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Rubber plant root properties induce contrasting soil aggregate stability through cohesive force and reduced land degradation risk in southern China

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Abstract

In southern China, Hainan Island faces land degradation risks due to poor soil physical properties, such as a high proportion of microaggregates (< 0.25 mm), low soil organic matter (SOM) content, and frequent uneven rainfall. The cohesive force between soil particles, which is influenced by plant root properties and root-derived SOM, is essential for improving soil aggregate stability and mitigating land degradation. However, the mechanisms by which rubber root properties and root-derived SOM affect soil aggregate stability through cohesive forces in tropical regions remain unclear. This study compared rubber plants of varying ages to assess the effects of root properties and root-derived SOM on soil aggregate stability and cohesive forces. Older rubber plants (> 11-years-old) showed greater root diameters (RD) (0.81–0.91 mm), higher root length (RL) densities (1.83–2.70 cm/cm^3), and increased proportions of fine (0.2–0.5 mm) and medium (0.5–1 mm) roots, leading to higher SOM due to lower lignin and higher cellulose contents. Older plants exhibited higher soil cohesion, with significant correlations among root characteristics, SOM, and cohesive force, whereas the random forest (RF) model identified aggregates (> 0.25 mm), root properties, SOM, and cohesive force as the key factors influencing mean weight diameter (MWD) and geometric mean diameter (GMD). Furthermore, partial least squares-path models (PLS-PM) showed that the RL density (RLD) directly influenced SOM (path coefficient 0.70) and root-free cohesive force (RFCF) (path coefficient 0.30), which in turn affected the MWD, with additional direct RLD effects on the SOM (path coefficient 0.45) and MWD (path coefficient 0.64) in the surface soil. Cohesive force in rubber plants of different ages increased macroaggregates (> 0.25 mm) and decreased microaggregates (< 0.25 mm), with topsoil average MWD following the order: CK (0.98 mm) < 5Y_RF (1.26 mm) < MF (1.31 mm) < 11Y_RF (1.36

mm) < 27Y_RF (1.48 mm) < 20Y_RF (1.51 mm). Rubber plant root properties enhance soil aggregate stability and reduce the land degradation risk in tropical regions.

Keywords: Rubber plant root traits; soil organic matter; cohesive force; aggregate stability; land degradation

1. Introduction

Land degradation is a serious global issue that increases as a consequence of growing population and climate change, currently impacting > 75% of land and projected to affect > 90% by 2050 (Perović et al., 2021; Prăvălie et al., 2021; Thomas et al., 2023). Land degradation in tropical regions, such as Hainan Island, southern China, is primarily caused by poor soil physical properties (high proportion of microaggregates (< 0.25 mm) and low soil organic matter (SOM)) along with the uneven and high frequency of rainfall events during the summer season (May–October) and current global climate change, leading to severe land degradation in the form of water erosion (Shao et al., 2024; Zhu et al., 2022). In addition, zonal ferro-alumina lateritic soils (ferralsols) on Hainan Island, classified as having low resilience and sensitivity according to the tropical soil resilience-sensitivity matrix, are particularly prone to soil erosion (Li et al., 2022). Consequently, the current soil erosion area on Hainan Island has increased 4.8-fold compared to that in 2000, according to a third national soil erosion remote-sensing survey (Yu et al., 2016). Soil aggregates are fundamental to soil function, and their stability influences carbon cycling, nutrient storage, soil fertility, infiltration rate, and resistance to soil degradation (Hok et al., 2021; Rabot et al., 2018; Yudina and Kuzyakov, 2023). Therefore, it is imperative to enhance soil aggregate stability by implementing suitable management practices that protect the integrity of the environment and ensure sustainable agricultural productivity.

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Natural rubber (*Hevea brasiliensis Willd. ex A. Juss*) plantations have recently expanded rapidly across mainland Southeast Asia (Xu et al., 2023; Yang et al., 2024). Rubber plants are recognized for their effectiveness in improving soil aggregate stability through their root properties and in mitigating soil erosion (Kurmi et al., 2020; Sun et al., 2021). Plant roots influence soil aggregate size distribution by positively affecting fine roots length (FRL), which closely interacts with soil particles, and negatively affecting coarse roots length (CRL), which disintegrate into larger particles (Ali et al., 2022; Chen et al., 2021; Kumar et al., 2017). Plant morphological root traits, such as root diameter (RD) and root length (RL) density (RLD), and their chemical composition, including lignin and cellulose content, have been shown to alter carbon deposits in soil pools and their sequestration (Poirier et al., 2018b; Rossi et al., 2020). Nevertheless, various studies have suggested that soil particles and roots have a restricted contact area with plant root-derived SOM, which is a dominant factor in soil particle fluctuation through the soil cohesive force, particularly after the plant roots have died (Ali et al., 2022; Chen et al., 2017). Variations in soil particles and root-derived SOM further adjust soil cohesion.

Soil cohesive forces, such as those from SOM and plant root morphological and chemical properties (Wang et al., 2018a; Wang et al., 2020), are effective in stabilizing slope soils to restrain soil and water runoff by enhancing soil-particle interactions, facilitating flocculation between soil particles, and minimizing soil erosion (Smith et al., 2021; Wang et al., 2018a). Among these factors, SOM plays a complex role and is generally beneficial for improving particle flocculation. However, SOM can also allow the dispersion of aggregates owing to an excess charge on SOM coupled with negative charges from soil particles (He et al., 2021; Melo et al., 2021). The addition of plants and their roots allows for additional soil organic carbon (SOC) accumulation in the soil (Rossi et al., 2020). Roots can also bind soil particles via cohesive forces, thus increasing aggregate stability

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(Forster et al., 2022; Poirier et al., 2018a; Wang et al., 2020). Dominant root traits influence soil particles through cohesive forces, and their subsequent effects on soil aggregate stability remain unknown.

To date, few studies on rubber plant roots have focused on soil aggregation in the tropical region of Hainan Island (Sun et al., 2021; Zou et al., 2021), and there is a complete lack of information regarding the mechanisms related to rubber plant root morphological and chemical properties, root-derived SOM, and cohesive forces in aggregate formation. We hypothesized that rubber plantations of different stand ages would promote soil cohesive forces through root properties and SOM among soil particles, thereby improving aggregate stability. The aims of this study were to: 1) investigate the impact of stand-age rubber plant root traits and root-derived SOM on aggregate properties, and 2) explore the interconnections between root morphological and chemical characteristics, SOM, cohesive forces, and soil aggregate stability. The findings of this research will help improve management practices in the tropical regions of Hainan Island and reduce land degradation problems by improving aggregate stability and overall environmental quality.

2. Materials and methods

2.1. Experimental site overview

The study was conducted on Hainan Island in Danzhou (19°4′3′′−19°12′42′′N, and 109°47′6′′−110°1′2′′E, 182–255 m above sea level). In the study area, the annual averages for temperature, precipitation, and solar radiation are 23.5°C, 1831 mm, and 4579 MJ·m^{-2}·yr^{-1}, respectively. November–April of the following year is the dry season, whereas May–October is the rainy season. Rubber (*Hevea brasiliensis)* and areca (*Areca catechu* L.) are the two primary commercial crops

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in the experimental region. According to the USA Soil Taxonomy System, the soil is classified as a laterite ferralsol (Schad, 2023). The soil in the rubber plantation was composed of 43.71% sand, 8.28% silt, and 48.01% clay. The basic physical and chemical characteristics of the samples are listed in Table. 1.

2.2. Experimental design

Rubber plantations with four different stand ages were selected from the field. The treatments included five-year-old rubber forests (5Y_RF), with 2018 rubber trees (clone PR-107) planted at the recommended density (3 × 7 m, 480 plants·ha^{-1}) and crown density 30 %; 11-year-old rubber forests (11Y_RF), with 2012 rubber trees (clone PR-107) planted at the recommended density (3 × 7 m, 431 plants·ha^{-1}) and crown density 90 %; 20-year-old rubber forests (20Y_RF), with 2003 rubber trees (clone PR-107) planted at the recommended density (3 × 7 m, 346 plants·ha^{-1}) and crown density 90 %; 27-year-old rubber forests (27Y_RF), with 1996 rubber trees (clone PR-107) planted at the recommended density (3 × 7 m, 300 plants·ha^{-1}) and crown density 90 %; and mixed forest (MF) and control (no forest plants) (CK). The MF comprised cinnamon (*Cinnamomum Verum*) trees (planted in 2014) along with 20-year-old rubber plants. We established a randomized complete block design with three replicates. We selected 18 plots (30 × 30 m) separated by a transitional zone. Rubber plants with different stand ages were selected based on similar topographies (slope and gradient) and management practices. Rubber plantation canopy heights were approximately 20 m. The rubber plant rotation duration was approximately 40 yr, and the first latex tappings in this region occurred when the trees were five- or six-years-old. Chemical fertilizers were applied at the initial rubber plantation development stage according to local conventional farming practices. Additional details regarding the rubber plantations at the experimental site can be found in the study by Sun et al. (2021).

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2.3. Root morphological and chemical composition analysis

In January 2024, three replications per depth per forest plot of soil samples with roots were taken at soil depths of 0–20 and 20–40 cm, using cutting rings (200 cm^3). Using the methodology outlined by Chen et al. (2021), the following root features were measured: RD, root mass density (RMD), RLD, and root surface area density (RSD). The cutting ring cores were placed in nylon bags and taken to the laboratory, where they were submerged in water for an hour before being manually washed using 0.55-mm sieves to collect the roots. The roots were scanned using an Epson Perfection V800 photo scanner (© 2024 Epson America, Inc), and WinRHIZO Pro Version 2009c software was used to assess the RD and RL. By dividing the entire RL and root surface area by the cutting-ring volume (cm^3), respectively, the RLD and RSD were calculated. The roots were oven-dried at 50°C, and the RMD was calculated by dividing the dry root mass by the cutting-ring volume. Furthermore, using data from the WinRHIZO analyzer, the root system was classified into four types based on RD: RD < 0.2 mm (very fine roots (VFRL)), RD 0.2–0.5 mm (fine roots (FRL)), RD 0.5–1 mm (medium roots (MRL)), and RD > 1 mm (CRL).

Chemical composition (cellulose and lignin) analysis of the roots was performed on three subsamples of the root classes (RD < 0.5, 0.5–1, and > 1 mm). Briefly, 1 mg of 65 °C oven-dried root powder (< 0.5 mm) was mixed with 5 ml acetic acid and heated for 25 min, followed by three deionized water washings and supernatant discarding. Subsequently, 10 ml of sulfuric acid (10%) and 10 ml of potassium dichromic (0.1 mol L^{-1}) solutions were added, vortexed, and heated in a 100 °C water bath for 10 min. After cooling, 5 ml KI solution (20%) and 1 ml starch (0.5%) were added, shaken for 10 min, and then titrated with 0.2 mol L^{-1} sodium thiosulfate to determine cellulose and lignin contents (Zhang et al., 2014).

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2.4. Soil cohesive force determination

Soil samples of approximately 2000 g were collected from depths of 0–20 and 20–40 cm during root collection. Soil samples were air-dried and divided into two parts. One part was ground to 100 μm for SOM determination using the oxidation method described by Walkley and Black (1934). The second part was dry-sieved to retain aggregates < 5 mm, and visible roots were removed. These soil samples were stored for subsequent analysis of the remolded soil root-free cohesion force (RFCF), which was determined according to the method described by Huang et al. (2022). Briefly, four subsamples of intact root–soil composite cores were collected from each depth in three replicated plots using cutting rings (diameter = 10 cm, height = 6.37 cm) simultaneously during the root collection described in Section 2.3. These intact cores were used to determine soil cohesive forces. Soil cohesive force (c) was measured by assessing soil shear strength (τ) and vertical load (σ) applied to the shear surface, and c was calculated using the relationship between τ, σ, and c as described in Equation 1. In addition, soil (< 5 mm) without visible roots was remolded into cutting rings (diameter = 10 cm, height = 6.37 cm) according to the soil bulk density (Table. 1) at each soil depth in the rubber plots to measure the soil RFCF. In total, 48 core soil samples per treatment were used for soil cohesive force analysis. Both the remolded root-free and root–soil composite core samples were saturated with deionized water. After saturation, four subsamples from each depth and treatment were tested using an LH-DS-4 direct shear tester (Nanjing Technology Co., Ltd.), which has a shear strain accuracy of 0.01 mm and a shear stress accuracy of 0.01 N. The shear tester comprised a shear box, a sensor, a vertical compression device, and a displacement measurement system with specifications of 61.8 mm in diameter and a height of 20 mm. For the direct shear tests, four predetermined vertical loads (25, 50, 75, and 100 kPa) were applied. The shear rate of displacement was set at 0.8 mm/min, and the

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soils were sheared until failure, indicated by reaching the peak τ value on the computer. The relationship between the peak τ values and vertical loads (σ) was established according to Mohr–Coulomb's law, and soil cohesion (c) was calculated as described in Equation 1.

$$\tau = c + \sigma \tan\varphi \qquad (1)$$

where τ is the soil shear strength (kPa), σ is the vertical load applied to the shear surface (kPa), c is the soil cohesive force (kPa), and φ is the soil internal friction angle (°).

2.5. Soil aggregate analysis

Soil samples from depths of 0–20 and 20–40 cm were collected in each treatment simultaneously with root sample collection. The soil was allowed to air dry and then gently ruptured along its natural cracks before it was passed through an 8 mm mesh sieve to determine the soil aggregate size distribution and stability. We used a wet sieving method to separate aggregates < 8 mm into four size groups: large macroaggregates (LMA) (> 2 mm); macroaggregates (MA) (2–0.25 mm); microaggregates (MIA) (0.25–0.053 mm); and small microaggregates (SMA) (< 0.053 mm). Briefly, three replicates of 100 g of soil were immersed in deionized water for 10 min in a beaker before being transferred to a series of sieves with decreasing mesh sizes (2, 0.25, and 0.053 mm) and gently shaken in water with a 4-cm vertical vibration amplitude for 10 min. Subsequently, the soil that remained after each sieve was washed and transferred to a beaker, and all aggregate sizes (> 2, 2–0.25, and 0.25–0.053 mm) were oven-dried for 48 hours at 60 °C before being weighed. The mass of aggregates < 0.053 mm was determined by subtracting the total soil mass from the total mass of other aggregate sizes (Elliott, 1986). Equations 2 and 3 were used to compute the geometric mean diameter (GMD) and mean weight diameter (MWD, mm), respectively (Kemper and Rosenau, 2018).

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$$MWD = \sum_{i=1}^{n} W_i^* X_i \quad (2)$$

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

$$GMD = \exp\left[\sum_{i=1}^{n} W_i * \ln(X_i)\right] \quad (3)$$

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

2.6. Statistical analysis

Prior to data analysis, Shapiro–Wilk ($P > 0.05$) and Levene's tests ($P > 0.05$) (Razali and Wah, 2011) were used to evaluate the normality and homogeneity of variances using SPSS 25 (IBM Corp., Chicago, USA). Origin 2021 software was used to assess each index, and Tukey's pairwise test was used to determine statistical significance at $P < 0.05, 0.01$, and 0.001. Pearson's correlations among root characteristics, SOM, soil aggregate parameters, and soil cohesive force were assessed using Origin software (OriginLab Corp.), and key factors were predicted using a random forest (RF) model constructed using the R software RandomForest package (v4.3.1) (Team, 2017). The partial least squares-path models (PLS-PM) were performed in R software (v4.3.1) using the "*plspm*" package to elucidate the pathway through which plant root characteristics, SOM, and soil cohesive forces influence soil aggregate stability. Figures were created using Origin 2021 (OriginLab Corp.).

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3 Results

3.1. Root distribution and chemical composition

Significant differences in root morphological traits were observed among rubber plantations of different stand ages (Fig. 1). The RD varied notably with the age of the rubber plant (Fig. 1a). The largest RD was found in 27Y_RF, followed by the MF at depths of 0–20 cm and 20–40 cm, respectively. Specifically, the largest RD for 27Y_RF was 0.84 mm and 0.91 mm at depths of 0–20 cm and 20–40 cm, respectively. By contrast, the smallest RD, found in five-year-old rubber plantations (5Y_RF), ranged from 0.42 to 0.45 mm across both depths, respectively. The differences in RD among rubber plants of varying stand ages depended on soil depth, with the most pronounced differences observed at a depth of 0–20 cm. Moreover, significant variations in RLD were observed between rubber plantations of different stand ages, as shown in Fig. 1b. 27Y_RF exhibited the highest RLD, ranging from 1.83 to 2.81 cm/cm^3, followed by MF (2.01–2.06 cm/cm^3) and 20Y_RF (1.93–2.70 cm/cm^3) at both depths. The RLD differences among rubber plants of various stand ages were influenced by soil depth, with the most noticeable differences occurring at a depth of 0–20 cm. In addition, the RSD and RMD were significantly different among rubber plantations of different stand ages (Fig. 1c, and d). Furthermore, RD distribution, represented as a percentage of RL within each RD class, also differed among rubber plantations of various stand ages (Fig. 2). In the 5Y_RF, 11Y_RF, and MF plantations, VFRL (< 0.2 mm) predominated at both soil depths. Conversely, in the 20Y_RF and 27Y_RF plantations, the roots were uniformly distributed across the soil depths, with a relatively high percentage of MRL (0.5–1 mm).

The root chemical composition varied among rubber plantations of different stand ages and RD classes (Fig. 3). The cellulose contents in stand-age rubber plants were significantly different (Fig. 3a). The 20Y_RF roots had higher cellulose content than those of the 27Y_RF, followed by

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the 11Y_RF. Similarly, the cellulose content differed among the RD classes. For example, cellulose in the 5Y_RF was less than that in other stand-age rubber plants for FRL (< 0.5 mm). Moreover, there were significant differences in lignin content among the stand-age rubber plants and between the RD classes (Fig. 3b). For example, the lignin contents in the 20Y_RF were less than that in the 5Y_RF for RL < 0.5 mm. Cellulose and lignin contents are indicators of root contribution to SOM. Thus, the lower lignin and higher cellulose content in the 20Y_RF resulted in the highest SOM content ranging from 21.16 to 23.37 g/kg, followed by that in the 11Y_RF ranging from 20.56 to 22.68 g/kg, and the 27Y_RF ranging from 21.04 to 21.78 g/kg within soil depth (Fig. 3c).

3.2. Soil cohesive force under different stand-age rubber plantations

There was a significant difference in the RFCF among rubber plantations of different stand ages (Fig. 4a). The CK (without plants) RFCF was 17.92 and 20.25 kPa at depths of 0–20 and 20–40 cm, respectively, and the RFCF matric significantly increased with the introduction of rubber plantations of different stand ages. For example, at 0–10 cm soil depth, compared to the CK, the ability of rubber plants to improve the soil cohesive force followed the order MF > 27Y_RF > 20Y_RF > 11Y_RF > 5Y_RF. For the 20Y_RF, the increases in RFCFs relative to the CK were 169.73 and 156 % at 0–20 and 20–40 cm, respectively. Generally, older rubber plants (> 11-years-old) yielded a greater RFCF than younger rubber plants.

The root–soil composite cohesive force exhibited different patterns among rubber plantations of different stand ages compared to that of the RFCF (Fig. 4b). The root–soil composite cohesive force showed significant differences among rubber plantations of different stand ages and with that in the CK at 0–20 cm depths, whereas the root–soil composite force was significantly greater with plants than with that in the CK at 20–40 cm depth. However, there were no significant

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differences in the root–soil composite cohesive forces among the different plantations within the 20–40 cm soil depth. This is likely because rubber plants of different stand ages (20Y_RF, 27Y_RF, and MF) had greater root–soil interactions, likely due to thicker RD, higher RLD, higher percentage of MRL, and higher SOM at a depth of 0–20 cm. Overall, both cohesive forces were significantly correlated with RLD, VFRL, FRL, and SOM (Fig. 6). These results indicate that rubber plantations of different stand ages have a greater ability to improve soil cohesive forces.

3.3. Soil aggregate properties under different stand-age rubber plantations

Soil aggregate properties exhibited different patterns among the various rubber plant treatments (Fig. 5). Soil aggregates sizes were predominantly 2–0.25 mm, followed by > 2 mm, and 0.25–0.053 mm, and aggregate sizes > 0.0053 mm were less dominant in all rubber plantations of different stand ages compared to that in the CK at the respective soil depths (Fig. 5a–f). In the CK, the percentages of aggregates 2–0.025 mm were 23.76 and 26.84 % at depths of 0–20 and 20–40 cm, respectively. Compared to the CK, rubber plantations of different stand ages showed a significant increase in 2–0.25 mm aggregates at both soil depths. However, the proportion of aggregates > 2 mm, significantly increased in rubber plantations of different stand ages compared to that in the CK at respective soil depths, in the order 20Y_RF > 11Y_RF > 27Y_RF > MF > 5Y_RF. Simultaneously, the proportion of aggregates < 0.053 mm was significantly reduced in rubber plantations of different stand ages compared with the CK. As a result of the increase in macroaggregates (> 2 mm) and the decrease in microaggregates (< 0.053 mm) following rubber plantation treatments of varying stand ages, aggregate stability (measured by MWD and GMD) improved to varying extents, in the following order: 20Y_RF > 27Y_RF > 11Y_RF > MF > 5Y_RF > CK.

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3.4 Relationship among root traits, SOM, cohesive force, and soil aggregate stability

The Pearson correlation analysis indicated that the soil RFCF was positively and strongly associated with MWD and GMD with a correlation coefficient of 0.81 and 0.91 (0–20 cm), and 0.81 and 0.89 (20–40 cm), whereas the soil RFCF was significantly negatively correlated with small microaggregates (< 0.053 mm) (r = −0.74 and −0.79) for both depths (Fig. 6). A similar trend was observed for the root–soil composite cohesive force. Generally, a large cohesive force was consistent with high RLD, high proportions of FRL and MRL, and high SOM, particularly in older rubber plants, and was responsible for its capacity to maintain higher aggregate stability.

The RF model further identified the importance of various soil factors in predicting soil aggregate stability (MWD and GMD) at both soil depths (Fig. 7). At both depths, LMA (> 2 mm) and MA (2–0.25 mm) were the most influential factors, contributing significantly to soil stability, followed by SOM and FRL (FRL_0.2–0.5 mm). Root properties and soil cohesive forces also play substantial roles, particularly at deeper soil depths (20–40 cm), where cohesive forces become more prominent. Root traits are essential for enhancing soil aggregate stability, and their impact varies with depth, underscoring the complex interactions between roots and soil structure in ecosystem functions. In addition, the PLS-PM explicated the indirect and direct impact of root properties, SOM, and cohesive forces on soil aggregate stability (Fig. 8). Among the factors measured in the surface soil (0–20 cm), RLD (path coefficient 0.64, $P < 0.05$) directly influenced SOM (path coefficient 0.45, $P < 0.05$) and the MWD. In addition, RLD had a strong direct effect on SOM (path coefficient 0.70, $P < 0.05$). Furthermore, RLD directly altered RFCF (path coefficient 0.30, $P < 0.05$), which further affected the MWD. In contrast, RLD directly influenced the root soil composite cohesive force (RSCCF), however, the RSCCF did not directly influence the MWD. A similar trend was observed in the deep soil (20–40 cm).

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4 Discussion

4.1. Stand-age rubber plant root influence on soil cohesive forces

Rubber plantations of different stand ages exhibited different root morphological traits. Our results demonstrated that the plant roots of rubber plantations aged < 11-years-old were influenced by soil properties at 0–20 and 20–40 cm depths, as indicated by a sharp decline in RD and RLD (Fig. 1), and restricted root growth due to an increase in soil bulk density and a decrease in macropores. Similarly, Sun et al. (2021) observed that at the same research site, older rubber plants (13-years-old) exhibited a preference for growing in macropores compared to younger plants (four-years-old), which was attributed to their superior root properties and lower soil bulk density. In contrast, the 27Y_RF and MF were minimally influenced by soil properties due to the high percentage of FRL and MRL, which likely enlarged medium soil pores and facilitated penetration through capillary soil pores (< 30 μm) (Ali et al., 2022; Chen et al., 2021; He et al., 2022). Older rubber plants possess a higher proportion of FRL and MRL and produce a greater amount of root exudates, which likely function as lubricants to facilitate root growth in compacted soils with a higher bulk density (Chen et al., 2017; Sun et al., 2023). In our study, older rubber plants demonstrated a higher root penetration ability than younger plants, which likely modified the soil cohesive forces.

Our results indicate that rubber plant roots of different stand ages were more effective in enhancing soil cohesive forces in tropical regions than in the CK (no rubber plants) (Fig. 4). Many studies have shown that plant roots positively affect soil detachment rates during rainfall events, which can be attributed to an increase in soil cohesive forces (Huang et al., 2022; Shen et al., 2021). Our findings further validate the hypothesis that rubber plantations of different stand ages produce different soil cohesive forces, which are associated with their root characteristics and contributions

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to SOM. The variation in the enhancement of root–soil composite cohesive forces among rubber plantations of different stand ages was due to their distinct root properties. Younger rubber plants (< 20Y_RF) were more effective at increasing soil cohesion in the topsoil (0–20 cm), whereas older plants improved soil cohesion in both the topsoil and deeper layers compared to that in the CK (Fig. 4) because of their higher root tensile strength, soil shear strength, and greater RD and RLD. However, the RD and RLD of younger plants were significantly reduced in the subsoil, thereby diminishing their impact on soil cohesion. In contrast, older rubber plants enhance soil cohesive forces because of their extensive root contact area with the soil and the high density of their crisscrossing FRL and MRL networks, which effectively bind and wrap soil particles (Huang et al., 2022; Vannoppen et al., 2015, 2017). In the current study, RLD and a substantial proportion of FRL and MRL in older rubber plants enhanced root–soil contact and strengthened the soil at both depths (Figs. 1, and 2).

The influence of roots on the cohesive force of root-free soils can be ascribed to their indirect contribution to SOM. Soils from older rubber plantations exhibited high SOM content (Fig. 3c), which enhanced clay particle cohesion by reducing the surface tension of water within the clay–organic matter matrix (Wuddivira et al., 2009). RD and chemical composition (cellulose) altered carbon sequestration in various soil pools, enhancing carbon accumulation in the coarse silt fraction (20–50 µm), while decreasing carbon accumulation in particulate organic matter (Liao et al., 2023; Zhang et al., 2014). Similarly, roots with higher cellulose/lignin ratios facilitate the accessibility of substrates to polymer-hydrolyzing enzymes, thereby accelerating the degradation of plant organic matter (Barto et al., 2010; Halder et al., 2021; Zhang et al., 2014). In addition, root exudates facilitate root penetration into compacted soil layers and increase the distribution frequency of SOM in deeper soil horizons (Oleghe et al., 2017). In general, older rubber plants

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exhibited a greater RLD, higher percentage of FRL and MRL, and increased SOM than younger rubber plants, which led to a higher RFCF.

4.2. Aggregate stability responses to soil cohesive forces under different stand-age rubber plantations

Our study provides comprehensive insights into soil aggregate stability across rubber plantations at different stages of stand maturity. Soil cohesive forces driven by plant root traits are key factors in enhancing soil aggregate stability. The soil cohesive force increased aggregate stability (MWD and GMD) at the same soil depth (Fig. 5). The results also indicated that cohesive forces not only governed macroaggregate stability but also played a role in microaggregate formation. The MWD increased across rubber plantations of different stand ages because of the significant enhancement in soil cohesive forces. Rubber plants older than 11 years exhibited the highest aggregate stability at the same soil depth, which was consistent with the trend observed in their RFCF (Fig. 4). High soil cohesion has also been documented to limit soil dispersion rates and mitigate gully erosion (Wuddivira et al., 2013). Although the soil RFCCF was highest in older rubber plantations, the highest SOM content likely played a positive role in stabilizing soil particles (Kamau et al., 2020). SOM had a positive effect on soil particles as its dispersive properties became evident only once the soil aggregates were broken down. High SOM content also weakens the electrostatic repulsive forces by influencing the overlap of oppositely charged electric double layers (Ali et al., 2023; Yu et al., 2020). In addition, the higher MWD observed in rubber plantations older than 11 years, compared to those in the 5Y_RF and CK, indicated that the MWD of older rubber plants was not adversely affected by the excessive release of SOC from the mechanical breakdown of macroaggregates.

These findings highlight the importance of understanding the specific mechanisms by which soil cohesive forces contribute to aggregate stability. In this study, the soil aggregate portion

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(< 0.25 mm) was comparatively higher in the rubber plantations than in the control in this study. Rubber plant roots and SOM positively enhanced cohesion between soil particles (Fig. 5a–f). The soil cohesive force regulates soil aggregate stability using the following approaches: First, smaller aggregates, due to their higher surface area to volume ratio with water, can create surface tension between particles, indirectly creating a cohesive force, helping to hold them together (Wang et al., 2023). Second, soil particles, particularly clay and organic matter, often carry electrical charges that can lead to electrostatic attraction, further stabilizing the soil particles (Kaiser and Asefaw Berhe, 2014; Wuddivira et al., 2009). Similarly, SOM has a positive effect on clays because the dispersive effect of SOM is not expressed until the aggregates are broken (Melo et al., 2021). High SOM also weakens the electrostatic repulsive force in ultisols through its additional impact on the overlap of oppositely charged electric double layers (Ali et al., 2023; He et al., 2021; Yu et al., 2020). Third, the water in the small pores between the soil particles creates a capillary force that contributes to the soil cohesive force, which agglomerates the small particles (Deviren Saygin et al., 2021). In general, stand-age rubber plantations positively improved soil aggregate stability compared to the control through soil cohesion. In young rubber plantations, legumes such as kudzu should be planted. Furthermore, the development of a forest rubber understory economy can significantly enhance soil health by increasing biodiversity, with diverse plant roots improving soil structure, promoting microbial activity, preventing erosion, and contributing to organic matter through leaf litter and root biomass, thereby improving soil fertility. Future research should focus on evaluating the mechanisms by which various understory plants in rubber plantations reduce soil erosion.

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5. Conclusion

In this study, we explored the potential mechanisms of different stand-age rubber plant root morphological properties, root-derived SOM, and root chemical compositions on soil aggregate stability improvement through soil cohesive forces. Our findings indicate that natural rubber plantations of different stand ages exhibit distinct root distribution patterns, with 27-year-old rubber forests (27Y_RF) and MF showing greater RLD and higher percentages of FRL and MRL RD classes than those of younger plantations. The higher percentages of FRL and MRL in older rubber plants (> 11-years-old), along with their high SOM content, contributed to a stronger soil cohesive force than that observed in younger rubber plants and the control plots. The higher SOM content in older rubber plants was driven by the higher cellulose content and lower lignin percentages in their FRL and MRL. Consequently, rubber plants older than 11 years increased the soil cohesive force (with and without roots) compared to younger rubber plants and the control, thereby enhancing aggregate stability and reducing soil particle dispersion. These findings have significant practical implications and may assist in the development of management policies aimed at restoring the soil quality of degraded land in the tropical regions of Hainan Island. They emphasize the importance of selecting rubber plants with optimal root characteristics to enhance aggregate stability through soil cohesive force, thereby sustaining long-term agricultural productivity and maintaining environmental quality.

Credit authorship contribution statement

Waqar Ali: Writing - original draft, visualization, Investigation, Data curation, formal analysis. **Amani Milinga:** Investigation, Data curation. **Tao Luo**: visualization, formal analysis, **Mohammad Nauman Khan**: Writing – review & editing. **Asad Shah:** Writing – review & editing. **Khurram Shehzad:** Investigation, formal analysis. **Qiu Yang:** Investigation, Funding

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acquisition, review & editing. **Huai Yang:** Writing – review & editing, **Wenxing Long:** Investigation, Data curation. **Wenjie Liu:** Validation, Supervision, Resources, Conceptualization, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgment

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Table captions

Table. 1. Basic physical and chemical characteristics of the experimental site.

Treatments	Soil depth (cm)	pH	BD (g/cm^3	TOP (%)	SMC (%)	SOM (g/kg)	AN (mg/kg)	AP (mg/kg)	AK (mg/kg)
CK	0 -20	4.17	1.52	26.37	17.46	12.34	11.92	1.69	24.42
	20 - 40	4.21	1.56	23.26	15.25	11.36	11.45	1.56	18.15
5Y_RF	0 -20	4.37	1.39	28.39	19.25	20.98	11.63	2.79	34.62
	20 - 40	4.13	1.52	23.01	17.63	16.30	10.67	1.73	17.97
11Y_RF	0 -20	3.89	1.43	24.81	21.67	22.68	11.84	2.31	25.23
	20 - 40	4.02	1.51	23.1	20.77	20.56	10.42	1.7	16.44
20Y_RF	0 -20	4.08	1.36	24.98	21.41	23.37	10.67	2.33	29.02
	20 - 40	4.22	1.43	20.31	20.2	21.16	10.39	1.99	23.12
27Y_RF	0 -20	4.08	1.32	25.05	23.68	21.78	11.77	2.39	25.83
	20 - 40	4.26	1.41	25.24	19.9	21.04	10.17	1.84	18.92
MF	0 -20	4.42	1.31	29.52	22.76	21.20	13.47	1.81	36.15
	20 - 40	4.35	1.39	26.58	20.11	20.29	12.84	1.33	19.94

Note: BD: Bulk density; TOP: Total porosity; SMC: Soil moisture content; SOM: Soil organic matter; AN: Available nitrogen; AP: Available phosphorus; AK: Available potassium.

Figure captions

Figure. 1. Different stand-age rubber plantation root morphological properties with soil depths.

Figure. 2. Root diameter distribution of rubber plants at different stand ages represented by the

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root length percentage across four class diameters.

Figure. 3. Different stand-age rubber plantation root chemical compositions and soil organic matter (SOM) distributions.

Figure. 4. Soil cohesive force distribution under different stand-age rubber plantations. (a) Root free cohesive force, (b) Root–soil composite cohesive force.

Figure. 5. Different stand-age rubber plantation aggregate size distributions and soil aggregate stabilities (MWD and GWD) with soil depths.

Figure. 6. Pearson correlations ($P < 0.05$) for all root traits, aggregate stabilities, soil organic matter, and soil cohesive forces. RD: root diameter; RLD: root length density; RSD: root surface area density; RMD: root mass density; VFRL: very fine root length; FRL: fine root length; MRL: medium root length; CRL: coarse root length; SOM: soil organic matter; RFCF: root-free cohesive force; RSCCF: root–soil composite cohesive force; LMA: large macroaggregates (> 2 mm); MA: macroaggregates (2–0.25 mm); MIA: microaggregates (0.25–0.053 mm); SMA: small microaggregates (< 0.053 mm); GMD: geometric mean diameter; MWD: mean weight diameter. The dark brown color indicates a positive correlation, and the pine green color indicates a negative correlation.

Figure. 7. Random forest model ($P < 0.05$) to identify the key predictors of mean weight diameter (MWD) and geometric mean diameter (GMD). RD: root diameter; RLD: root length density; RSD: root surface area density; RMD: root mass density; VFRL: very fine root length; FRL: fine root length; MRL: medium root length; CRL: coarse root length; SOM: soil organic matter; RFCF root-free cohesive force; RSCCF: root–soil composite cohesive force; LMA: large macroaggregates (> 2 mm); MA: macroaggregates (2–0.25 mm); MIA: microaggregates (0.25– 0.053 mm); SMA: small microaggregates (< 0.053 mm).

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Figure. 8. Partial least squares-path models (PLS-PM) (P < 0.05) indicating the indirect and direct impact of root properties, soil organic matter, and cohesive forces on soil aggregate stability at 0–20 cm (a, and b) and 20–40 cm (c, and d). The numbers near the arrows are standardized path coefficients. The blue line indicates the positive direction and the red line indicates the negative direction. RD: root diameter; RLD: root length density; SOM: soil organic matter; RFCF: root-free cohesive force; RSCCF: root–soil composite cohesive force; MWD: mean weight diameter.

Figure. 1.

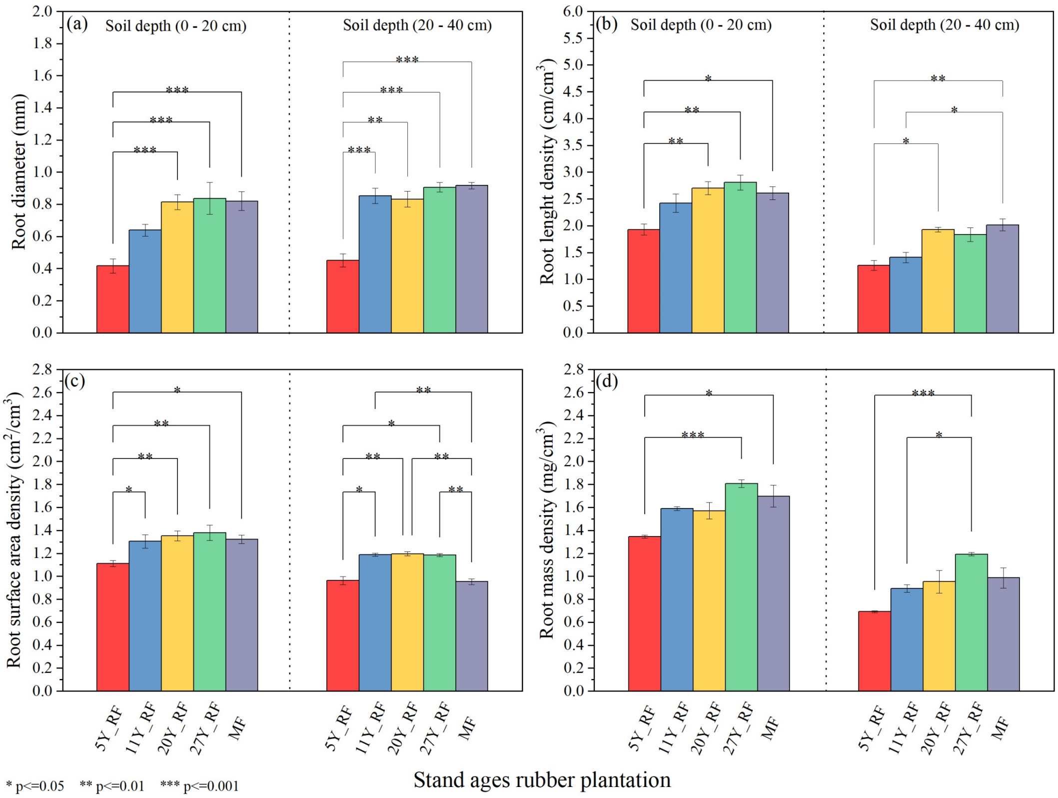

Figure. 2.

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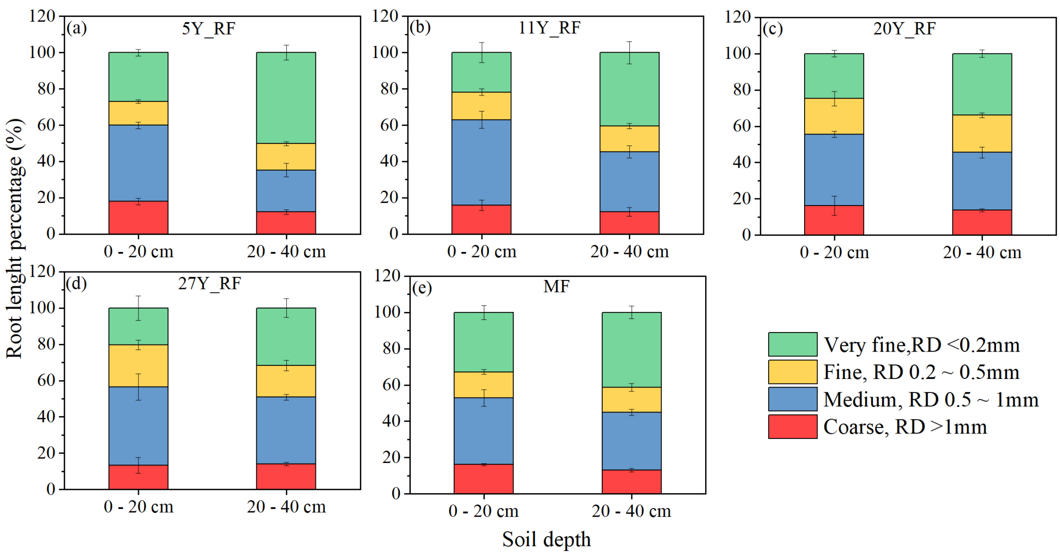

Figure. 3.

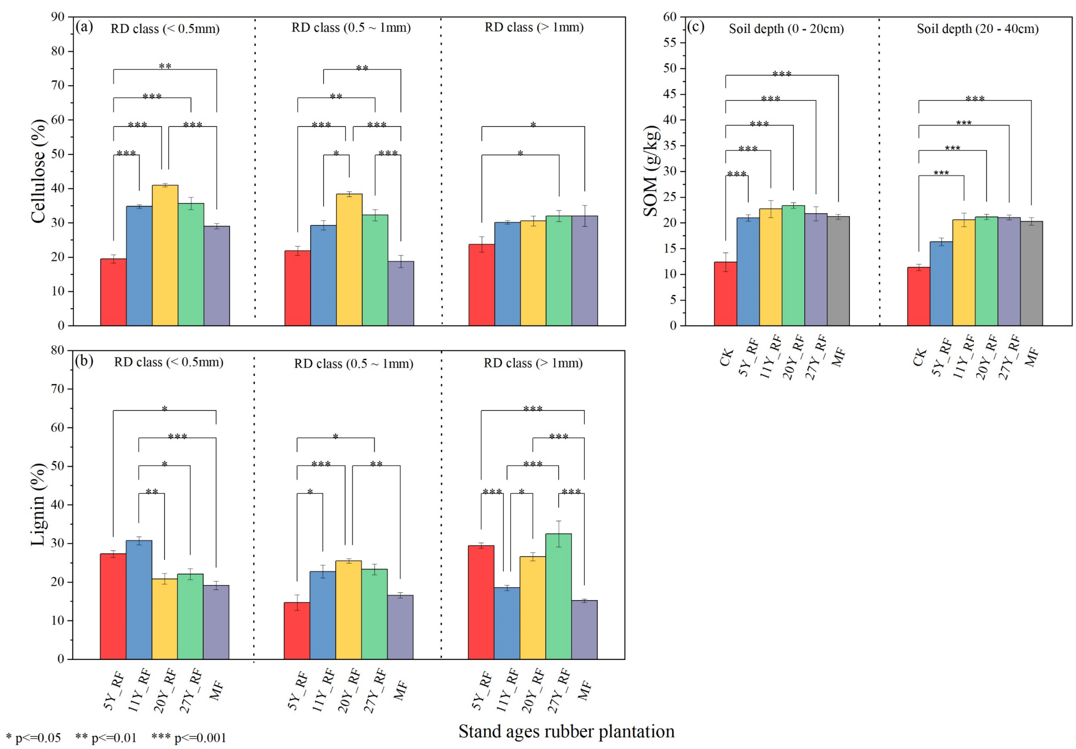

Figure. 4.

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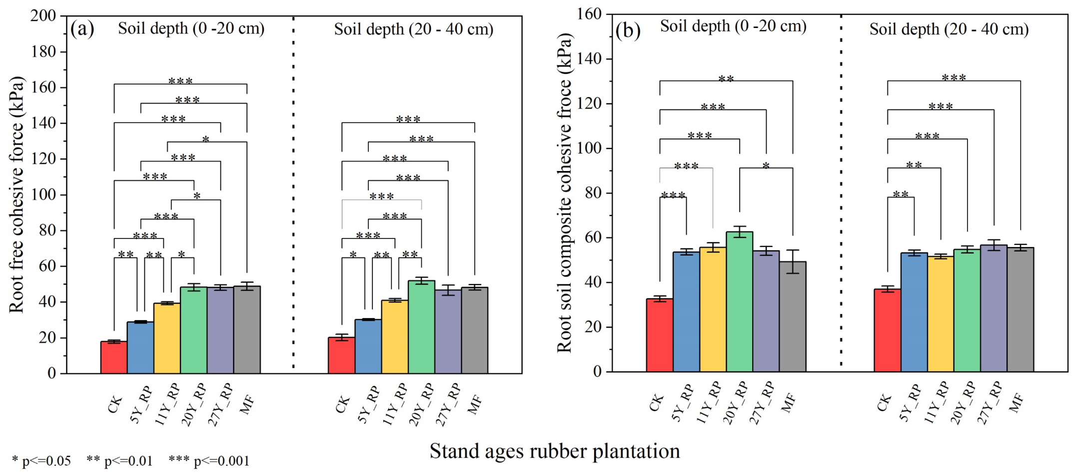

Figure. 5.

https://doi.org/10.5194/egusphere-2024-3602
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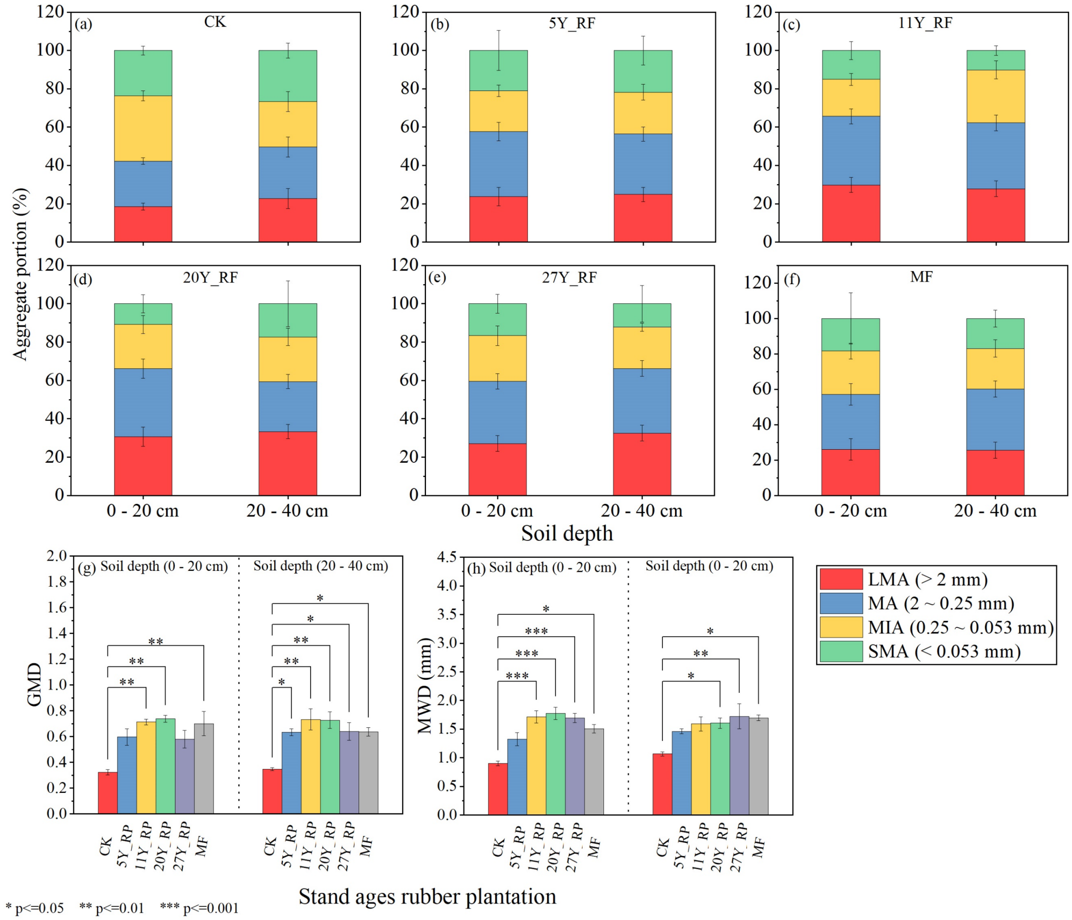

Figure. 6.

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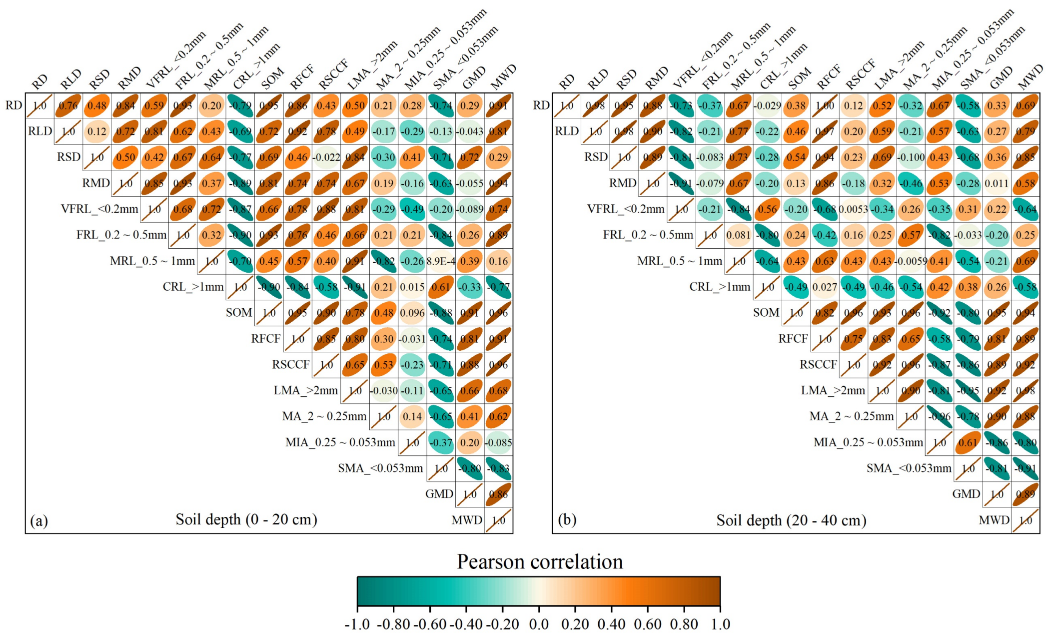

Figure. 7.

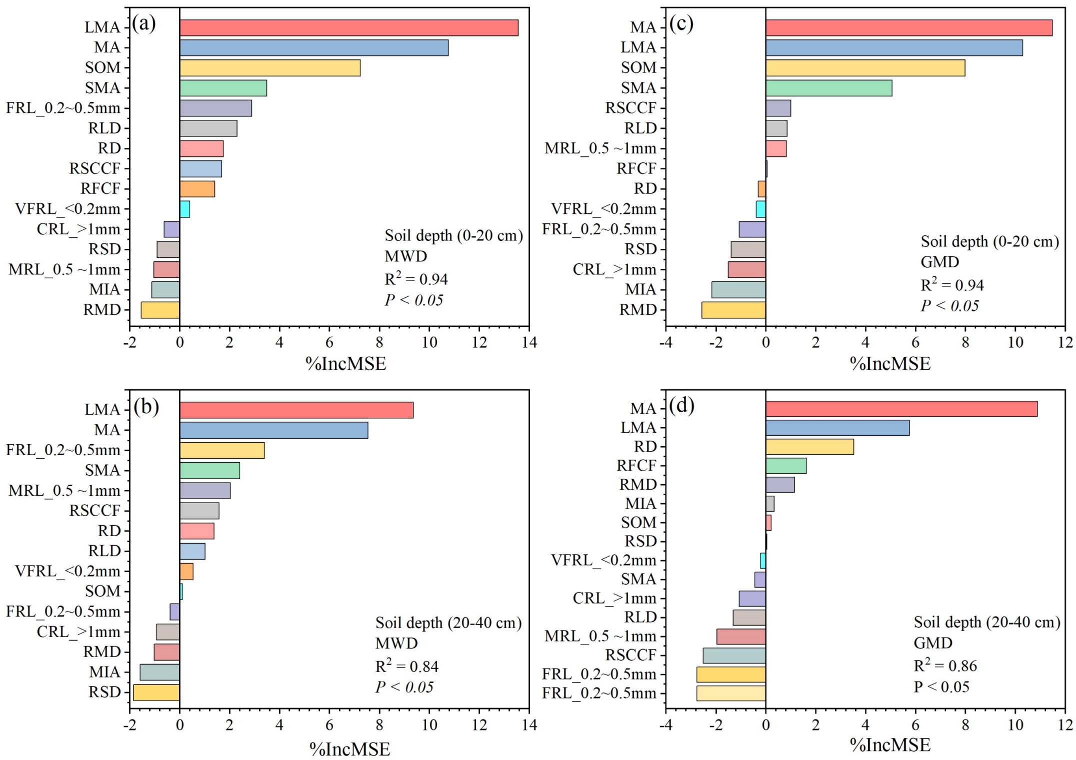
(a)
LMA
MA
SOM
SMA
FRL_0.2~0.5mm
RLD
RD
RSCCF
RFCF
VFRL_<0.2mm
CRL_>1mm
RSD
MRL_0.5 ~1mm
MIA
RMD
Soil depth (0-20 cm)
MWD
R² = 0.94
P < 0.05
%IncMSE
(c)
MA
LMA
SOM
SMA
RSCCF
RLD
MRL_0.5 ~1mm
RFCF
RD
VFRL_<0.2mm
FRL_0.2~0.5mm
RSD
CRL_>1mm
MIA
RMD
Soil depth (0-20 cm)
GMD
R² = 0.94
P < 0.05
%IncMSE
(b)
LMA
MA
FRL_0.2~0.5mm
SMA
MRL_0.5 ~1mm
RSCCF
RD
RLD
VFRL_<0.2mm
SOM
FRL_0.2~0.5mm
CRL_>1mm
RMD
MIA
RSD
Soil depth (20-40 cm)
MWD
R² = 0.84
P < 0.05
%IncMSE
(d)
MA
LMA
RD
RFCF
RMD
MIA
SOM
RSD
VFRL_<0.2mm
SMA
CRL_>1mm
RLD
MRL_0.5 ~1mm
RSCCF
FRL_0.2~0.5mm
FRL_0.2~0.5mm
Soil depth (20-40 cm)
GMD
R² = 0.86
P < 0.05
%IncMSE

Figure. 8.

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