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RESEARCH ARTICLE

Different fall/winter cover crop root patterns induce contrasting red soil (Ultisols) mechanical resistance through aggregate properties

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Abstract

Purpose Red soil (Ultisol) with high clay content and low aggregation results in high soil mechanical resistance and often suppresses crop root growth and productivity. Bio-tillage can be an effective tillage method to reduce the high soil mechanical resistance. This study aims to investigate different bio-tillage plants' root effects on soil mechanical resistance through soil aggregates properties.

Methods The experiment designed 5 fall/winter cover crops (2 raps cultivars, lucerne, one-year vetiver (Vet_1Y) and six-year vetiver (Vet_6Y) as bio-tillage before summer maize and one control treatment. Plant root morphological and chemical traits, soil organic carbon (SOC), soil aggregate properties and soil mechanical resistance (measured and fitted values using model) were determined.

Results The fibrous-rooted vetiver showed the largest root length density (RLD) (ranging from 2.71 to 4.82 cm cm^{-3}), highest root diameter (RD) in deep soil depth, highest percentage of fine roots (0.2–0.5 mm), while lowest root lignin/cellulose ratio than tap-rooted lucerne and rapes. These root properties resulted in the highest improvement in the macroaggregate (> 5 mm and 5–2 mm) percentage for vetiver and especially for perennial Vet_6Y compared to other crops and control. Finally, fibrous-rooted vetiver contributed to the least soil mechanical resistance values followed by lucerne and two rapes compared to fallow. This was attributed to their positive root effect on improvement in macroaggregate and decrease in soil bulk density.

Conclusion Our finding suggested that fibrous-rooted vetiver can be selected as a bio-tillage plant to improve soil physical properties, especially to reduce high mechanical resistance in clayey red soil.

Highlights
- Cover crops root performance were compared in clayey red soil (Ultisols)
- Fibrous-root vetiver shows the largest RLD and deeper root distribution in Ultisols
- RLD, fine and medium root portion, lignin/cellulose ratio, and SOC were beneficial for aggregation
- High macroaggregate % and low bulk density decrease soil mechanical resistance
- Fibrous-rooted vetiver reduces the most in soil mechanical resistance

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Introduction

High soil mechanical resistance due to compaction by intensive field traffic or high clay content often suppresses crop roots growth and productivity. Red soil (Ultisol) in subtropical climate has low organic matter content, high proportion of microaggregate, and high subsoil bulk density (>30 cm, 1.5 g cm^{-3}) (Yang et al. 2013), and therefore, results in its high soil mechanical resistance. High soil mechanical resistance in these soils is common (>2 MPa), and tillage only provides a temporary solution. An alternative solution to this problem is bio-tillage (He et al. 2022a).

Bio-tillage, using deep-rooted plant roots as a tillage tool to improve soil quality, may be an effective approach to reduce soil mechanical resistance (Zhang and Peng 2021). Research showed that cover crops including oat (*Avena sativa L*) and vetiver significantly reduced soil mechanical resistance compared to control (no plant) (He et al. 2022a; Mupambwa and Wakindiki 2012), probably through the developing of root channels, changing in soil water content, and building in good soil aggregate structure (Han et al. 2015a; Jabro et al. 2021). However, cover crop roots were reported to result in different soil aggregation and their subsequent effect on reduction in soil compaction, probably because cover crop root types and cover crop application years can induce contrasting soil aggregation properties. Firstly, plants with high root length density (RLD) (i.e., RLD of buckwheat = 0.3 cm cm^{-3}) and high root biomass generally favored macroaggregate formation by entrapping microaggregate together (Hudek et al. 2022; Poirier et al. 2018; Vannoppen et al. 2017;). In addition, research showed that 34 continuous years of cover crop (hairy vetch) application in a silt loam soil showed an obvious improvement in aggregate mean weight diameter (MWD) (3.01 mm) and lower penetration resistance (1.27 MPa) compared to no cover soil (Nouri et al. 2019). In contrast, a two-year-period cover crop oat (*Avena sativa L*) before soybean season did not significantly improved soil physical properties (Bertollo et al. 2021).

Except for the cover crop root traits' effect, the soil properties (i.e., texture and soil organic carbon) also determined the degree of root beneficial effect on soil aggregation and the concomitant soil mechanical resistance. The contrasting influence of the same type of cover crop on aggregation was reported in different textured soils. In a silt loam soil, tap-rooted alfalfa (*Medicago sativa*) resulted in a 19% increased in soil aggregation than switchgrass (*Panicum virgatum*) and bare soil (Li et al. 2015; Rasse et al. 2000). However, in clayey soil, the fibrous-root vetiver with a high RLD and high percentage of root (<0.2 mm) penetrated more into the space between soil particles and allowed a higher opportunity to re-orientate and change the interaction between soil particles than tap-rooted lucerne (Chen et al. 2021). In addition, various SOC as a result from roots (morphological and chemical properties) might also induce different soil aggregation. Fibrous root plant (*Zoysia matrella* L) had the highest SOC (10.7 g/kg) compared to taproot crop (*Amorpha fruticose* L) (6.4 g/kg) in a clayey soil (Hao et al. 2020), due to the fact that plant roots having a lower lignin/cellulose ratio were more easily decomposed gradually into SOC than roots with a higher lignin/cellulose ratio (Zhang and Wang 2015) and thus was beneficial for its high aggregation. Generally, the matching between root traits and soil properties (texture and structure) affected the root-soil interaction and, therefore, will influence the formation or destruction of soil aggregates and soil mechanical resistance.

In subtropical climate of clayey red soil region, the climate allowed for 2 or 3 cycles of crop rotation (Chen et al. 2021) and provided a possibility of using different cover crops to alleviate the high soil mechanical resistance of red soil through their root positive effect on soil aggregation. However, the compatibility of the cover crop root system with the clayey red soil and their function on aggregate still remain unclear. We hypothesize that fibrous root plants are better than taproot plants to increase higher aggregate stability through the direct intrinsic root traits and their indirect effect SOC content than taproot, which further reduces soil mechanical resistance of red soil. The objectives of this research were to 1) investigate fall/winter cover crop root traits' influence on aggregate properties; and 2) to investigate the relationship between root traits, aggregate, and soil mechanical resistance.

Materials and methods

Study site description and research design

The study site was located at a research station (30°01'N, 114°21'E) affiliated with the Huazhong Agricultural University in southeast Hubei, China. The study site had an annual mean temperature of about 16.8 °C, annual mean precipitation of about 1474 mm, and average potential evaporation of 1497 mm. The rainy season mainly occurred from April to June, accounting for about 70% of total precipitation. The cropping system in this region allows for two or three crops per year, with different cover crops in autumn–winter, and the cover crops are generally harvested in the following spring to make way for summer maize or rice. At the study site, the red soils are developed from Quaternary red clay and are classified as Ultisols using the USDA Soil Taxonomy system, and the basic soil properties are shown in Table 1.

The experimental field included 24 plots, and each plot was 2 m × 3 m and used three plant species as treatments to investigate their root traits, root traits effects on soil organic carbon, soil aggregate stability and their subsequent effect on soil mechanical resistance. The plant species included two oilseed rapes: Rape_C (*Brassica napus* L. *cv.* Huashuang 4) and Rape_D (*Brassica napus* L. *cv.* Xinan 28) (a variety with a strong rooting ability) (Chen et al. 2021), lucerne (*Medicago sativa* L. cv. Ladino) (Luc_1Y), and one-year-old vetiver grass (*Chrysopogon zizanioides* L. *cv.* Wild) (Vet_1Y). In order to compare the annual and perennial cover crop root effects on soils, 6-year-old vetiver (Vet_6Y) was also selected as one of the treatments, which was planted in 2014 without grazing until 2021. Rape and lucerne are dicotyledonous crops with taproot systems, while vetiver grass is a monocotyledon with a fibrous root system. Rape and lucerne were sown in late September of 2018, 2019 and 2020 and thinned mid-November of each year to achieve 5 rows (row width was 20 cm) with 14 plants per row per plot. The experiment also had a control treatment, as fallow in winter. Each treatment had four replications in a randomized block design. NPK fertilizers were applied to each plot annually following local recommendations (N: 100 kg ha^{-1} as $CO(NH_2)_2$; P: 100 kg ha^{-1} as $Ca(H_2PO_4)_2 \cdot 2H_2O$; K: 50 kg ha^{-1} as KCl).

Root traits measurement

In May 2021, soil samples containing roots were collected using cutting rings (200 cm^3) from three soil depths (0–10, 10–20, and 20–40 cm) in three replications, with three subsamples (cores) per depth per treatment (Chen et al. 2021), in order to obtain root morphological traits (root diameter, root length density, root volume density, and root surface density) and chemical traits (lignin, and cellulose). In this study, we only used the root traits from the year 2021 to better display the 3-year effect of cover crop roots on the soil. The cutting ring cores were then transported/stored in nylon bags, soaked in water for 1 h, and then washed by hand using a sieve with a mesh size of 0.55 mm to collect the roots. The roots were then scanned with an Epson perfection V800 photo, and the root length (RL), root diameter (RD), root surface area (RSA), and root volume (RV) were analyzed with WinRHI20 Pro Version2009c. Root length density (RLD), root surface area density (RSD), and root volume density (RVD) were further calculated as the RL, RSA, and RV divided by soil volume (cm cm^{-3}). The RLD, RSD and RVD were calculated as Eqs. 1–3. In addition, using data collected from the WinRHI20 analyzer, the root system was further divided into four classes very fine root (RD < 0.2 mm), fine root (RD 0.2–0.5 mm), medium root (RD 0.5–1 mm), and coarse root (RD > 1 mm). Determination of root chemical composition (lignin and cellulose) was conducted on three subsamples of root classes (root diameter < 0.5, 0.5–1, and > 1 mm) collected above according to the method in Zhou et al. (1997).

$$Rootlengthdensity(RLD, cm/cm^3) = rootlength(cm)/soilvolume(cm^3) \tag{1}$$

$$Rootsurfaceareadensity(RSD, cm^2/cm^3) = rootsurfacearea(cm^2)/soilvolume(cm^3) \tag{2}$$

$$Rootvolumedensity(RVD, cm^3/cm^3 \times 10^{-3}) = rootvolume(cm^3)/soilvolume(cm^3) \times 10^{-3} \tag{3}$$

Soil sampling, soil organic carbon and aggregate measurement

Soil samples were also collected from depths of 0–10, 10–20, and 20–40 cm during root collection (May 2021). Soils were air-dried and separated into two parts. The first part was ground to 100 µm for determination of bulk soil SOC and the SOC on each size of soil aggregate (> 5, 5–2, 2–0.25, 0.25–0.053, and < 0.053 mm) (the separation of aggregates sizes were described below) by the oxidation with potassium dichromate (WALKLEY and BLACK 1934).

The second part was gently broken along the natural cracks and passed through an 8 mm mesh sieve in order to further analyze soil aggregate size distribution and aggregate stability. Aggregates (< 8 mm) were separated by the wet sieving method into five size classes (> 5, 5–2, 2–0.25, 0.25–0.053, and < 0.053 mm). Briefly, triplicates of 100 g of soil were submerged for 10 min in deionized water in a beaker, and then the aggregates were transferred to a series of sieves with successively reducing mesh diameter (5, 2, 0.25, and 0.053 mm), which were submerged into water to gently shaken for 10 min with 4-cm amplitude vertical vibration. After that, the soils retained in each sieve were washed and transferred into the beaker, and all the sizes of aggregates (> 5, 5–2, 2–0.25, and 0.25–0.053 mm) were oven-dried at 60 °C for 48 h and then weighed. The < 0.053 mm aggregate portion was obtained by subtraction of mass of other aggregate sizes from the total soil mass (Elliott 1986). The mean weight diameter (MWD, mm) and geometric mean diameter (GMW) were calculated as Eq. 4 and Eq. 5 (Kemper and Rosenau 1986).

$$MWD = \sum_{i=1}^{n} W_i^* X_i \tag{4}$$

where X_i is the mean diameter of the aggregate fraction, *i and* W_i is the mass proportion of the aggregate fraction *i.*

$$GMD = \exp\left[\sum_{i=1}^{n} W_i * \ln(X_i)\right] \tag{5}$$

where *Wi* is the mass proportion of the aggregate fraction, *i* and *Xi* is the mean diameter of the aggregate fraction *i.*

Soil mechanical resistance analysis

The soil mechanical resistance was measured by a SC900 soil hardness tester in 0–45 cm soil in the field, with the resistance readings being obtained every 2.5 cm across a different range of field soil water content in each treatment during 2021. Soil mechanical resistance was repeated 5 times per treatment plot across a range of soil water content periods. During soil mechanical resistance measurement, samples for soil water content at a depth of 0–10, 10–20, and 20–40 cm were also collected using soil probes, and soil water content was determined by the oven-dried method. Soil Bulk density (3 replicates) was also determined at depth of 0–10, 10–20, and 20–40 cm. Except for the measured soil mechanical resistance values, soil mechanical resistance was also predicted from soil water content values following models in Eq. (6) (da Silva et al. 1994).

$$Q = a * \theta^b \tag{6}$$

where Q is the soil mechanical resistance (kPa); θ is the volumetric water content (cm^3/cm^3); a, b are model parameters.

Statistical analysis

Soil aggregates size portions, and MWD under the treatments (fallow, Rape_C, Rape_D, Luc_1Y, Vet_1Y, and Vet_6Y) were tested by a General linear univariate model and was further tested for the differences among treatments by Duncan test using SPSS 25 (IBM Corp., Chicago, USD). The significant level was set as $\alpha = 0.05$. Simple Pearson correlation between root traits, soil aggregate properties, and soil mechanical resistance were assessed in Origin ($P < 0.05$), and all the figures were also plotted by using Origin 2021.

Table 1 Basic physical and chemical properties of experimental site

Soil depth	pH	Soil Bulk density	Cation exchange capacity	Organic matter	Alkaline hydrolysis N	Available P	Available K	Sand (%)	Silt (%)	Clay (%)
(cm)		(g/cm^3)	(cmol/kg)	(g/kg)	(mg/kg)	(mg/kg)	(mg/kg)			
0–10	5.22	1.35	19.86	11.53	56.95	30.17	175.00	19.22	35.21	45.57
10–20	5.20	1.32	18.52	9.24	41.60	27.47	165.63	25.49	28.96	45.55
20–40	5.10	1.45	17.73	4.34	37.90	7.32	59.38	22.90	33.34	43.76

Sand: 2–0.05 mm, Silt: 0.05–0.002 mm, Clay: < 0.002 mm

Results

Root traits of different fall/winter cover crops

In the clayey red soil, there were significant differences in most of the root morphology between the cover crops. The root diameters (RD) of the cover crop were significantly different (Fig. 1a). The largest RD occurred for rape, followed by vetiver grass and then lucerne at all depths. For example, the largest RD of Rape_D displayed as 1.06, 1.24, and 1.40 mm at 0–10, 10–20, and 20–40 cm, respectively. The smallest RD of Luc_1Y ranged from 0.8 to 1 mm over all three depths. The difference of RD among cover crops also depended on the soil depths, and the most evident difference of RD among cover crops occurred at 20–40 cm. In addition, the RD distribution that was expressed as a percentage of RL at each RD class also differed between species (Fig. 2). Both rapes were dominated by coarse roots through soil depths, and in contrast, the root of vetiver and lucerne were uniformly distributed among soil depths, and their fine (0.2–0.5 mm) and coarse (> 1 mm) roots accounted for a relatively higher percentage than that of rapes. Also, annual and perennial vetiver grass differed in the percentage of fine root length, with Vet_6Y being significantly higher than Vet_1Y. Generally, vetiver grass, possessing the largest RLD and a high percentage of fine and medium root, was probably helpful to their deeper root penetration in clayey red soil among all crops.

There were significant differences in root length density (RLD) between cover crops, as shown in Fig. 1b. Different from the RD order among crops, the vetiver grass had the highest RLD, followed by lucerne and then rapes at all depths. For example, the RLD of Vet_6Y ranged from 4.82 to 2.71 cm/cm^3, Luc_1Y ranged from 4.24 to 2.72 cm/cm^3 and Rape_C and Rape_D ranged from 3.55 to 1.75 cm/cm^3. The RLD among cover crops also depended on soil depths, and the most visible difference of RLD among crops occurred in 20–40 cm. There was also a significant difference of root surface area density (RSD), whereas no significant difference in RVD among treatments (except for 20–40 cm) (Fig. 1cd). The mean lignin/cellulose ratio was smaller in vetiver than that in other treatments for root < 0.5 mm, while the opposite trend occurred for coarse root (> 1 mm) (Fig. 1e).

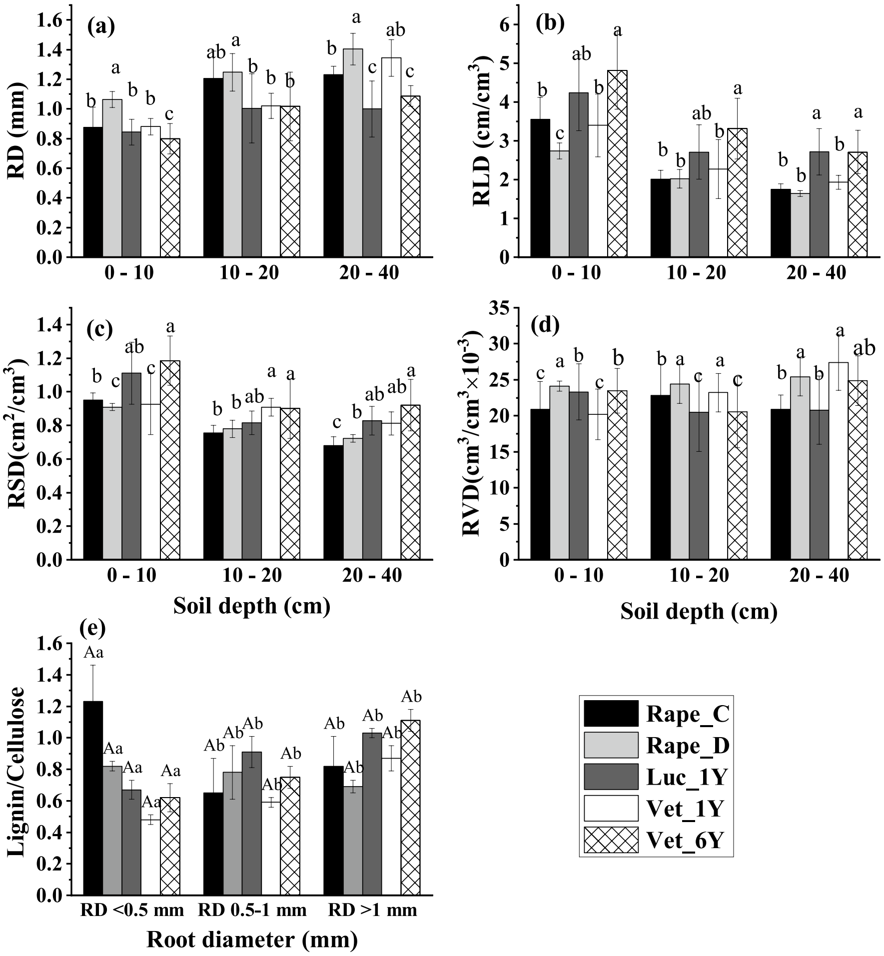

Fig. 1 Different cover crops root traits and lignin/cellulose ratio distribution. (**a**) Root diameters (RD), (**b**) Root length density (RLD), (**c**) Root surface area density (RSD), (**d**) Root volume density (RVD) (**e**) lignin/Cellulose ratio. In (**a**)-(**d**) Different lower-case letters represent significant difference of RD, RLD, RSD, and RVD among cover crops at each depth, while in (**e**) different lower-case indicate significant difference between diameter classes within each treatment. Different capitalized letters indicate significant difference among treatments at the same diameter class

Effect of crop root on aggregate size distribution

Soil aggregates were dominated by the size of 2–0.25 mm followed by 5–2 mm and then > 5 mm for all treatments except for Vet_6Y (at 0–10 cm) (Fig. 3abc). For aggregate 2–0.25 mm, fallow has percentage of 34.42%, 38.17% and 35.91% at 0–10, 10–20, and 20–40, respectively. Compared to fallow, cover crops significantly decreased the 2–0.25 mm percentage at 0–10 and 10–20 cm, while no significant differences occurred among treatments at 20–40 cm. However, for aggregate > 2 mm (2–5 and > 5 mm), cover crops significantly increased this portion compared to fallow at both 0–10 and 10–20 cm, with an order of vetiver > lucerne > rapes. At the same time, < 0.053 mm portion was significantly reduced after cover crops compared to fallow. In addition, annual and perennial vetiver grass yielded different results, and Vet_6Y as a long-term cover crop treatment contributed to a higher degree of improvement in aggregate (> 5 and 2–0.25 mm) than annual vetiver (Vet_1Y). Due to the improvement in macroaggregate (> 2 mm) and decline in microaggregate percentage (< 0.053 mm) after cover crop treatments, the aggregate stability (MWD and GMD) was improved in different degrees among cover crops, with an order of vetiver > lucerne > rapes > fallow (Fig. 3de).

The cover crop also induced significantly higher values of SOC in various sizes of aggregate than that in fallow, with an order of Vet_6Y > Vet_1Y > Luc_1Y > Rape_D > Rape_C > Fallow (Fig. 4). High SOC was then beneficial for the improvement in macroaggregate parentage and MWD and GMD. High SOC after all cover crops can be attributed to

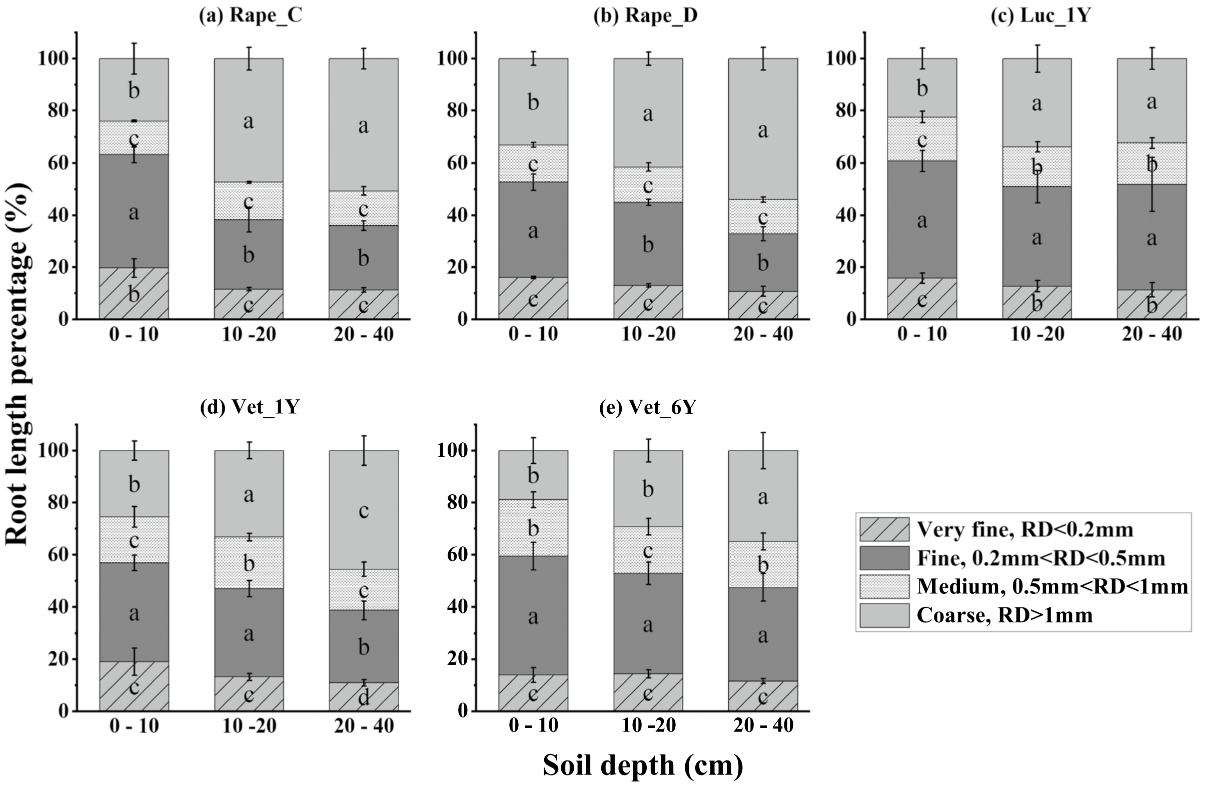

Fig. 2 The root diameter distribution of the crops, presented by the root length percentage at four diameter classes. Different lowercase letters for each rotation crop indicate significant differences of root length percentage over root diameter classes at the same depth

the roots and was further confirmed by the positive correlation between fine and medium root percentage, low lignin/cellulose ratio and SOC (Fig.S1). Fine and medium roots were mainly responsible for the SOC improvement, while coarse root (> 1 mm) played a negative role in SOC. The low lignin/cellulose ratio of roots (< 0.5 mm) was also beneficial to SOC accumulation (Fig. S1).

The effect of cover crop root on soil aggregation can be attributed to the root traits and SOC that were derived from roots. For example, at 0 to 10 cm depth the RLD, RSD, and fine and medium root percentage were positively correlated with large macroaggregate (LMA, > 5 mm) percentage and then improved aggregate stability (MWD and GMD) (r = 0.94, 0.79). However, coarse root yielded in a negative effect on MWD (r = -75). The root traits also further influenced aggregate through their indirect modification of SOC, and SOC played the dominant roles in increment in aggregates (> 5 mm and 0.25 ~ 0.053 mm) and MWD (Fig. 5).

Cover crop roots effect on soil mechanical resistance

Different fall/winter cover crop root systems induced contrasting soil mechanical resistance in soil depths (Fig. 0.6). Measured soil mechanical resistance values were significantly reduced after cover crops compared to fallow but reduced to different extent among cover crops. For the measured soil mechanical resistance values, a 0–10 cm rapes yielded the lowest soil mechanical resistance (616.13 kPa) followed by lucerne (627.31) and Vetiver (642.16 kPa) (Fig. 6a). However, at subsurface 20-40 cm, vetiver yielded the lowest soil mechanical resistance (1031.62 kPa) (Fig. 6c). Predicted soil mechanical resistance values from soil water content (θ) displayed similar order among cover crops as that in measured soil mechanical resistance. For example, at the surface

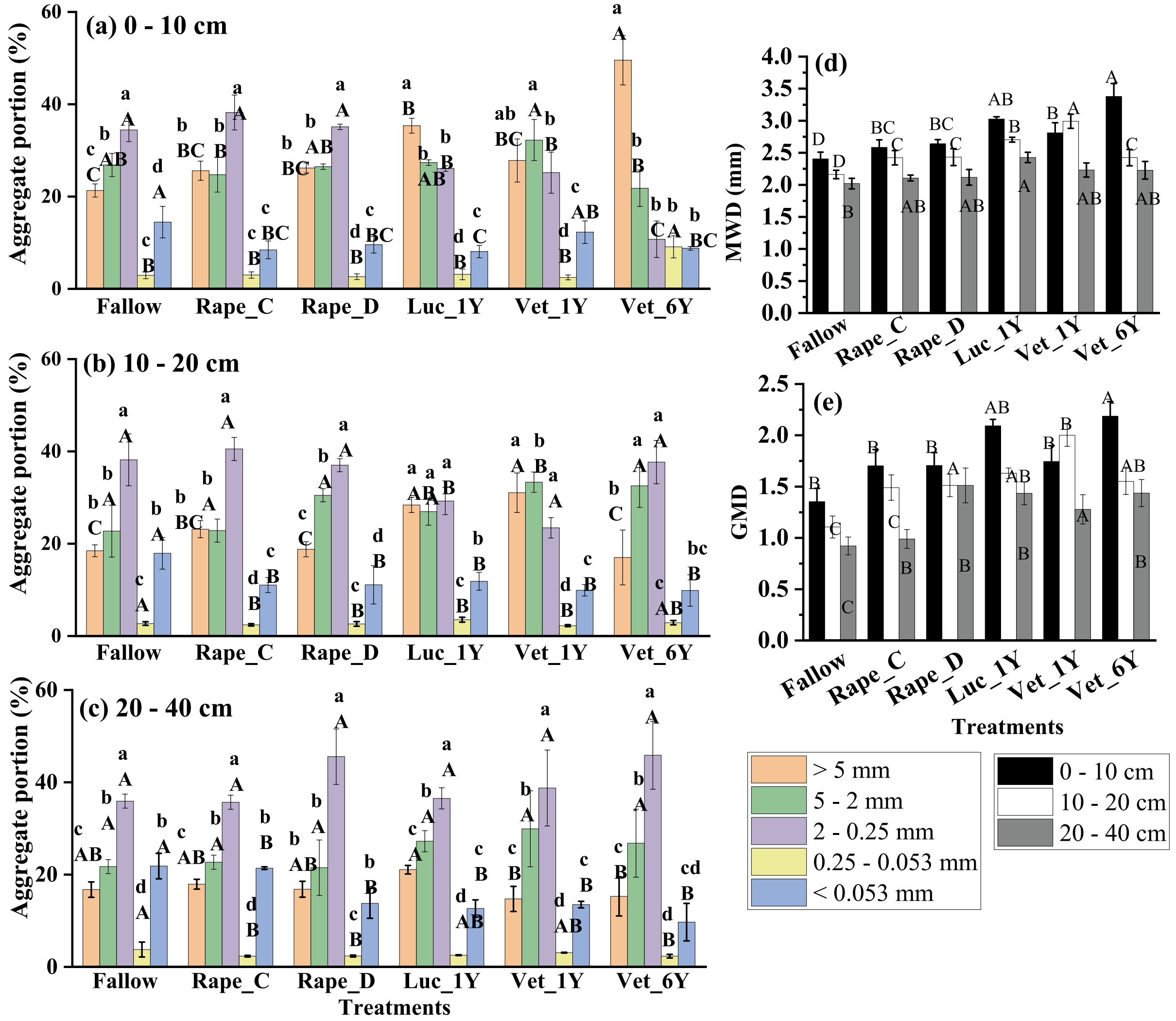

Fig. 3 Aggregate size distribution and soil aggregate stability (MWD and GWD) for different treatments over depths. Different lower-case letters indicate significant difference between aggregate size classes within each treatment at the same depth. Different capitalized letters indicate significant differences of aggregate size or MWD or GMD between treatments at the same depth

0–10 cm (averagely θ of 0.3 cm^3/cm^3), the predicted soil mechanical resistance was Fallow (2093.79 kPa), Vet_6Y (1488.36 kPa), Luc_1Y (1326.12 kPa), Rape_C (1243.70 kPa), Vet_1Y (116.17 kPa) and Rape_D (1105.16 kPa) (Fig. 6d). Good linear regression existed between the measured and predicted soil mechanical resistance values ($R^2=0.76$) (Fig. 6h). This indicated that soil water content that was dependent on cover crop types was one of the key factors in influencing and predicting soil mechanical resistance.

The Pearson correlation further indicated the root beneficial effect of cover crop on soil mechanical resistance through roots and aggregate (Fig. 5, Fig. S1). An increase in the percentage of macro aggregate (>5, 5–2 mm) due to cover crop root traits (RLD, fine and medium root, and low lignin/cellulose ratio) can result in decrease in soil mechanical resistance (r = -0.11, -0.78, -0.76). This explained why fibrous-rooted vetiver facilitated the least soil mechanical resistance value compared to other cover crops and fallow.

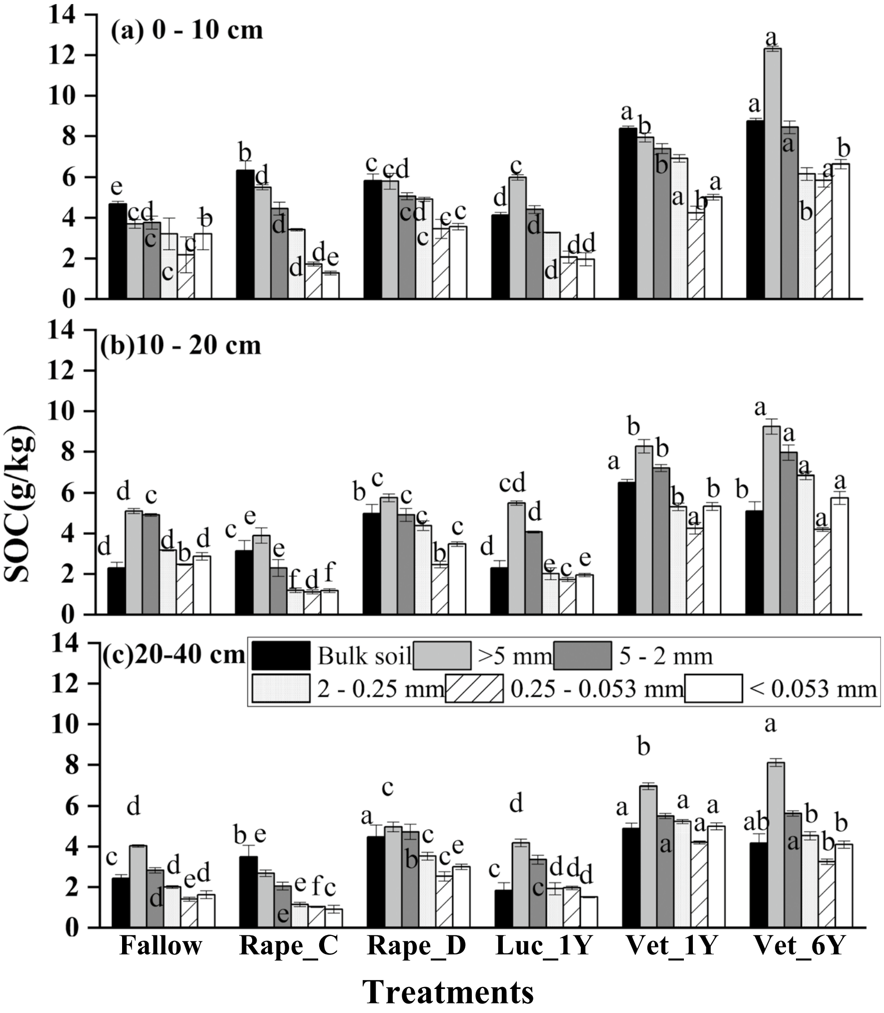

Fig. 4 The soil organic carbon content in bulk soil and aggregate sizes for different treatments. Different lower-case letters indicate significant differences of SOC between treatments at the same aggregate size and bulk soil

Discussion

Root distribution in clayey red soil

Our results suggested that fibrous-rooted cover crop (vetiver) displayed a deeper root distribution and better root-drilling ability than the taproot plants (lucerne and rapes), which was attributed to the high RLD, high percentage of the fine and medium root. Contrary to most of other studies, taproot crops generally penetrated the compacted soil better than fibrous root crops (Chen and Weil 2010; Han et al. 2015b). The fibrous root crops (Vet_1Y and Vet_6Y) demonstrated better penetration than taproot crops in our study. Similarly, greater vetiver fibrous root penetration was also found in the same clayey red soil compared to taproot crops (Chen et al. 2021). This can be ascribed to the special root traits of vetiver. Firstly, vetiver achieved a higher very fine and fine roots proportion at high density than rape and lucerne in deeper soil depth, which allowed them adaptable to grow in compacted deep soils with a small proportion of soil capillary pores (about 13%) and low nutrients content (Amiri et al. 2019). Secondly, vetiver grass fine roots contain a high cellulose/lignin ratio, which produced high root tensile strength and facilitated their high drilling ability in soil (Zhang et al. 2014). Comparatively, tap-rooted rape only had its thick taproot distributed at shallow 0 ~ 20 cm and counted a small proportion of the total root length, which can seriously restrict the root growth in compacted clay soils (Chen et al. 2021). For another taproot crop, lucerne's growth was restricted in humid subtropical climates with acid soil compared to temperate

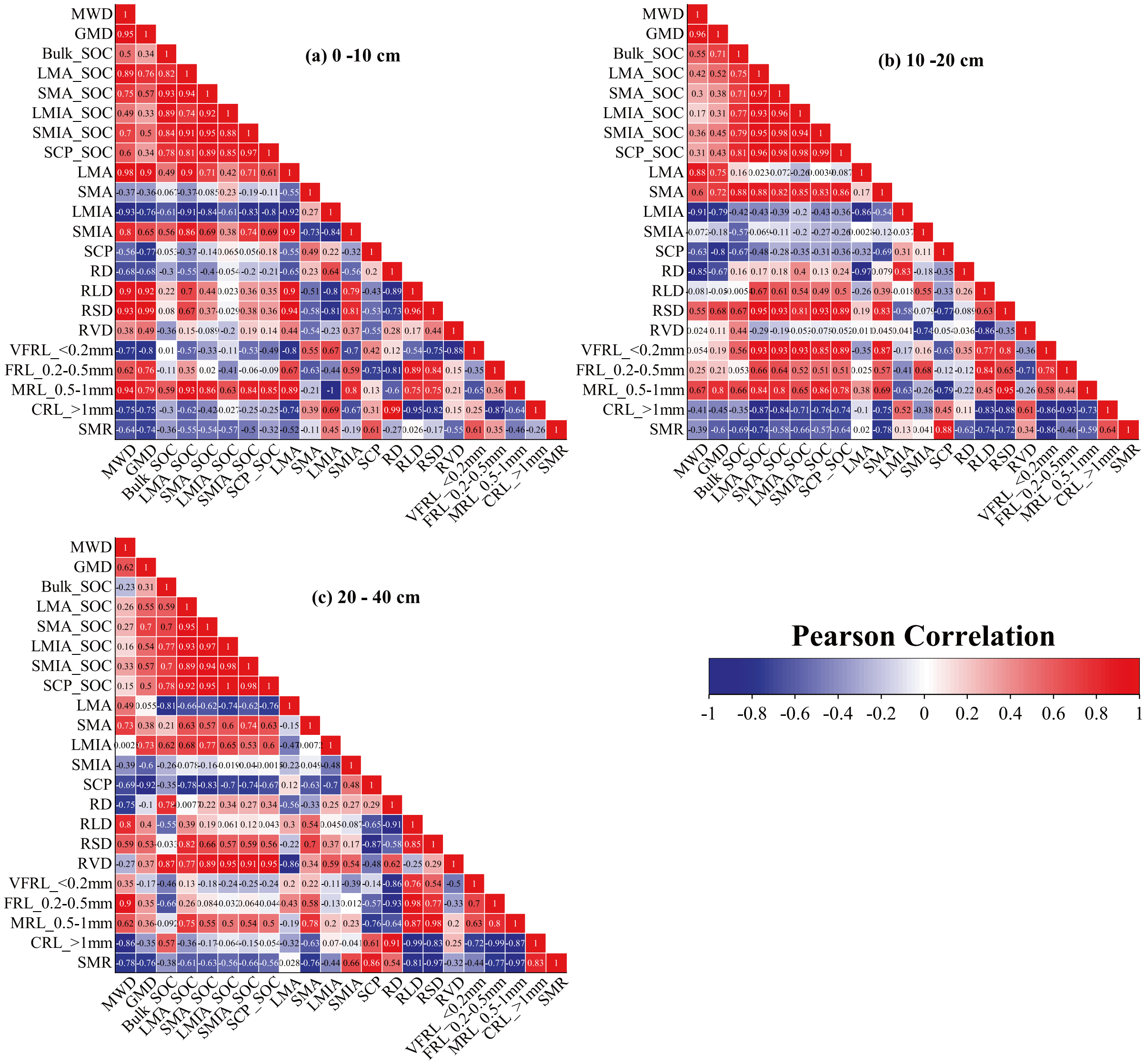

Fig. 5 Pearson correlations ($P < 0.05$) for all root characteristics, aggregate stability, soil organic carbon, and soil mechanical resistance. MWD: mean weight diameters; GMD: geometric mean diameters; SOC: soil organic carbon; LMA: large macroaggregates (> 5 mm); SMA: small macroaggregate (5-2 mm); LMIA: large microaggregate (2–0.25 mm); SMIA: small microaggregate (0.25–0.053 mm); SCP: silt clay portion (< 0.053 mm); RD: root diameter; RLD: root length density; RSD: root surface area density; RVD: root volume density; VF_{RL}: very fine root length; $F_{RL:}$ fine root length; M_{RL}: medium root length; C_{RL}: coarse root length; SMR: soil mechanical resistance. The red color indicates a positive correlation, and blue color represent a negative correlation

climates. Therefore, in this study, fibrous root crop (vetiver) exhibited higher drilling ability than taproot crops in clayey red soil.

In addition, the perennial crop (Vet_6Y) also performs better penetration ability than the annual crop (Vet_1Y) in clayey red soil. Perennial crop roots are not dormant between growing seasons and that root growth never entirely ceases (Rytter and Rytter 2012), and thus the 6-year-continuation growth of coarse and medium root of Vet_6Y in the early years increased medium macropores (> 15 μm) and reduced inactive pores (Chen et al. 2021), which allowed for more root proliferation and extension into deep compacted soil layer. However, for annual

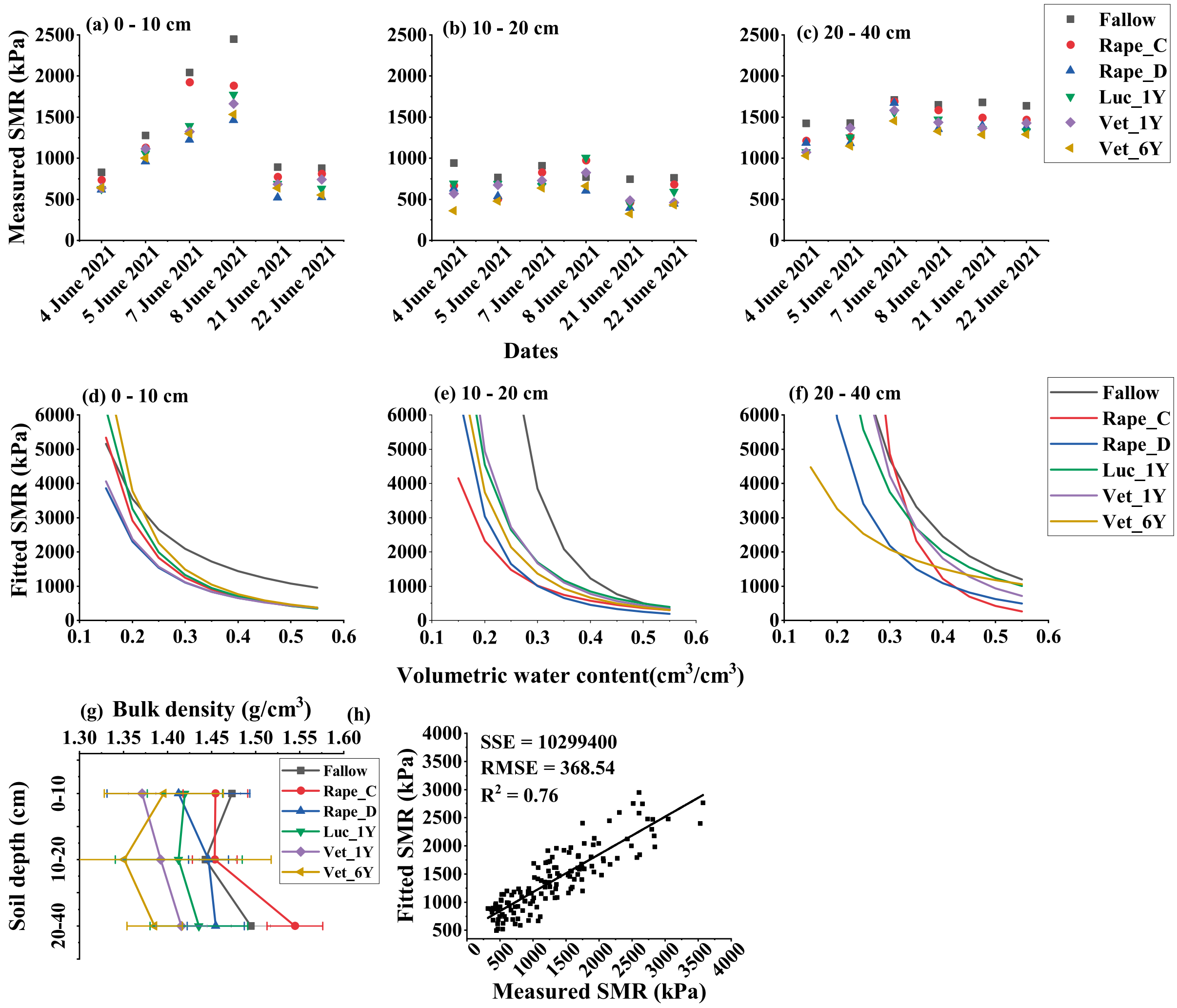

Fig. 6 Different cover crop roots effect on measured soil mechanical resistance (SMR) with different dates (**a**, **b**, **c**) and fitted soil mechanical resistance under a range of soil water content (**d**, **e**, **f**) and the Bulk density during soil mechanical resistance measurement (**g**) and the relationship between measured and predicted soil mechanical resistance (**h**)

vetiver (Vet_1Y), the coarse and medium roots have occupied the initial macropores in soils, leaving only micropores (capillary pores) for very fine roots to penetrate, resulting in poorer penetration in soil than Vet_6Y.

Effect of root trait distribution on soil aggregate

Our results confirmed the hypothesis that fibrous-root plant resulted in higher aggregate stability through the direct intrinsic root traits and indirect SOC. After cover crop treatment, soils with high soil macroaggregate percentage can increase the resistance to raindrop erosion by improving water infiltration rate and reducing surface runoff in rain season (Xue et al. 2019), and enhanced soil water availability for plants in the dry season (Aug. to Nov.) (He et al. 2019). The beneficial effect of cover crop on soil aggregation can be associated with the below approaches.

Firstly, plant alive roots can perform on soil aggregate through the root entrapping effect or segmentation effect (Poirier et al. 2018; Tisdall and Oades 1982). Plants with greater higher root length per unit volume generally favored macroaggregate formation and increased aggregate MWD (Poirier et al. 2018). Among all the roots, the fine root (< 0.2 mm) allowed close contact with soil particles and allowed them to penetrate and re-orientate soil particles to form a new size structure (Chen et al. 2021). Similarly, Demenois et al. (2018) proposed that plant Cyperaceae *(Costularia arundinacea*) that have a higher percentage of fine root (0.21 – 1.0 mm, 72%) reduced the microaggregate proportion in a larger magnitude than plant Myrtaceae *(Tristaniopsis* and *Arillastrum)*. However, coarse roots tended to disintegrate large macroaggregates and resulted in release and increase in microaggregate (Kumar et al. 2017). In our study, vetiver had high RLD, fine and medium percentage, and relatively low coarse root percentage and thus was reasonable to result in its greater percentage of macroaggregate (5–2 mm) and higher aggregate MWD (3.37 mm) than Rape and Lucerne (Fig. 3). The positive effect of live plants with high RLD and fine roots on aggregate stability can also be indicated by their improvement in soil cohesion by root clumping of fine soil particles together (Smith et al. 2021; Wang et al. 2018). In our study, vetiver resulted in soil cohesion of 46.5 kPa, which was higher than that in Rape (30.25 kPa) and Lucerne (33 kPa) (Fig. S2), further demonstrated stronger beneficial effect of fibrous-root crop than taproot crops on aggregation of clayey soil.

Secondly, plant root decay and the addition of SOC into soils were another important factor of soil aggregation (Xiao et al. 2020). Dead fine roots (<2 mm) were accessible to decomposition because fine roots generally had low lignin/cellulose ratio, stimulated the activities of arbuscular mycorrhizae (Barto et al. 2010; Halder et al. 2021) and thus leaded to a faster root decomposition rate, C sequestration and assisted with the formation of stable aggregates. However, coarse roots (>2 mm) were not completed decomposition for many years. In our study, large percentage of vetiver fine roots and their low lignin/cellulose ratios compared to taproot crop roots probably yielded higher macroaggregate percentage through acceleration of the C turnover rate.

Effect of root and soil aggregate on soil mechanical resistance

Soil properties (soil water content and bulk density) that were highly dependent on aggregate and intrinsic root traits were the key factors determining soil mechanical resistance. For example, higher soil mechanical resistance occurred during the dry season owing to low soil water content and high bulk density (He et al. 2022a). A clayey soil with high percentage of macroaggregate after organic fertilization promoted available soil water content while slowed down soil drying rate (He et al. 2022b). Therefore, vetiver soil with high percentage of macroaggregate was reasonable to slow down water loss and retain high amount of soil water and reduce its soil mechanical resistance in our study. Soil bulk density of the compacted layer was also able to be reduced through development of soil macro and micropores after the formation of soil aggregation, which probably facilitated a decline in soil mechanical strength (Steele et al. 2012).

Plant roots can also play an important role in influencing soil mechanical resistance. Root with high tensile strength was reported to be more obvious in influencing soil mechanical resistance than root with low tensile strength (Smith et al. 2021). This was also confirmed in (Ye et al. 2017) study that the fine root of fibrous-rooted Bahia grass had high tensile strength and induced low soil mechanical resistance. In our study, fibrous-root vetiver yielded the lowest soil mechanical resistance values at subsoils, whereas taproot rapes cultivars reduced the surface soil mechanical resistance only at surface soil, and the two cultivars did not show an obvious difference.

Red soils are prone to have water deficit issues in intermittent seasonal drought in subtropical monsoon climate, which further increases the soil mechanical resistance and harmed crops (He et al. 2022a, b). High soil mechanical resistance teared off crop roots, prevented further penetration into deep soils, and resulted in a huge loss in corn yield (Lin et al. 2016). According to our results, using cover crops is an effective alternative solution for mitigating these detrimental impacts in the dry season through changing soil aggregate stability, soil water content, and soil bulk density. In this study, fibrous-root vetiver penetrated the compacted subsoil well and reduced most in soil mechanical resistance, which will facilitate the crop extension into deep soils to pursue water and nutrients in the subsequent season.

Conclusions

Cover crops' root performance and distribution patterns were different in the clayey red soil. Compared with taproot crops (rape and lucerne), the fibrous-rooted vetiver resulted in deeper root drilling in the compacted subsoil due to its higher RLD and a higher percentage of fine and medium root in subsoil. Fibrous-rooted vetiver also increased soil macroaggregate (> 2 mm) proportion and aggregate stability due to the denser RLD, higher percentage of fine and medium root and faster production of SOC than that of taproot cover crops. Consequently, fibrous-rooted vetiver was more robust in reducing deep soil mechanical resistance in whole soil profile while taproot crops only performed better in reducing surface soil mechanical resistance in surface 0–10 cm. This was highly attributed to the improvement of soil macroaggregate percentage, MWD and GMD after vetiver treatment, and six-year period of vetiver can perform obviously greater beneficial effect than Vet_1Y. The results are useful for proper selection of cover crops as bio-tillage to improve physical properties of clayey red soil, especially reducing soil mechanical resistance.

Data availability statement

The data will be available on request.

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Declarations

Competing interest The authors declare that they have no competing financial interest or personal relationship that could have appeared to influence the work reported in the article.

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