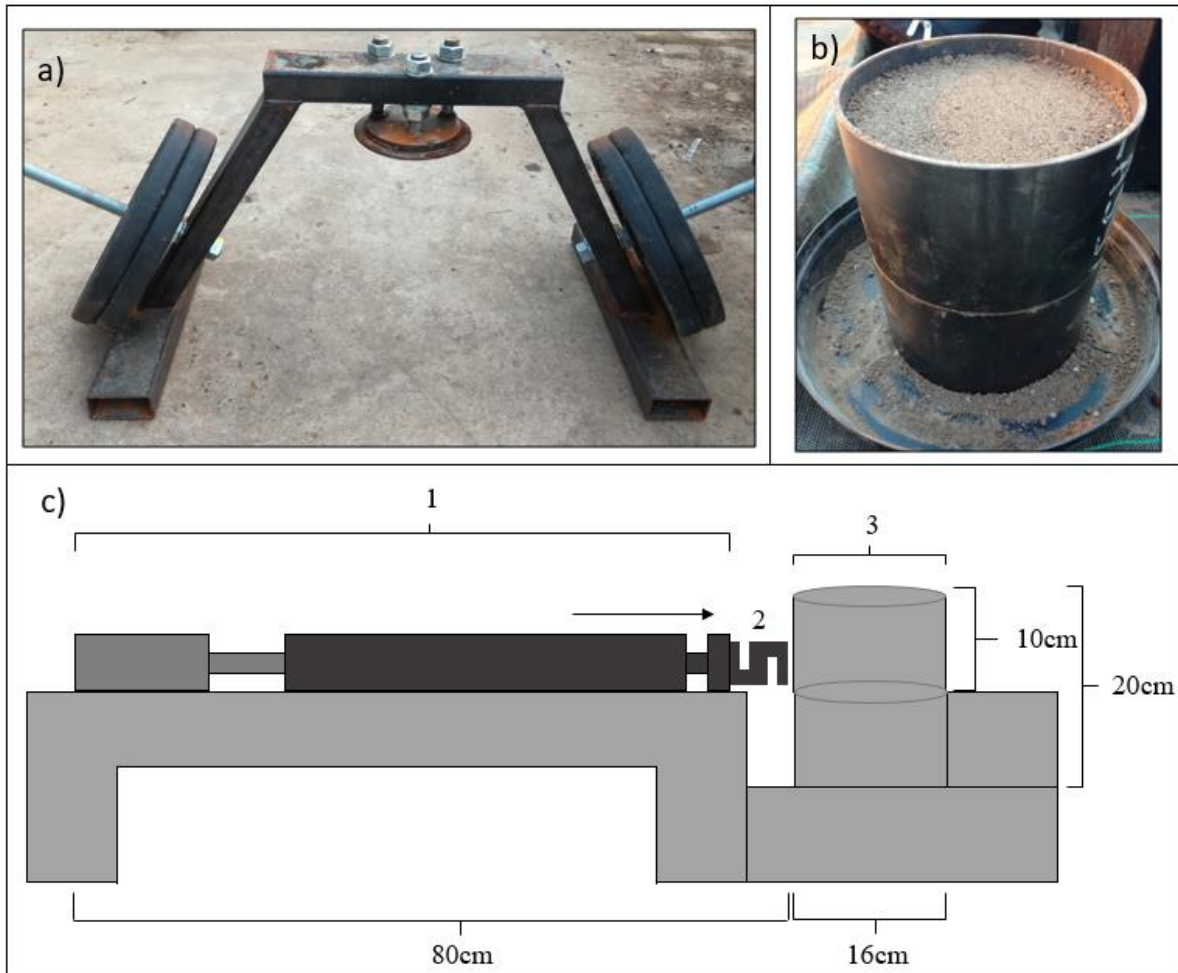


Figure 19 : Components and schema of the shear box: a) Homemade system built to apply normal stress on the soil cylinder b) Soil cylinders filled with remoulded soil used in the experiment. c) Shear box schema. 1) The computer-controlled motor and actuator 2) The H3-C3 500kg load cell 3) The soil cylinders

Table 11 : Soil water content and soil matric suction mean for each species. The letters showed differences between species.

	Soil water content (g.g <sup>-1</sup> )	Soil matric suction (kPa)
<i>Brassica napus</i>	0,11 ± 0,02 <sup>a</sup>	20.8 ± 6.07 <sup>a</sup>
<i>Vicia faba</i>	0,07 ± 0,01 <sup>b</sup>	6.73 ± 0.04 <sup>a</sup>
<i>Secale cereale</i>	0,11 ± 0,03 <sup>a</sup>	7.93 ± 0.31 <sup>a</sup>
<b>Bare soil</b>	0,12 ± 0,01 <sup>a</sup>	6.2 ± 1.7 <sup>a</sup>

Soil water content values are the mean and standard error of 12 replicates.

Soil matric suction 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.

### 6.2.3. Root trait characterisation

After the shear tests, all pots were emptied, and roots were manually separated from the soil. 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,  $\text{cm}\cdot\text{cm}^{-3}$ ), which is the root length divided by the soil volume; the root density (RD,  $\text{g}\cdot\text{m}^{-3}$ ), which is the roots' dry weight divided by the soil volume; the root volume density (RVD,  $\text{cm}^3\cdot\text{cm}^{-3}$ ), which is the roots' volume divided by the soil volume; the specific root length (SRL,  $\text{m}\cdot\text{g}^{-1}$ ), 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.



*Figure 20 : Scans of an entire root system of Vicia faba. The roots were cut and displaced in the tray before the scan. The taproot was not include in the scan analysis*

#### **6.2.4. 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.

## 6.3. Results

### 6.3.1. 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 (Chi square = 1.35, p-value = 0.25, df = 1) nor in ATRD (Chi square = 2.54, p-value = 0.11, df = 1) 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*. The root type of *Vicia faba* is thus difficult to determine and could be defined as being between a taproot system and a fibrous system.

Table 12 : 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

	<b>ARD</b> (mm)	<b>DMC</b> (g.g <sup>-1</sup> )	<b>SRL</b> (m.g <sup>-1</sup> )	<b>RLD</b> (cm.cm <sup>-3</sup> )	<b>RVD</b> (cm <sup>3</sup> .cm <sup>-3</sup> )	<b>RD</b> (g.m <sup>-3</sup> )	<b>TRVD</b> (cm <sup>3</sup> .cm <sup>-3</sup> )	<b>ATRD</b> (cm)
<b><i>Brassica</i></b>								
<b><i>napus</i></b>	0.35±0.06 <sup>b</sup>	0.18±0.03 <sup>a</sup>	38.6±9.1 <sup>b</sup>	2.05±0.85 <sup>b</sup>	0.0063±0.0054 <sup>b</sup>	525.1±133.8 <sup>b</sup>	0.001±0.0005 <sup>a</sup>	0.53±0.08 <sup>a</sup>
<b><i>Secale</i></b>								
<b><i>cereale</i></b>	0.34±0.05 <sup>b</sup>	0.13±0.01 <sup>b</sup>	77.4±14.2 <sup>a</sup>	2.82±0.91 <sup>a</sup>	0.0055±0.003 <sup>b</sup>	373.6±138.3 <sup>c</sup>	0	
<b><i>Vicia</i></b>								
<b><i>faba</i></b>	0.95±0.12 <sup>a</sup>	0.09±0.01 <sup>c</sup>	15.7±3.7 <sup>c</sup>	2.14±0.44 <sup>ab</sup>	0.0203±0.0076 <sup>a</sup>	1397.6±309.3 <sup>a</sup>	0.0008±0.001 <sup>a</sup>	0.64±0.16 <sup>a</sup>

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.



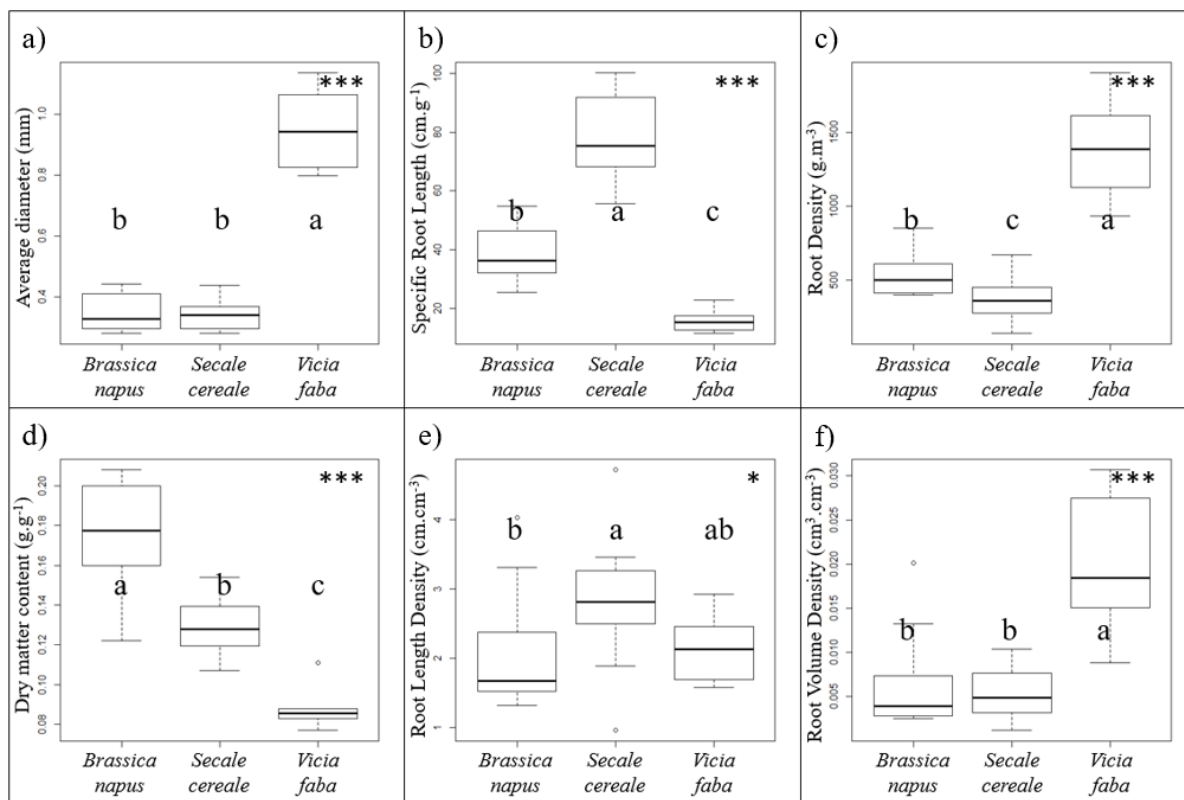


Figure 21 : Boxplots of each root traits for each species: a) the average diameter (mm), b) the specific root length (cm.g<sup>-1</sup>), the root density (g.m<sup>-3</sup>), the dry matter content (g.g<sup>-1</sup>), the root length density (cm.cm<sup>-3</sup>), the root volume density (cm<sup>3</sup>.cm<sup>-3</sup>). 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.

Table 13 : 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

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

### 6.3.2. 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 the angle of internal friction of 17.9° and a cohesion of 20.2 kPa, while *Brassica napus* reached the 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. The control reached an angle of internal friction of 10.5° and a cohesion of 9.6 kPa (Figure 22). The variance analysis of the regressions showed that only *Vicia faba* had a higher angle of internal friction and cohesion than the control without plants, while both *Secale cereale* and *Brassica napus* did not have significantly different angle of internal friction or cohesion than the control.

Table 14 : Soil internal friction angle and cohesion determined from the equation  $\tau = c + \sigma \tan \phi$  and the linear regression  $R^2$  for each species and the control without plants.

	<b>Internal friction angle</b>	<b>Cohesion (kPa)</b>	<b>R<sup>2</sup></b>
<b><i>Vicia faba</i></b>	17.9 <sup>o</sup> <sub>a</sub>	20.19 <sup>a</sup>	0.63
<b><i>Brassica napus</i></b>	15.6 <sup>o</sup> <sub>b</sub>	4.87 <sup>b</sup>	0.71
<b><i>Secale cereale</i></b>	12.6 <sup>o</sup> <sub>b</sub>	8.78 <sup>b</sup>	0.44
<b>Control without plant</b>	10.5 <sup>o</sup> <sub>b</sub>	9.58 <sup>b</sup>	0.68

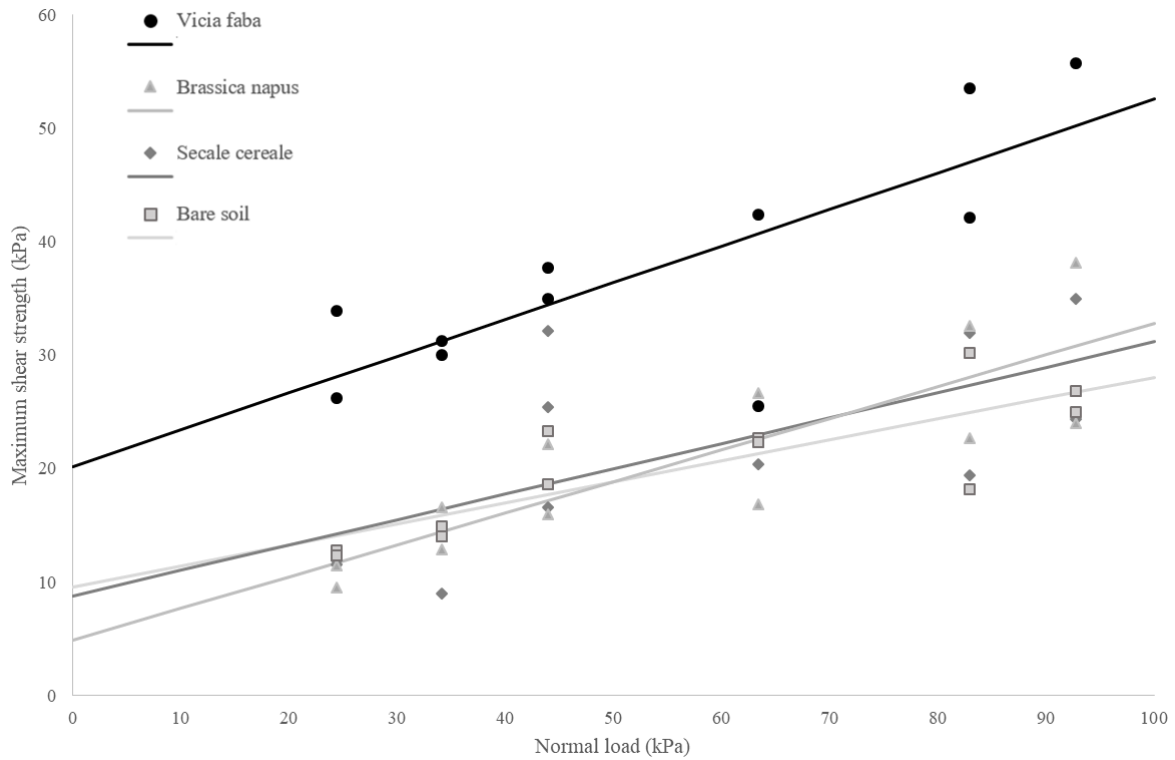


Figure 22 : Linear regression  $\tau = c + \sigma \tan \phi$  for each species and the control without plants.

## 6.4. Discussion

The main hypothesis of the present study states that roots of annual crop species will 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 of soil apparent cohesion. Surprisingly, *Vicia faba* also present a significant higher angle of internal friction, as indicated by the increase compared to the control soil without roots (Fig. 3). Our results suggest that some annual crop species could have a positive effect on soil shear strength. Bias in the determination of shear stress due to stresses building up during the test at the edges of the soil core is possible and encourage to choose larger soil core. In our study, a mean strain at failure of 3.5 mm was considered small as compared to the diameter of the soil cores. In addition, the size of the soil cores of the present study followed the ASTM recommendation of ratio between the size of the sample and the maximum particle size of the material to be tested (ASTM Standard D 420–D 4914, Soil and Rock, Annual Book of ASTM Standards Vol. 04.08, ASTM International, West Conshohocken, PA).

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). A rooted soil does thus not present systemically a higher shear strength. The soil reinforcement to shear does also not rely on the root type. Therefore, the effects of roots on shear strength would then be controlled by root traits. Thus, 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 that 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) are involved in soil shear strength, notably in the slope's protection against landslides. In comparing root traits and soil shear strength between 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 remain similar. It indicates that these three root traits do not directly influence the soil shear strength. Contrary to the landslide literature, our results showed that RLD of these annual crop species did not influence shear strength as it did not discriminate *Vicia faba* from the other species. . The low RLD of these crop species ( $2.1-2,8 \text{ cm.cm}^{-3}$ ) compared to perennial herbaceous, shrub and tree species (more  $300 \text{ cm.cm}^{-3}$ ), would explain the absence of relationships between RLD with soil shear strength in this study. Interesting result is that annual crop specie with low RLD can positively influence soil shear strength. Results showed that soil shear strength was highest in the specie with the high ARD and RVD. This result is contradictory to the literature because root diameter is negatively correlated with the root tensile strength that is an important root trait involved in soil shear strength (Bischetti et al., 2005; De Baets et al., 2008; Gyssels et al., 2005; Operstein and Frydman, 2000; Wu et al., 1979). ARD would not be a root trait involved in soil shear strength in annual crop species. RVD in *Vicia faba*

reflects the number of roots and was, therefore, expected to play a role in the increase of shear strength by roots. RDV could play an important role in soil shear strength. The divergence of root traits effects on soil shear strength in the literature could be also explained by the various methods (Freschet et al. 2020), as the variation of the soil moisture content (e.g. saturated, partially saturated, no saturated, no known), the larger soil core in shear box, the vast differences in magnitude of root traits between annual crops and perennial plants (Roumet et al. 2006) that are principally represented by shrubs and trees in landslide literature (Freschet et al. 2020). . This may hinder the generalisability of the results from these studies to agroecosystems and explain the contradictions between our results and the literature. However, other root traits not measured in this study could also play a role in soil shear strength, such as the insertion angle of the roots or the roots' vertical and horizontal distribution in the soil (Stokes et al. 2009). Future studies examining the effects of root traits on soil shear strength should include a larger range of root traits in crop species.

In our study, *Vicia faba* was found to be related to a larger cohesion and angle of internal friction. RVD appeared to be the root trait involved in both soil cohesion and the angle of internal friction increase. Here, *Vicia faba* high value of RVD is mainly due to its fibrous system and not due to a large taproot. It is thus related to the root capacity to spread and colonize the soil. The root effects seems not to be due to the root capacity to resist tension (root tensile strength) as *Vicia faba* provide the highest ARD. The main hypothesis is thus that the air replacement by roots in the soil (i.e. the pore filling) is the main responsible of the soil reinforcement without any root special capacity to resist tension.

The roots effects on the angle of internal friction is in accordance with the study by Graf et al. (2009). The current authors found a positive root effect on the angle of internal friction. They applied a maximum normal stress of 100 kPa during the shear tests, which was larger than the maximum normal stress used in studies in which evidence of roots' effect on soil angle of internal friction was lacking. The hypothesis is thus that roots could influence positively the soil angle of internal friction, but a low maximum normal stress applied during shear tests might prevent identifying this effect (Giadrossich et al. 2017).

Our results indicated an increase of  $0.14 \text{ kPa kPa}^{-1}$  in the slope of *Vicia faba* compared to the control treatment without plants. This means that with a normal stress of 300 kPa, which could be found beneath tyres of agricultural machinery (Lamandé and Schjønning 2011a), shear strength would be increase by 42 kPa thanks to this angle of internal friction increase. In the contexts of landslide protection and riverbank stability, normal stress is applied by overburden soil and is therefore lower. In these contexts, a small increase in soil shear strength by friction could thus easily be outcompeted by a significant increase in cohesion due to large perennial plants roots. It could also explain why roots effect on the angle of internal friction was not identified. In agroecosystems, the friction increase by roots could play a major role to prevent soil shearing during traffic in agricultural fields. Our results provide a step toward a better understanding of the effects of crop roots on soil shear strength through the increase of both soil cohesion and angle of internal friction.

## **6.5. Conclusion**

This 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 soil compaction mitigation. The type of root (fibrous or taproot) did not influence soil shear strength. Our results showed crop species with low root length density could improve soil shear strength and that the root volume density may be the main root trait correlated to a higher soil 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 large root traits gradient and undisturbed soil sample from agricultural fields.

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# DISCUSSION

## 7. DISCUSSION

Numerous technological advances, soil management practices, modelling approaches and agroecological practices ensuring bio-alleviation of soil compaction were developed and adapted in recent years to cope with soil compaction in agrosystems. Agricultural system advocating reduced tillage or no-tillage such as conservation agriculture simultaneously increased in popularity and adoption in Europe (Friedrich et al., 2012). These conceptual systems offers many advantages such as reducing soil erosion (Palm et al., 2014), increasing soil biodiversity (Henneron et al., 2015), optimizing phosphorus acquisition (Honvault et al., 2020) or reducing nitrate leaching (Martens, 2001) but also numerous drawbacks such as weed infestation (Nichols et al., 2015) or yield loss (Pittelkow et al., 2015). The absence of tillage also lead to surface compaction in surface which was conventionally attenuated by this practice. Existing solutions are mainly designed for conventional system and might not be adaptable to conservation agriculture. To cope with compaction, conservation agriculture mainly rely on bio-alleviation by roots and soil fauna (Büchi et al., 2018; Capowiez et al., 2012). However, the regeneration of a compacted soil is a slow process and can take years. The hypothesis guiding this PhD is that roots which are nearly constantly present in a conservation agriculture system could play a role not only on the compaction alleviation but also directly on compaction during traffic. In agrosystems, soil compaction is derived from two processes: compression (the vertical stress) and shearing (the horizontal stress). Compression induce a decrease of soil pore volume, while shear modify the shape of the soil pore system affecting pore continuity. Both processes induce harmful consequences on soil services which eventually can decrease crops yields. Roots effects on soil shear strength have been highlighted in different context such as landslide or riverbank stability (Ghestem et al., 2014; Pollen and Simon, 2005; Schmidt et al., 2001). We thus attempted to examine whether roots might be able to conserve soil physical properties during traffic thanks to their effects on soil reinforcement to shear. The objective of this PhD was hence to validate the potential capacity of roots to conserve soil physical properties during traffic. The functional approach taken provide insight of the root-soil relationships involved in the conservation of soil physical properties during traffic, producing novel knowledge toward the potential optimal cover crop designs to cope with soil compaction.

## **7.1. Evidences of the root effects on soil physical properties conservation during traffic and their implication in compaction mitigation**

### **7.1.1. Trait effects on soil properties conservation during traffic**

The conservation of soil properties during traffic could be a good complementary solution to reduce the loss of soil services induced by compaction. The objective of our first experiment was to examine the relationships between root traits and soil physical properties after traffic to understand the role of roots in the reduction of soil compaction during traffic. Our results showed a clear link between roots length per soil volume and a better conservation of soil capacity to let air and water flow (Chapter 1). Our second experiment also supported root capacity to conserve soil physical properties during traffic (Chapter 2). In both cases, one of the major results was that roots did not systematically permit to conserve soil properties during traffic. Roots thus appear to be able to prevent soil compaction and conserve soil physical properties during traffic but this capacity is linked to specific root traits.

Our hypothesis is that the soil physical properties conservation by roots is due, at least partially, to a soil reinforcement by roots. This hypothesis is based on evidence of the root capacity to increase soil shear strength in other contexts (e.g. Pollen-Bankhead and Simon, 2010; Schmidt et al., 2001; Stokes et al., 2009). However, compaction induced in agrosystems has fundamental particularities in the:

- *Rates and ranges of deformation*: Vertical and horizontal stress are applied to the soil over a very short amount of time in agrosystems (Keller and Lamandé 2010). Applied vertical stress by agricultural machinery is much greater than overburden stress (e.g. Lamandé and Schjønning 2011), and shearing mainly occurs in the shallow soil layer (<30 cm in depth) (Berisso et al. 2013) where the soil is not necessarily saturated.

Deformation also occurs though the whole soil profile rather than along a single shearing plane.

- *Root traits:* Species encountered are mainly annual or biannual crop species with the range of root traits it implies and stress happens where roots are the most densely present (Osman and Barakbah 2006).

Therefore, root traits highlighted as key factors in other context might not be as important in agrosystems. Compared to the landslide context where the objective is to increase soil shear strength of specific vulnerable layers, in agrosystem the objective should be to reinforce the soil profile homogeneously to avoid weak points, vulnerable to deformation. Traits related to a homogeneous distribution of roots in the soil could thus play a central role in compaction mitigation. Root traits related to the density of roots per soil volume could thus be of particular interest. Three root traits reflected the density of roots in the soil: the root length density, the root density and the root volume density which are respectively the roots length, dry weight and volume per soil volume. However, plants with taproots for example can have most of their root volume or weight concentrated in that structure, and thus the root density and root volume density are not always related to a homogeneous distribution of roots in the soil. The best way to assess the root capacity to occupy the soil might be to measure only the weight or volume density of the fibrous system. It allows to take in account the length but also the thickness of the fibrous system which might play a complementary role in soil physical properties conservation during traffic. Architectural root traits could also be interesting such as the root angle of insertion in the soil (Ghestem et al., 2014) or the root typology (Physical organisation of root branching, Stokes et al. (2009)). The morphology of the pore system and the root architecture could be studied using X-ray computed tomography (Naveed et al., 2016) coupled with air permeability measurement to better understand the root effects and their capacity to conserve soil physical properties.



### **7.1.2. Relationships between root traits, soil physical properties and stress applied and their application to the conservation of soil physical properties**

The second experiment highlighted that identical root attributes did not have the same effects on the soil physical properties conservation according to the soil properties or the type or the range of stress applied. The root capacity to conserve soil physical properties is thus not only related to the root traits expression but depend on complex processes involving root traits, soil properties and their response to the stress applied. Stress induced by traffic in agrosystems propagate through the whole soil profile in every direction and deformation will mostly happen where the stress is the highest (close to the tyres) and/or where the soil is the weakest. Soil strength could be heterogeneous, mostly between the different horizontal layers as only the topsoil can be tilled and some layer could be compacted (e.g. plowpan). In our experiment we highlighted species that were able to (1) conserve soil physical properties regardless of the stress applied and the initial soil physical properties (2) only conserve soil physical properties when the stress applied is lower or (3) only conserve soil physical properties when the soil is not tilled (i.e. when the soil initial strength is higher). Interestingly, no single root trait measured was able to differentiate the species effects on soil properties conservation. Even the root length density did not discriminate species from one-another which could have explained their different impacts on soil physical properties conservation. Our experiment however does support that roots are able to play a major role in the soil physical properties conservation during traffic. However, roots effects depend on root traits which have yet to be fully identified and also on the soil properties and on the type and range of stress applied. There is thus a need to further investigate the different processes that could be involved in the soil properties conservation by roots during traffic in agrosystem.

### **7.1.3. Roots increasing soil shear strength: a plausible explanation**

Our in-situ experiment produced solid evidences of the role of roots in soil physical properties conservation during traffic. The next step is now to understand the processes through which roots

conserve soil physical properties. As described earlier, compaction could be divided in two sub-processes: the horizontal stress and the vertical stress which are respectively called shear and compression. Both of these processes are detrimental to the soil pore system as the compression will decrease pore volume while shear will break pore continuity. Both will thus directly be related to the soil physical properties measured with the bulk density highlighting soil compression and the air permeability underlining soil shear. Compression is often considered as the most harmful process because of the deep deformation induced by compression. Shear stress moreover mainly induces soil deformation close to the surface. Therefore, in a conventional system where soil is frequently tilled, shear's consequences are mainly erased while compression's consequences remain pronounced in the deep soil layers. In a no-tilled or reduced-tilled system, the adverse effects of shearing could become the most harmful process as it will decrease or even nullify the top soil capacity to let air and water properly flow through the soil. In the in-situ experiments, the soil physical properties conservation was observed at 0.1m depth directly after traffic (i.e. soil was not tilled between the traffic and the measurement). Consequently, the conservation observed should be related to the soil reaction to shear which should be observed under such circumstances.

Roots roles in soil shear strength were already widely described in the context of landslide or riverbank stability (Pollen and Simon, 2005; Stokes et al., 2009). However, most studies work with tree and shrub species, or perennial herbaceous species which produces different gradient of root traits than the roots attributes of annual species. We thus decided to assess shear strength reinforcement by the roots of annual species. The comparison between a bare soil and three species highlighted that annual roots were able to increase soil shear strength significantly (Chapter 3). Roots could thus have increased soil shear strength in the in-situ experiments in a similar manner which could explain, at least partially, the soil physical properties conservation. Among the three studied crop species, only one specie presented a significantly higher soil shear strength than the bare soil. The presence of roots thus did not increase soil shear strength systematically. As observed in for the soil physical properties conservation, the roots capacity to increase soil shear strength depends on a number of specific root traits. In our experiment, the main root traits that discriminate specie impact on soil shear strength reinforcement was not the root

length density but the root volume density and the root average diameter which were significantly higher in Faba bean. This supports the hypothesis that the root length density might not be the only root traits involved in the conservation of soil physical properties and that the thickness of the fibrous system should play a complementary role. However, we observed a difference between the roots capacity to conserve soil physical properties and roots capacity to increase soil shear strength. Indeed, it seems that roots is more often capable to conserve, at least some soil physical properties, than capable of increasing soil shear strength. It thus raise the hypothesis that roots capacity to maintain soil physical properties during traffic might not only due to a soil reinforcement to shear. The first possible complementary process is the soil reinforcement to compression by roots. Evidences of an effect of roots on soil compression strength are scarce, but Kleinfelder et al. (1992) showed that roots are able to increase soil compressive strength. However, the context is yet again different from our system of interest and the studies conclude that strength acquired by perennial roots was not large enough to withstand stress induced by moving cattle. In the field, the potential soil reinforcement to compression by roots of annual plants might be insignificant compared to the high compressive stress induced by traffic.

The second possible complementary process could be that roots prevent pores breakages without systematically increasing soil strength. Pollen (2007) stated that “soil is strong in compression but weak in tension. Conversely, roots are weak in compression but strong in tension”. The hypothesis is that roots do not increase soil shear strength sufficiently to avoid deformation during traffic. However, roots inside pores will resist tension and will not break during shearing which will keep the pore more tortuous but continuous (Figure 23).

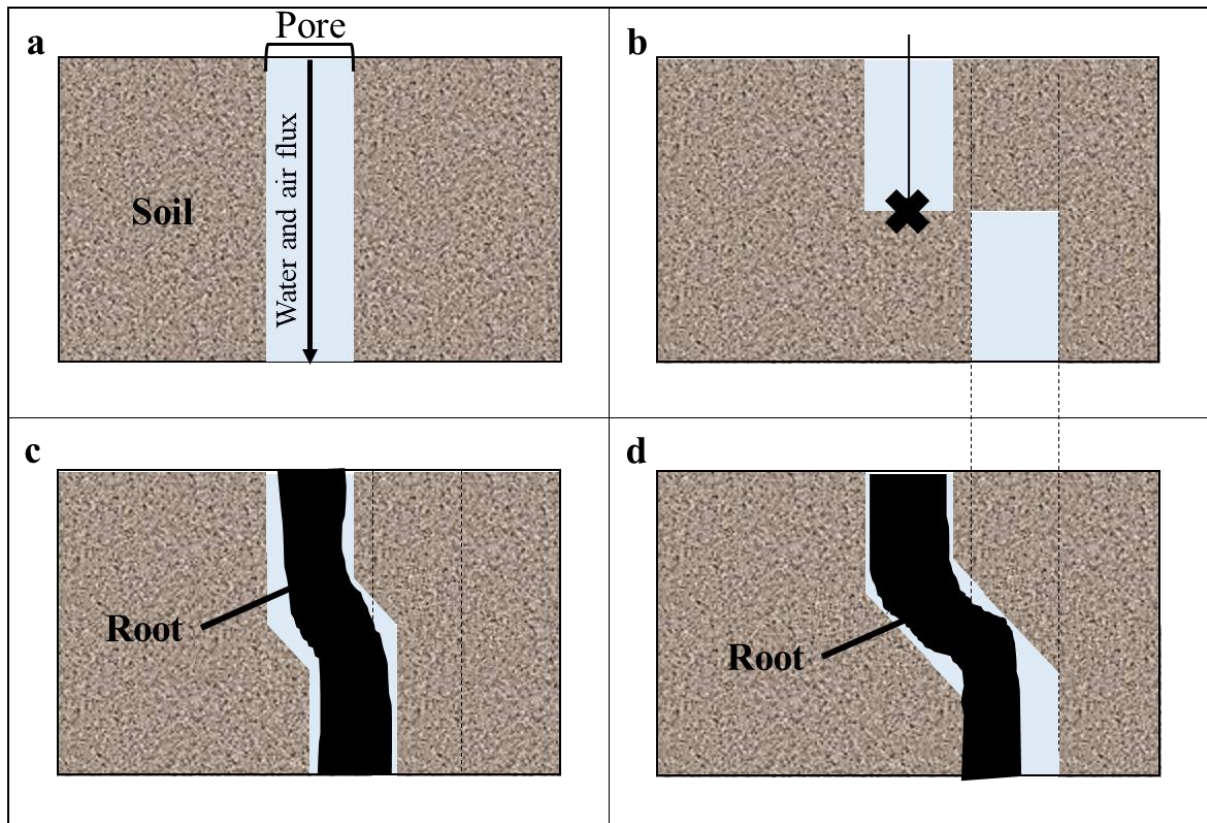


Figure 23: Schematic representation of soil deformation after shearing stress. The dotted lines represent the bare soil deformation. a: Soil before shear : water and air can flow freely through the pore. b: Soil after shear : without roots pore continuity is broken. Air and water cannot flow anymore through the pore. c: Rooted soil after shear : Root increase soil shear strength and limit soil deformation. Pore continuity is not broken and water and air can still flow through the pore. d: Hypothetic rooted soil after shear : Root did not increase soil shear strength and soil deformation is the same. Root did not break and kept the pore continuous, which allow air and water to flow through.

## 7.2. Knowledge gaps and perspectives to improve the understanding of plant capacity to conserve soil properties during traffic

### **7.2.1. Study perspectives for the integration of the effects of root traits on soil reinforcement processes to conserve soil physical properties during traffic**

Highlighting evidences of the plants' implication in the conservation of soil physical properties during traffic was the first step of this thesis. We underline that root traits of annual crop species are able to increase soil shear strength and that it should explain at least partially the soil physical properties conservation. However, more studies are required to well-understand how plants are able to conserve soil physical properties during traffic. Previous studies highlighted the major role of the root tensile strength in soil reinforcement. Our studies highlight mainly morphological root traits involved in the conservation of soil physical properties during traffic. Future studies should thus assess the gradient of root tensile strength present in annual plants and identify the role it could play conjointly with root morphological traits in soil reinforcement or in soil physical properties conservation in agrosystems. Soil shear strength and soil physical properties conservation should also be measured simultaneously. Doing so would allow us to examine whether soil reinforcement to shear is the major factor playing a role in the conservation of soil physical properties.

Other process not taken into account in our study could also be influential such as the role of the aboveground biomass on the stress transmission which was hardly ever measured in literature. Silva et al. (2016) showed that presence of straw can reduce the pressure applied on the soil by increasing the contact area. Dense living biomass could thus serve as a mat of sort, reducing the stress applied on the soil and could decrease deformation induced on the soil. Finally, the role of the soil microorganisms was not taken into account in our experiment. Their relationship with soil structure is known (Cui and Holden, 2015) and their activities could be shaped by the roots (Mendes et al., 1999). The hypothesis is that different microbial communities would have been promoted by the species selected and could have had various effects on soil aggregation and on soil structure which could finally influenced the conservation of soil properties during traffic.

## **7.2.2. Functionally diverse mixtures to optimize the compaction mitigation during traffic**

Roots are able to counteract the deformation and their capacity to colonize the soil and fill the pore seems to be a key factor to conserve soil physical properties during traffic. Roots distribution in the soil is highly heterogeneous given the high variation of architectural root traits among species and varieties and the high root plasticity in response to soil heterogeneity in the same species (Figure 24). Reinforcing the topsoil is most important as it's where the stress will be the highest. However even if the reinforced topsoil is less deformed, it will not limit stress propagation and deformation can occur deeper if soil is weaker in deeper layers. Complementarity effects could thus be expected for plant associations with architectural root traits reinforcing both the soil surface as well as the deeper layers and thus fully limiting deformation. Diverse species with contrasting architectural and morphological root traits in mixtures would be the best-suited solution to colonise and reinforce the different parts of the soil homogeneously. A Perspective is then to study the plausible complementarity between architectural root traits by comparing monospecific and multispecific crops presenting high functional diversity and their effects on soil properties conservation. Our experiments only highlighted the role of the root morphology and its distribution in the soil, however other root traits could be involved including root traits related to the root capacity to increase soil shear strength independently of the density as for example the root tensile strength. Species selected should thus present root traits influential on two properties: (1) the root capacity to increase soil shear strength and (2) the spreading pattern that will define the preferential growing horizon. We highlighted that root capacity to increase soil shear strength is one process involved in the soil physical properties conservation during traffic but other processes might also play a role. Once the process is well-identified and understood, multispecific crops could also be selected to provide even higher benefits via several simultaneous processes.

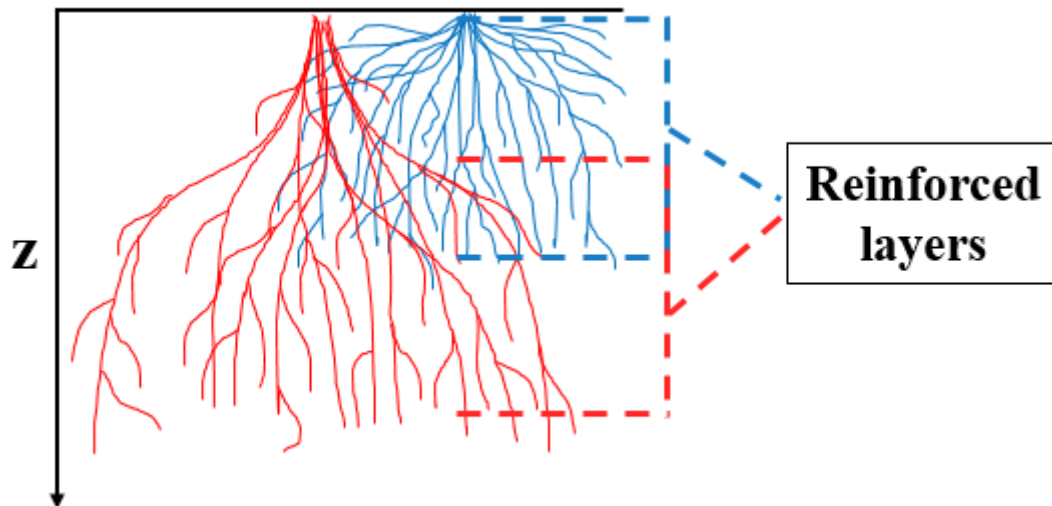


Figure 24: Schematic representation of architectural diversity and its effect on soil reinforcement. Blue roots reinforce the topsoil while red roots will mainly reinforce the layer underneath.

### 7.2.3. Designing cover crops using spatial diversity to conserve soil properties during traffic and provide supplementary services

Cover crops offer to provide a wide range of ecosystems services as opposed to main crops which are selected to correspond to the specific expectations (yield and/or quality). Cover crops could thus be selected to provide optimal soil reinforcement to properly conserve soil properties during traffic. However, it could affect other services commonly provided by cover crops and trade-offs could occur between services (Figure 25, Schipanski et al., 2014). A conventional agricultural system in the North of France typically does not involve many field operations during the cover-cropping period. In this context, cover crops generally grow during winter between September and March which is also a critical period as the soil is the wettest. The two most common operations during this period are manure spreading and sowing if the cover crops are not destroyed before. The most harmful operation is manure spreading as the machinery is heavier. To reduce the trade-offs between services provided by cover crops, a spatial diversification is conceivable. The principle would be to sow cover crops by strip with different services selected for each strip. This way, manure spreading could occur on specific strip conceived to provide high root length density and/or high root volume density which will provide efficient soil reinforcement to limit soil compaction induced during the operation. On the other hand,

side strip could be selected to provide others services such as reduced nitrate leaching or limiting erosion. However, the general spreading width is not that large compared to the general tractor width which constrain side strips size. Cover crops design could thus be conceived spatially to optimize soil reinforcement and also to supply other services. The challenges of managing cover crop designs and providing targeted services based on the functional trait approach are to take in account the intraspecific variation of root traits and the effects of abiotic factors as well as the effects of plant functional diversity on soil services. The next step is then to design for adapted complementary solutions in order to maximize the prevention of soil compaction spatially in the field and temporally for every field operations to conserve soil properties and other services ensured by cover crops

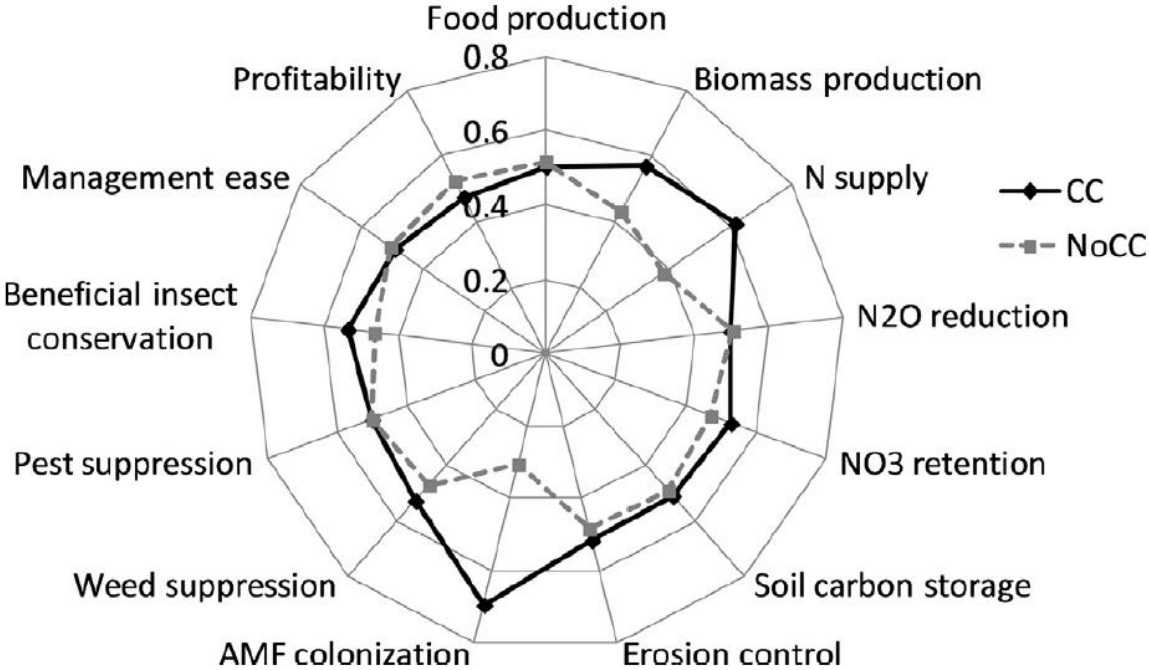


Figure 25 : Normalized values for 11 ecosystem services and two economic metrics averaged across the 3-year rotation of cropping systems with (CC) and without (NoCC) cover crops. (Schipanski et al., 2014)

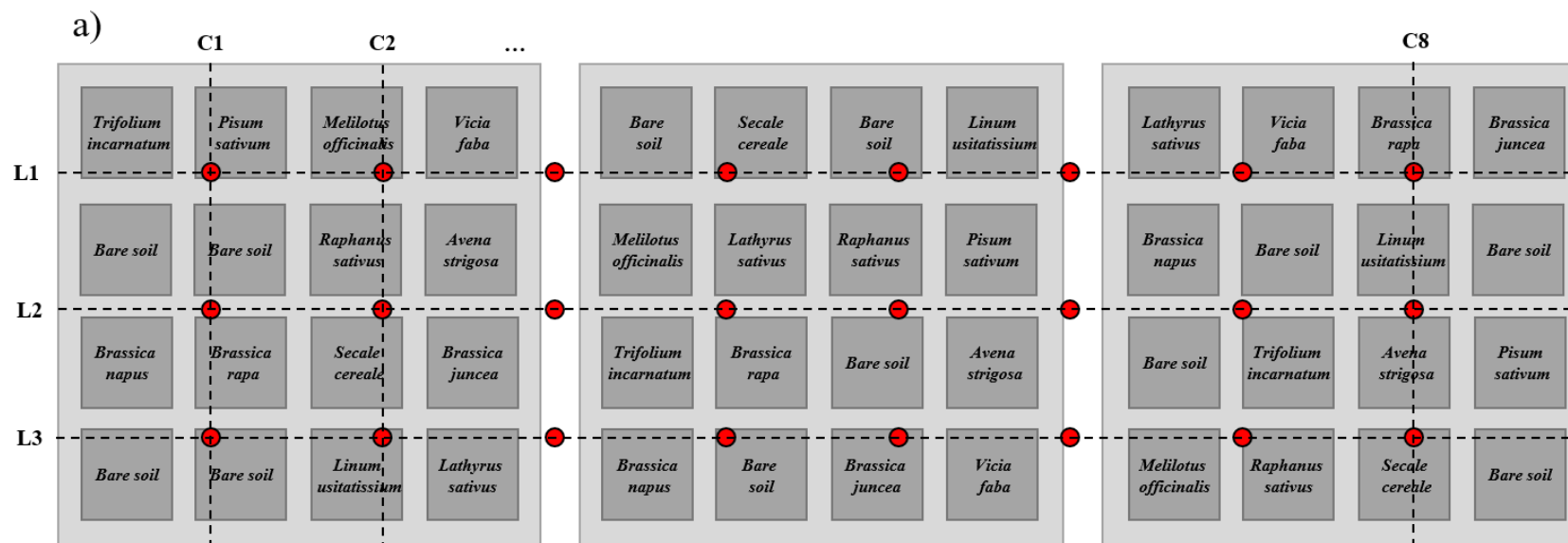


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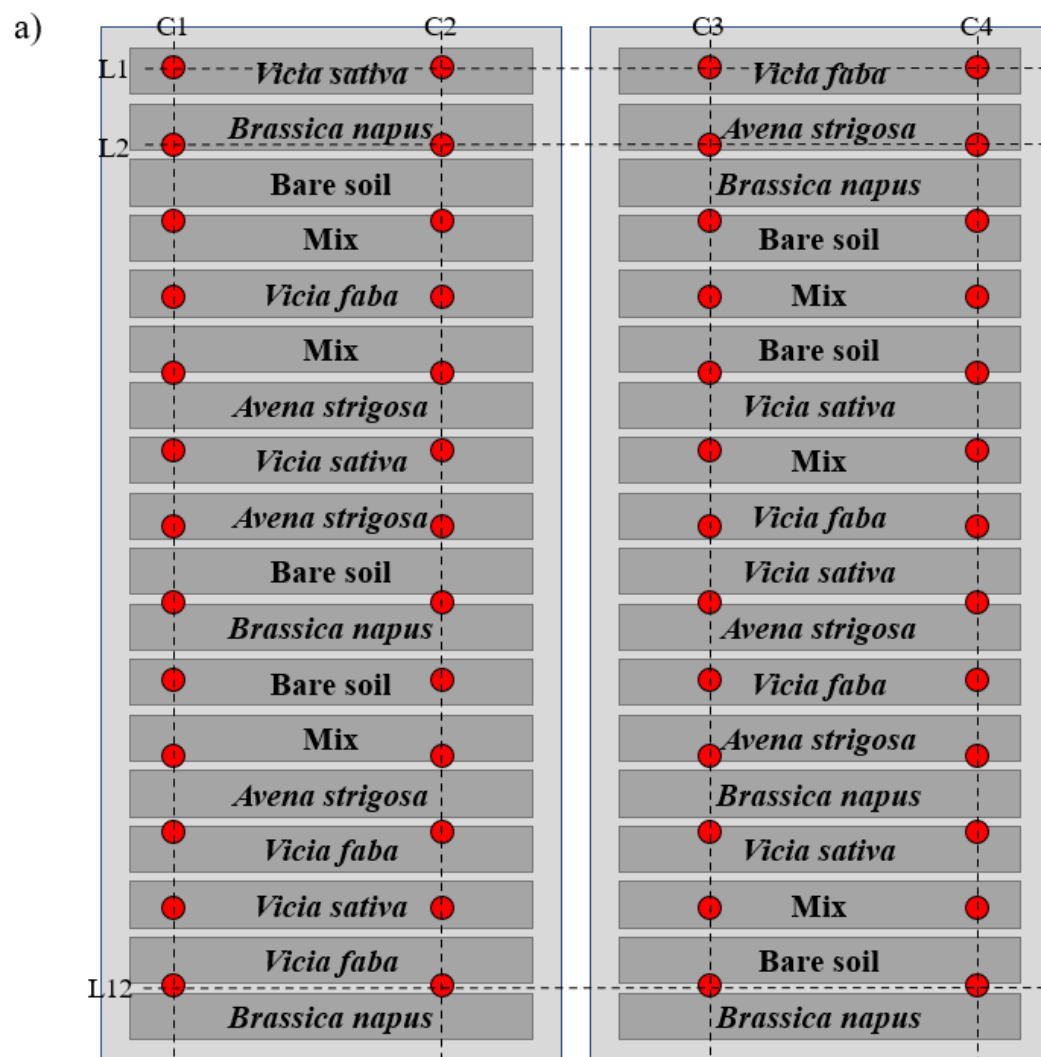
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# Appendices



b) Bulk density (g.cm <sup>-3</sup> )	C1	C2	C3	C4	C5	C6	C7	C8
L1	XX	1.31	XX	1.26	1.21	1.23	1.25	1.27
L2	1.40	1.26	1.32	1.29	1.30	1.31	1.21	1.24
L3	1.30	1.22	1.24	1.17	1.24	1.19	1.23	1.26

Appendice 1 : (a) Experimental design of the first experiment. Bulk density variation was measured on the whole plot before the experiment implementation. To do so, bulk density was measured on 24 points distributed in three lines (L1, L2 and L3) and eight columns (C1,C2... and C8). (b) Bulk density value for each point before the experiment implementation.



b) Bulk density (g.cm<sup>-3</sup>)

	C1	C2	C3	C4
L1	1.40	1.28	1.33	1.35
L2	1.28	XX	1.35	XX
L3	XX	1.36	1.36	1.36
L4	1.38	1.34	1.30	XX
L5	XX	1.41	XX	1.35
L6	1.35	1.44	1.45	1.34
L7	1.34	1.41	XX	1.25
L8	1.34	XX	1.31	1.39
L9	1.34	1.33	1.34	1.43
L10	XX	XX	1.41	1.36
L11	1.40	1.50	1.43	1.40
L12	XX	XX	1.51	1.28

Appendice 2 : (a) Experimental design of the second experiment. Bulk density variation was measured on the whole plot before the experiment implementation. To do so, bulk density was measured on 48 points distributed in twelve lines (L1, L2... and L12) and four columns (C1, C2, C3 and C4). (b) Bulk density value for each point before the experiment implementation



Code	Species	BD (g.cm <sup>-3</sup> )	Soil water content (g.g <sup>-1</sup> )	Air Flow	Permea (µm <sup>2</sup> )	Soil weight (g)	Soil dry weight (g)	Permeaspe (µm <sup>2</sup> )
B1_Av_0	Avenastrigosa	1.37	0.19	0.75	11.78	167.66	136.60	77.79
B1_Av_0	Avenastrigosa	1.37	0.17	0.80	12.56	163.92	136.50	66.75
B1_Av_0	Avenastrigosa	1.34	0.11	1.75	27.48	149.28	133.60	86.68
B1_Av_30	Avenastrigosa	1.33	0.18	0.75	11.78	162.42	132.60	65.59
B1_Av_30	Avenastrigosa	1.26	0.15	3.80	59.67	147.35	125.90	206.02
B1_Col_0	Brassicinapus	1.47	0.09	0.80	12.56	161.19	147.00	45.00
B1_Col_0	Brassicinapus	1.20	0.08	3.85	60.46	130.12	120.00	141.86
B1_Col_0	Brassicinapus	1.37	0.08	1.35	21.20	148.19	136.80	61.04
B1_Col_30	Brassicinapus	1.43	0.07	1.80	28.27	156.44	142.60	86.97
B1_Col_30	Brassicinapus	1.39	0.07	3.10	48.68	149.61	138.50	141.75
B1_Col_30	Brassicinapus	1.47	0.07	0.85	13.35	158.26	146.70	43.53
B1_Fev_0	Viciafaba	1.46	0.16	0.24	3.77	172.89	146.00	24.15
B1_Fev_0	Viciafaba	1.44	0.12	0.45	7.07	164.59	144.40	30.81
B1_Fev_0	Viciafaba	1.44	0.15	0.85	13.35	169.37	143.60	75.52
B1_Fev_30	Viciafaba	1.37	0.15	0.80	12.56	160.79	137.40	55.85
B1_Fev_30	Viciafaba	1.40	0.15	0.55	8.64	165.36	140.30	43.88
B1_Fev_30	Viciafaba	1.35	0.11	1.70	26.70	151.66	135.10	88.30
B1_Ges_0	Lathyrussativus	1.31	0.09	1.50	23.55	143.32	130.80	65.49
B1_Ges_0	Lathyrussativus	1.35	0.14	0.70	10.99	157.64	134.90	45.55
B1_Ges_0	Lathyrussativus	1.34	0.18	1.00	15.70	162.42	133.90	83.78
B1_Ges_30	Lathyrussativus	1.29	0.17	2.25	35.33	155.98	129.40	157.34
B1_Ges_30	Lathyrussativus	1.26	0.19	1.00	15.70	154.99	126.10	73.22
B1_Ges_30	Lathyrussativus	1.27	0.18	0.90	14.13	155.20	127.40	64.17
B1_Mel_0	Melilotusofficinalis	1.39	0.07	1.50	23.55	149.64	139.40	67.57
B1_Mel_0	Melilotusofficinalis	1.34	0.07	1.80	28.27	144.09	134.10	75.99
B1_Mel_0	Melilotusofficinalis	1.30	0.07	3.10	48.68	140.24	129.90	126.44
B1_Mel_30	Melilotusofficinalis	1.39	0.07	2.80	43.97	149.76	139.00	127.46

B1_Mel_30	Melilotusofficinalis	1.38	0.06	1.35	21.20	146.57	137.60	57.55
B1_Mel_30	Melilotusofficinalis	1.27	0.07	4.10	64.38	136.23	126.90	158.23
B1_Mou_0	Brassicajuncea	1.37	0.07	0.85	13.35	148.02	137.30	37.91
B1_Mou_0	Brassicajuncea	1.20	0.08	8.00	125.63	129.96	119.50	295.76
B1_Mou_0	Brassicajuncea	1.39	0.10	1.00	15.70	153.22	138.60	51.00
B1_Mou_30	Brassicajuncea	1.60	0.10	0.24	3.77	176.94	160.00	18.80
B1_Mou_30	Brassicajuncea	1.29	0.09	2.05	32.19	140.89	128.80	86.58
B1_Mou_30	Brassicajuncea	1.50	0.08	1.50	23.55	161.94	149.50	82.13
B1_Nav_0	Brassicarapa	1.51	0.09	0.70	10.99	166.01	150.70	43.38
B1_Nav_0	Brassicarapa	1.44	0.09	1.60	25.13	158.12	143.80	86.51
B1_Nav_0	Brassicarapa	1.45	0.09	1.55	24.34	158.15	144.70	82.34
B1_Nav_30	Brassicarapa	1.49	0.10	0.80	12.56	164.90	148.70	49.78
B1_Nav_30	Brassicarapa	1.49	0.10	0.55	8.64	164.66	148.80	33.82
B1_Nav_30	Brassicarapa	1.46	0.09	0.65	10.21	160.61	145.80	36.76
B1_Pois_0	Pisumsativum	1.43	0.09	1.00	15.70	156.62	142.50	52.77
B1_Pois_0	Pisumsativum	1.45	0.11	2.30	36.12	162.97	145.30	143.87
B1_Pois_0	Pisumsativum	1.28	0.09	4.00	62.81	141.35	128.40	172.19
B1_Pois_30	Pisumsativum	1.40	0.12	1.00	15.70	159.77	140.30	62.13
B1_Pois_30	Pisumsativum	1.28	0.12	2.10	32.98	145.01	127.90	101.41
B1_Pois_30	Pisumsativum	1.37	0.11	3.45	54.18	153.28	136.60	183.52
B1_Pois_30	Pisumsativum	1.31	0.07	1.90	29.84	141.07	131.10	77.71
B1_Rad_0	Raphanussativus	1.32	0.08	1.20	18.84	143.08	131.50	51.45
B1_Rad_0	Raphanussativus	1.46	0.10	0.75	11.78	162.41	146.10	45.04
B1_Rad_0	Raphanussativus	1.45	0.11	0.42	6.60	162.38	145.20	25.73
B1_Rad_30	Raphanussativus	1.49	0.09	0.50	7.85	163.08	149.20	28.70
B1_Rad_30	Raphanussativus	1.34	0.09	3.25	51.04	147.39	134.30	150.03
B1_Rad_30	Raphanussativus	1.45	0.09	1.10	17.27	158.72	145.10	59.09
B1_Sei_0	Secalecereale	1.34	0.09	2.80	43.97	147.79	133.80	131.99
B1_Sei_0	Secalecereale	1.43	0.15	0.30	4.71	169.02	143.10	26.59

B1_Sei_0	Secalecereale	1.38	0.09	3.00	47.11	151.94	138.40	147.44
B1_Sei_30	Secalecereale	1.51	0.09	0.80	12.56	166.14	151.20	49.25
B1_Sei_30	Secalecereale	1.42	0.10	0.55	8.64	158.48	142.00	31.30
B1_Sn_0	Baresoil	1.38	0.18	0.70	10.99	169.19	138.40	74.77
B1_Sn_0	Baresoil	1.36	0.18	1.10	17.27	165.71	135.50	105.18
B1_Sn_0	Baresoil	1.38	0.13	0.75	11.78	158.59	137.70	47.34
B1_Sn_30	Baresoil	1.32	0.15	1.65	25.91	154.82	132.20	102.36
B1_Sn_30	Baresoil	1.39	0.16	1.10	17.27	165.14	139.10	90.08
B1_Sn_30	Baresoil	1.29	0.16	3.80	59.67	153.49	129.40	239.21
B1_Tre_0	Trifoliumincaranatum	1.35	0.12	1.65	25.91	153.07	134.50	91.05
B1_Tre_0	Trifoliumincaranatum	1.27	0.09	4.10	64.38	138.82	126.90	168.98
B1_Tre_0	Trifoliumincaranatum	1.33	0.10	2.70	42.40	146.88	132.50	126.81
B1_Tre_30	Trifoliumincaranatum	1.38	0.07	1.60	25.13	149.43	138.30	73.04
B1_Tre_30	Trifoliumincaranatum	1.35	0.09	4.30	67.52	147.65	134.50	199.32
B1_Tre_30	Trifoliumincaranatum	1.25	0.07	11.00	172.74	133.52	124.50	411.81
B2_Av_0	Avenastrigosa	1.22	0.11	10.00	157.03	136.39	121.90	418.76
B2_Av_0	Avenastrigosa	1.17	0.09	3.90	61.24	128.22	116.60	144.25
B2_Av_0	Avenastrigosa	1.25	0.10	1.80	28.27	137.91	124.80	74.90
B2_Av_30	Avenastrigosa	1.28	0.12	6.50	102.07	145.10	128.40	311.86
B2_Av_30	Avenastrigosa	1.18	0.14	4.30	67.52	137.59	118.30	197.91
B2_Av_30	Avenastrigosa	1.34	0.09	1.50	23.55	147.43	134.40	69.20
B2_Col_0	Brassicnapus	1.25	0.07	7.00	109.92	133.88	124.60	263.94
B2_Col_0	Brassicnapus	1.30	0.13	1.35	21.20	149.30	130.10	71.72
B2_Col_0	Brassicnapus	1.36	0.11	1.10	17.27	152.38	136.20	57.24
B2_Col_30	Brassicnapus	1.23	0.07	3.50	54.96	132.26	123.00	129.94
B2_Col_30	Brassicnapus	1.38	0.08	1.30	20.41	150.22	138.30	60.74
B2_Col_30	Brassicnapus	1.23	0.11	6.00	94.22	138.47	122.80	261.97
B2_Fev_0	Viciafaba	1.48	0.15	0.70	10.99	174.23	147.50	72.43
B2_Fev_0	Viciafaba	1.35	0.13	1.30	20.41	155.42	134.70	77.83



B2_Fev_0	Viciafaba	1.30	0.13	1.85	29.05	149.46	130.40	98.20
B2_Fev_30	Viciafaba	1.40	0.10	0.70	10.99	155.08	139.70	37.14
B2_Fev_30	Viciafaba	1.38	0.12	0.90	14.13	157.59	137.90	54.36
B2_Fev_30	Viciafaba	1.55	0.12	0.24	3.77	176.43	155.10	21.43
B2_Ges_0	Lathyrussativus	1.44	0.16	2.05	32.19	172.11	144.30	209.61
B2_Ges_0	Lathyrussativus	1.43	0.15	1.30	20.41	169.06	143.00	115.86
B2_Ges_0	Lathyrussativus	1.57	0.17	0.22	3.45	188.89	157.00	55.05
B2_Ges_30	Lathyrussativus	1.52	0.15	0.23	3.61	179.24	152.30	27.62
B2_Ges_30	Lathyrussativus	1.43	0.16	0.28	4.40	170.87	143.00	27.81
B2_Ges_30	Lathyrussativus	1.26	0.16	2.20	34.55	151.27	126.40	136.29
B2_Lin_0	Linumusatissium	1.32	0.11	1.50	23.55	149.21	132.40	75.87
B2_Lin_0	Linumusatissium	1.27	0.07	2.50	39.26	136.22	126.90	96.46
B2_Lin_0	Linumusatissium	1.40	0.15	1.20	18.84	163.77	140.00	89.34
B2_Lin_30	Linumusatissium	1.32	0.08	4.40	69.09	142.95	131.50	187.97
B2_Lin_30	Linumusatissium	1.35	0.07	2.00	31.41	144.33	134.80	84.02
B2_Lin_30	Linumusatissium	1.43	0.07	0.80	12.56	152.86	142.50	37.48
B2_Mel_0	Melilotusofficinalis	1.23	0.07	7.00	109.92	131.70	122.60	257.95
B2_Mel_0	Melilotusofficinalis	1.35	0.06	3.50	54.96	143.46	135.20	142.79
B2_Mel_30	Melilotusofficinalis	1.45	0.07	3.10	48.68	155.70	145.40	150.09
B2_Mel_30	Melilotusofficinalis	1.44	0.06	1.70	26.70	153.63	143.80	79.61
B2_Mel_30	Melilotusofficinalis	1.39	0.07	9.00	141.33	149.53	139.30	404.87
B2_Mou_0	Brassicajuncea	1.27	0.07	3.80	59.67	136.23	126.50	147.53
B2_Mou_0	Brassicajuncea	1.27	0.12	1.10	17.27	144.81	127.30	53.39
B2_Nav_0	Brassicarapa	1.25	0.16	1.45	22.77	147.81	124.80	81.79
B2_Nav_0	Brassicarapa	1.29	0.12	1.20	18.84	146.69	129.30	59.47
B2_Nav_0	Brassicarapa	1.44	0.12	1.10	17.27	162.59	143.60	70.64
B2_Nav_30	Brassicarapa	1.44	0.13	0.75	11.78	165.63	144.30	53.93
B2_Nav_30	Brassicarapa	1.41	0.11	0.85	13.35	159.20	141.00	50.81
B2_Nav_30	Brassicarapa	1.40	0.14	1.50	23.55	163.11	140.10	107.99

B2_Pois_0	Pisumsativum	1.43	0.14	0.65	10.21	165.88	142.80	49.36
B2_Pois_0	Pisumsativum	1.45	0.15	0.65	10.21	170.37	145.30	57.65
B2_Pois_30	Pisumsativum	1.19	0.15	10.00	157.03	140.42	119.40	491.39
B2_Pois_30	Pisumsativum	1.31	0.18	3.10	48.68	158.84	131.00	236.70
B2_Pois_30	Pisumsativum	1.33	0.20	2.60	40.83	166.27	132.87	286.13
B2_Rad_0	Raphanussativus	1.39	0.09	7.00	109.92	151.95	138.50	343.49
B2_Rad_0	Raphanussativus	1.28	0.09	4.10	64.38	140.28	127.80	173.14
B2_Rad_30	Raphanussativus	1.40	0.08	4.80	75.38	152.46	140.10	232.20
B2_Rad_30	Raphanussativus	1.48	0.09	0.48	7.54	163.46	148.10	28.65
B2_Sei_0	Secalecereale	1.36	0.13	1.05	16.49	156.04	135.60	63.04
B2_Sei_0	Secalecereale	1.45	0.14	0.75	11.78	169.31	144.90	63.59
B2_Sei_0	Secalecereale	1.45	0.13	0.44	6.91	165.87	144.50	31.81
B2_Sei_30	Secalecereale	1.35	0.09	1.65	25.91	148.13	135.00	76.88
B2_Sei_30	Secalecereale	1.44	0.11	0.55	8.64	161.14	144.10	32.96
B2_Sei_30	Secalecereale	1.43	0.13	0.70	10.99	164.82	143.10	50.15
B2_Sn_0	Baresoil	1.39	0.18	0.85	13.35	169.55	138.70	91.91
B2_Sn_0	Baresoil	1.41	0.18	0.65	10.21	172.38	140.50	79.84
B2_Sn_0	Baresoil	1.44	0.18	0.80	12.56	175.65	143.70	109.68
B2_Sn_30	Baresoil	1.38	0.18	0.70	10.99	167.52	137.80	68.67
B2_Sn_30	Baresoil	1.33	0.18	1.00	15.70	161.62	132.80	83.19
B2_Sn_30	Baresoil	1.44	0.17	0.55	8.64	173.66	144.30	62.55
B2_Tre_0	Trifoliumincaranatum	1.31	0.10	2.20	34.55	144.78	130.70	100.30
B2_Tre_0	Trifoliumincaranatum	1.23	0.07	4.65	73.02	132.37	122.80	173.59
B2_Tre_0	Trifoliumincaranatum	1.37	0.08	1.30	20.41	148.06	136.90	58.46
B2_Tre_30	Trifoliumincaranatum	1.29	0.09	1.50	23.55	141.28	129.20	63.60
B2_Tre_30	Trifoliumincaranatum	1.56	0.07	0.48	7.54	168.16	155.90	28.62
B2_Tre_30	Trifoliumincaranatum	1.30	0.07	2.65	41.61	139.29	129.70	105.81
B3_Av_0	Avenastrigosa	1.43	0.09	0.45	7.07	156.26	142.58	23.43
B3_Av_0	Avenastrigosa	1.47	0.09	0.55	8.64	160.88	147.20	30.47

B3_Av_0	Avenastrigosa	1.36	0.11	1.45	22.77	152.32	135.90	75.76
B3_Av_30	Avenastrigosa	1.40	0.11	0.60	9.42	158.12	140.10	35.15
B3_Av_30	Avenastrigosa	1.11	0.28	1.00	15.70	154.05	110.50	121.45
B3_Av_30	Avenastrigosa	1.33	0.14	0.49	7.69	154.60	133.10	29.51
B3_Col_0	Brassic napus	1.24	0.08	2.40	37.69	135.09	124.10	93.91
B3_Col_0	Brassic napus	1.23	0.07	3.60	56.53	132.64	122.80	135.26
B3_Col_30	Brassic napus	1.25	0.07	4.10	64.38	135.25	125.30	158.19
B3_Col_30	Brassic napus	1.40	0.08	2.75	43.18	152.33	140.10	132.50
B3_Col_30	Brassic napus	1.34	0.08	3.00	47.11	144.58	133.50	129.63
B3_Fev_0	Vicia faba	1.38	0.10	1.20	18.84	153.56	138.00	62.63
B3_Fev_0	Vicia faba	1.15	0.14	2.50	39.26	134.18	114.80	110.88
B3_Fev_0	Vicia faba	1.31	0.12	0.90	14.13	148.62	130.90	46.00
B3_Fev_30	Vicia faba	1.23	0.10	7.00	109.92	135.37	122.50	282.70
B3_Fev_30	Vicia faba	1.15	0.10	6.00	94.22	127.75	115.10	224.24
B3_Fev_30	Vicia faba	1.38	0.08	2.45	38.47	150.27	137.70	115.89
B3_Ges_0	Lathyrus sativus	1.48	0.15	1.00	15.70	174.74	148.40	103.22
B3_Ges_0	Lathyrus sativus	1.34	0.18	0.65	10.21	161.97	133.60	53.69
B3_Ges_0	Lathyrus sativus	1.33	0.16	1.05	16.49	158.71	133.10	75.05
B3_Ges_30	Lathyrus sativus	1.42	0.18	0.60	9.42	172.39	142.10	68.55
B3_Ges_30	Lathyrus sativus	1.23	0.16	2.25	35.33	146.84	123.40	126.37
B3_Ges_30	Lathyrus sativus	1.45	0.17	0.26	4.08	174.46	145.10	30.26
B3_Lin_0	Linum usitatissimum	1.51	0.14	0.32	5.03	174.12	150.50	29.38
B3_Lin_0	Linum usitatissimum	1.26	0.10	2.30	36.12	140.72	126.30	100.78
B3_Lin_30	Linum usitatissimum	1.24	0.08	4.90	76.95	135.18	123.80	193.03
B3_Lin_30	Linum usitatissimum	1.41	0.13	3.25	51.04	162.38	141.00	221.05
B3_Lin_30	Linum usitatissimum	1.27	0.11	3.20	50.25	142.72	127.30	145.89
B3_Mel_0	Melilotus officinalis	1.28	0.06	2.60	40.83	136.47	128.00	99.30
B3_Mel_0	Melilotus officinalis	1.44	0.07	1.00	15.70	153.99	143.90	47.25
B3_Mel_30	Melilotus officinalis	1.37	0.07	1.60	25.13	146.28	136.70	68.68

B3_Mel_30	Melilotusofficinalis	1.43	0.09	2.00	31.41	156.71	142.70	105.43
B3_Mou_0	Brassicajuncea	1.37	0.07	1.15	18.06	148.25	137.30	51.63
B3_Mou_0	Brassicajuncea	1.40	0.07	1.30	20.41	150.73	139.90	59.92
B3_Mou_30	Brassicajuncea	1.30	0.07	3.10	48.68	140.61	130.10	127.27
B3_Mou_30	Brassicajuncea	1.29	0.07	3.20	50.25	139.65	129.30	129.76
B3_Mou_30	Brassicajuncea	1.25	0.06	2.70	42.40	133.02	124.50	99.89
B3_Nav_0	Brassicarapa	1.27	0.08	3.60	56.53	138.59	127.20	146.79
B3_Nav_0	Brassicarapa	1.25	0.10	1.50	23.55	139.11	125.10	64.15
B3_Nav_30	Brassicarapa	1.34	0.08	1.60	25.13	145.86	134.20	70.80
B3_Nav_30	Brassicarapa	1.24	0.09	1.90	29.84	136.24	124.46	76.11
B3_Pois_0	Pisumsativum	1.42	0.09	1.10	17.27	155.94	142.40	56.87
B3_Pois_0	Pisumsativum	1.44	0.10	3.60	56.53	160.39	143.80	211.14
B3_Pois_0	Pisumsativum	1.39	0.10	0.60	9.42	154.19	138.60	31.59
B3_Pois_30	Pisumsativum	1.41	0.14	0.70	10.99	164.95	141.30	53.10
B3_Pois_30	Pisumsativum	1.41	0.15	0.60	9.42	166.82	141.00	50.53
B3_Pois_30	Pisumsativum	1.42	0.13	0.40	6.28	162.14	141.60	26.51
B3_Rad_0	Raphanussativus	1.32	0.11	1.00	15.70	148.16	131.50	49.77
B3_Rad_0	Raphanussativus	1.33	0.08	1.40	21.98	144.74	132.80	61.48
B3_Rad_0	Raphanussativus	1.34	0.16	0.65	10.21	159.06	133.50	46.69
B3_Rad_30	Raphanussativus	1.31	0.11	1.80	28.27	146.97	131.40	86.50
B3_Rad_30	Raphanussativus	1.31	0.11	3.00	47.11	146.96	131.20	144.65
B3_Rad_30	Raphanussativus	1.29	0.09	4.30	67.52	141.28	129.10	182.62
B3_Sei_0	Secalecereale	1.30	0.08	3.65	57.32	141.48	130.40	152.59
B3_Sei_0	Secalecereale	1.26	0.06	2.80	43.97	133.86	126.46	102.75
B3_Sei_0	Secalecereale	1.33	0.09	1.20	18.84	145.13	132.50	53.56
B3_Sei_30	Secalecereale	1.20	0.10	6.80	106.78	132.19	119.50	265.33
B3_Sei_30	Secalecereale	1.29	0.09	14.50	227.70	142.23	128.80	635.27
B3_Sei_30	Secalecereale	1.38	0.10	1.30	20.41	153.27	138.10	67.06
B3_Sn_0	Baresoil	1.43	0.19	1.90	29.84	177.07	143.40	302.84

B3_Sn_0	Baresoil	1.36	0.21	0.40	6.28	173.08	136.40	65.44
B3_Sn_0	Baresoil	1.40	0.20	0.65	10.21	175.01	139.54	106.63
B3_Sn_30	Baresoil	1.34	0.20	0.30	4.71	167.25	133.50	34.46
B3_Sn_30	Baresoil	1.40	0.20	0.24	3.77	174.88	139.50	38.94
B3_Sn_30	Baresoil	1.41	0.20	0.24	3.77	177.84	141.40	47.89
B3_Tre_0	Trifoliumincaranatum	1.27	0.10	1.70	26.70	141.57	127.30	75.00
B3_Tre_0	Trifoliumincaranatum	1.42	0.08	0.75	11.78	153.09	141.60	35.97
B3_Tre_0	Trifoliumincaranatum	1.41	0.07	1.50	23.55	151.83	141.00	70.03
B3_Tre_30	Trifoliumincaranatum	1.42	0.08	0.55	8.64	154.78	142.30	27.44
B3_Tre_30	Trifoliumincaranatum	1.24	0.07	4.10	64.38	133.05	123.60	153.77
B3_Tre_30	Trifoliumincaranatum	1.42	0.08	0.75	11.78	154.66	142.20	37.35

*Appendice 4 : Soil properties raw data of the first experiment*

## **Rôle des traits racinaires dans la conservation des propriétés du sol lors du tassement induit par le passage d'engins agricoles**

Le tassement du sol est reconnu comme une menace pour l'agrosystème. Les racines pourraient permettre une meilleure conservation des propriétés du sol, limitant les conséquences néfastes du tassement. Cette thèse vise à examiner:

- (1) les effets des traits racinaires sur la conservation des sols en utilisant de larges gradients de traits racinaires
- (2) le rôle de la structure du sol sur la réponse et l'effet des traits racinaires dans la conservation du sol
- (3) les effets des traits racinaires des cultures annuelles sur la résistance du sol au cisaillement

Des expériences in situ ont été mises en place pour répondre aux deux premiers objectifs. Pour répondre au troisième objectif, une expérience en laboratoire a été mise en place.

L'identification des effets des traits racinaires sur la conservation des propriétés du sol et l'examen de la relation racines-sol ont mis en évidence le rôle des racines dans la conservation des propriétés physiques du sol. La comparaison de la résistance au cisaillement du sol contenant des racines a mis en évidence la capacité des espèces annuelles à augmenter la résistance du sol au cisaillement. La conservation des propriétés physiques du sol peut-être dû à l'augmentation de la résistance du sol au cisaillement. Cependant, la conservation du sol ou l'augmentation de la résistance au cisaillement n'est pas systématique et dépend des traits racinaires, des propriétés du sol et de la déformation induite. Cette thèse constitue la première étape vers une compréhension plus profonde du rôle des racines dans la conservation des sols lors du passage d'engins agricoles.

**Mots-clés** : Conservation des sols, Tassement, Mécanique des sols, Physique des sols, Ecologie fonctionnelle ; Cisaillement ; Agrosystème ; Agriculture de conservation

## **Role of root traits in the conservation of soil properties during compaction induced by traffic for new services of cover crops**

Soil compaction is recognized as a major threat in agrosystem. Roots were considered to alleviate soil compaction but never as a possible solution to conserve soil properties during traffic. The thesis objectives are:

- (1) the root traits effects on soil conservation by using wide gradients of root traits
- (2) the role of soil structure on response and effect of root traits in the soil conservation
- (3) understand how roots could conserve soil properties by studying the effects of cover crop root traits on soil shear strength.

In-situ experiments were set up to answer first and second objectives. To answer the third objective, a laboratory experiment was implemented. A direct shear box was built during the thesis to measure the soil shear strength.

The identification of root traits effects on conservation of soil properties and the examination of the root-soil relationship highlighted key evidences of the role of roots in the soil conservation properties during traffic. The comparison of soil shear strength highlighted that annual species are able to increase soil shear strength. The conservation of soil properties during compaction could thus be due to the soils shear strength increase. However, all the experiments also highlighted that soil conservation or increase of soil shear strength is not systematic on a rooted soil and depend on root traits, soil properties and on the type and scale of deformation induced by traffic. This PhD work constitutes the first step for a deepest understanding of the role of roots in the soil conservation during traffic. Besides, it emphasizes the potential use of crops services to complement the existing solutions to cope with soil compaction.

**Keywords**: Soil conservation, compaction, soil mechanic, soil physics, Functional ecology, Shear, Agrosystem, Conservation agriculture