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Dynamics of soil aggregate-related stoichiometric characteristics with tea-planting age and soil depth in the southern Guangxi of China

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ABSTRACT

Soil ecological stoichiometry offers a sort of effective way to explore the distribution, cycling, limitation, and balance of chemical elements in tea plantation ecosystems. This study was aim to explore how soil organic C (OC) and nutrient contents (total N (TN), total P (TP), Ca^{2+}, Mg^{2+}, Fe^{2+}, and Mn^{2+}) as well as their stoichiometric ratios (C/N, C/P, N/P, Ca/Mg, and Fe/Mn) vary with tea-planting age (8, 17, 25, and 43 years) and soil depth (0-10, 10-20, 20-40, and 40-60 cm) at the aggregate scales in the southern Guangxi of China. Our results showed that tea-planting age and soil depth significantly influenced soil stoichiometric characteristics in various sized aggregates. In different aged tea plantations, soil OC, TN, and TP contents as well as C/N, C/P, and N/P ratios significantly decreased as the soil depth increased. In addition, soil Ca^{2+} and Mg^{2+} contents were significantly lower in the surface soil layer than the deeper soil layer, whereas soil Fe^{2+} and Mn^{2+} contents showed totally opposite trends, and no significant differences were detected among different soil depths in Ca/Mg and Fe/Mn ratios. Tea-planting age could influence the variations in soil stoichiometric characteristics, but such effects were more obvious at the 0-40 cm soil depth in contrast to the 40-60 cm soil depth. At the 0-40 cm soil depth, continuous planting of tea was beneficial for the cumulation of soil OC, total N (TN), Fe^{2+}, and Mn^{2+}, whereas soil Ca^{2+} and Mg^{2+} were susceptible to leaching losses over time. Compared with other tea-planting regions in China, soil C/N ratio was higher in this tea-planting region, whereas soil C/P and N/P ratios were much lower, indicating the lower contents of soil OC and TN, especially the TN. Therefore, an appropriate increase in the amount of N fertilizer should be applied in this tea-planting region. During the process of tea planting, the losses of soil Ca^{2+} and Mg^{2+}, especially the Ca^{2+} (as indicated by the decrease in soil Ca/Mg ratio), could lead to the soil acidification. Soil acidification could reduce Fe^{2+} absorption and enhance Mn^{2+} uptake by tea plant (as indicated by the increase in soil Fe/Mn ratio), thereby causing the aggravation of Fe^{2+} insufficiency and the emergence of Mn^{2+} toxicity to tea plant. Overall, this study improved the understanding of soil OC and nutrient dynamics in tea plantation ecosystems, and also provided supplementary information for soil ecological stoichiometry in global terrestrial ecosystems.

KEYWORDS

Tea-planting age; Soil depth; Soil aggregate; Ecological stoichiometry

1. Introduction

Ecological stoichiometry offers a sort of valid approach to explore the distribution, cycling, restriction, and balance of nutrients in terrestrial ecosystems (Yu et al., 2019), and plays a critical role in recognizing the influence factors and drive mechanisms in ecological processes (Su et al., 2019). On the one hand, carbon (C) is the most commonly seen element in plants (Prescott et al., 2020), and nitrogen (N) and phosphorus (P) are critical control factors for the growth of plants (Krouk and Kiba, 2020). The relationships amongst the three different elements are coupled (Elser et al., 2003). Soil C/N, C/P, and N/P ratios represent not only the equilibrium features of soil C, N, and P, but also the dynamics of fertility characteristics during the process of soil genesis (Bai et al., 2020). On the other hand, calcium (Ca), magnesium (Mg), iron (Fe), and manganese (Mn) are pivotal metallic nutritive elements for the development of plants (Liu et al., 2021a). Soil total Ca, Mg, Fe, and Mn may exceed the demand of a single plant by more than a thousand-fold and cannot sensitively reflect the needs of plants (Miner et al., 2018), but the available fractions of these nutrients may be insufficient or redundant, resulting in the deficiencies or abundances of plant nutrients (Otero et al., 2013). Thus, soil exchangeable Ca and

Mg as well as available Fe and Mn generate significant effects on the development of plants. Soil Ca/Mg ratio reflects the relative effectiveness of these two ions and influences the buffering capacity and acidification process in soil (Yin et al., 2016). Moreover, maintaining a proper soil Fe/Mn ratio is pivotal for healthy soil because a lower ratio may indicate that plants have encountered Fe depletion and Mn poisoning (Wang et al., 2017a).

Over the past decade, soil stoichiometric characteristics (mainly C-N-P, rather than Ca-Mg or Fe-Mn) has been broadly studied across the world (Tian et al., 2010; Yang et al., 2013; Zhang et al., 2016; Yue et al., 2017; Yu et al., 2018; Qiao et al., 2020). A wide agreement exists amongst these studies that soil depth is vital for the regulation of soil stoichiometric characteristics. Substantial studies have identified the decreasing trend of soil organic C (OC), total N (TN), and total P (TP) contents as the soil depth increased (Yue et al., 2017; Yu et al., 2018; Qiao et al., 2020), whereas conflicting vertical patterns were discovered for soil C/N, C/P, and N/P ratios. For instance, decreasing trend of the C/P and N/P ratios was observed as the soil depth increased in the data of the 2nd soil investigation in China (Tian et al., 2010). Nevertheless, larger C/N ratio in the deeper soil layer, not the surface soil layer, was identified in a mollisol plain in the northeast China (Zhang et al., 2016). Moreover, the C/N ratio displayed no remarkable change throughout different soil depths in an investigation of alpine grassland on the Qingzang Plateau (Yang et al., 2013). As shown above, inconsistent vertical patterns have been reported for the C-N-P stoichiometric ratios in different soil ecosystems. Meanwhile, these studies were mainly focused on the regional or global scales, rather than on the aggregate scales.

Soil aggregates constitute the fundamental parts of soil structure, and various sized aggregates exert different abilities in the supply and reserve of soil OC and nutrients (Six et al., 2004). Thus, to improve the comprehension about the structure and function of soil ecosystems, more efforts should be made to observe the soil stoichiometric characteristics at the aggregate scales (Xu et al., 2019; Cui et al., 2021). In recent period, lots of studies have reported the OC, TN, and TP distribution in various sized aggregates, but these studies are ended with different results. To be specific, some studies revealed the significant increases in the OC, TN, and TP contents as the aggregate size decreased (Sarker et al., 2018; Piazza et al., 2020). Nevertheless, some other studies drew the totally opposite trends (Lu et al., 2019; Liu et al., 2021b). These show that the changes of soil OC, TN, and TP at the aggregate scales have received great attention, whereas soil exchangeable alkali cations (i.e., Ca^{2+} and Mg^{2+}) and available micronutrients (i.e., Fe^{2+} and Mn^{2+}) are rarely investigated.

In the past century, under the remarkable increase in population pressure, continuous tillage and overmuch deforestation resulted in the dramatic decrease in soil fertility level in the southern Guangxi of China (Jiang et al., 2018). For the purpose of tackling these challenges, the Chinese government has rolled out the Grain for Green program in the hope of alleviating land deterioration via converting farmlands to forest lands or grass lands (Zeng et al., 2020). Since the initiation of such program, the south part of Guangxi has initiated the mode of transforming farmlands into tea (*Camellia sinensis* L.) plantations as per the local geography and natural resources (Zhang et al., 2017). Tea, as a pivotal cash crop, is commonly cultivated in the developing nations, particularly in China, India, Kenya, and Sri Lanka. China is the first nation to plant tea across the globe, with the tea-planting area reaching 3.17 million hectares in 2020 and presenting an elevating trend in the future (Chinese Tea Committee, 2020). Guangxi has the subtropic monsoon climate and marks the key tea-planting region in China. According to the statistics from Chinese Tea Committee (2020), more than 80% tea plantations of Guangxi are situated at impoverished counties, and tea-planting industry turns to be the staple industry on which poor counties depend to throw off poverty.

Our past studies indicated that the landuse shift from farmlands to tea plantations could ameliorate soil fertility level (Zheng et al., 2011). Nevertheless, during the process of tea planting, the variations in soil stoichiometric characteristics are still unclear. Meanwhile, since tea plant serves as a deep root plant, it is vital to reveal how stoichiometric characteristics change with increasing soil depth in tea plantation ecosystems. Thus, the present study was carried out to

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investigate how soil OC and nutrient contents as well as their stoichiometric ratios vary with tea-planting age (8, 17, 25, and 43 years) and soil depth (0-10, 10-20, 20-40, and 40-60 cm) at the aggregate scales (< 0.25, 0.25-1, 1-2, and > 2 mm). In addition, we assumed that the responses of soil OC and nutrient contents and their stoichiometric ratios to tea-planting age would be different amongst different soil depths.

2. Materials and methods

2.1. Experiment site

In January 2019, the present study was completed at the Hengxian Agriculture Experiment Center of Guangxi University (altitude of 557-563 m and slope degree of 13-15 °) (Figure S1). Subtropic monsoon climate is predominant. Yearly average rainfall and temperature register 1304 mm and 21.6 °C, separately. Exposed soil horizon occurs early in the Mesozoic, which gradually formed the Ultisols agrotype (IUSS Working Group, 2014). As early as in 1960s, due to the high economic value of tea (especially "*Baimao* tea"), massive hectares of farmlands were developed to tea plantations in such region. In the tea-planting course, tillage method is no tillage and tea-planting density is almost 6×10^4 plants ha^{-1}. Yearly fertilization regime has been displayed in our past studies (Wang and Ye, 2020). In all tea plantations, herbicides were not applied and yellow sticky boards were used to prohibit pests, because the color may attract pests and get them stuck on the boards. In addition, all tea plants were subjected to slight pruning in September each year.

2.2. Experiment design

In general, examining the same location persistently has been considered a quite effective approach in the monitoring of the variations in soil with time (Sparling et al., 2003). Nevertheless, the challenges in long-period soil monitoring have made it urgent to develop substitutional approaches to research the changes of soil over time, amongst which the most common approach is the 'space-for-time' alternative (Zanella et al., 2018). To be specific, disperse sites ('space') in diverse developmental phases are identified simultaneously to obtain a chronological sequence of ages ('time'). In accordance with the 'space-for-time' alternative, disperse spots of increasing ages display alike initial status and synchro-sampling at these disperse spots equals the re-sampling at the same spot in different ages.

In this study, such approach was used to explore the variations in soil stoichiometric characteristics in a chronological sequence of tea plantations. In general, certain underlying mixture effects exist in the spatial variations of soil, hence the present study manages to mitigate such effects via choosing tea plantations, which were cultured with the same tea variety ("*Baimao* tea") with different planting ages (8, 17, 25, and 43 years), and were located at the same unit associated with geomorphological status. Every tea-planting age was duplicated in quintuplicate, and afterwards generated 20 tea plantations. Separation amongst these tea plantations was completed with distances of > 800 m between each other, hence decreasing the space self-correlation and avoiding the pseudo-replication. For every tea plantation ($S \approx 1 \times 10^4$ m^2), a plot ($S = 20$ m × 20 m) was randomly established with distance of > 50 m away from the tea plantation margin.

2.3. Litterfall and soil sampling

For every plot, the 5 litterfall specimens had been acquired from the surface of soil in the 5 randomly chosen subplots ($S = 1$ m × 1 m), and afterwards were integrated into a composite litterfall specimen. An overall the 20 (4 tea-planting ages × 5 replicates) composite litterfall specimens were desiccated at the 80 °C until steady weight. Then, the weights of these desiccated litterfall specimens were measured, and the litterfall C (Nelson and Sommers, 1996) and N (Bremner, 1996) contents were detected. Soil sampling was completed in the same sites of the litterfall sampling. For every plot, the 5 soil specimens had been acquired by a spade from every soil layer (i.e., 0-10, 10-20, 20-40, and 40-60 cm) in the 5 subplots, and afterwards were integrated into a composite soil specimen. An overall the 80 (4 tea-planting ages × 4 soil layers × 5 replicates) composite soil specimens were gently separated into naturally formed aggregates, which were subjected to filtration by a 5 mm sifter to realize the removals of small stones, coarse roots, and macrofauna. After that, soil specimens were used for the aggregate separation. For every plot, moreover, extra 5 soil specimens were randomly chosen via cutting rings (V = 100 cm^{-3}, Ø = 50.46 mm, and depth = 50 mm) from every soil layer to assess the bulk density, clay (< 0.002 mm), pH, OC, and nutrients of bulk soil.

2.4. Soil aggregate separation

As per the process of wet screening, 250 g of every composite soil specimen was subjected to filtration via the 2, 1, and 0.25 mm sieves in a successive way (Kemper and Chepil, 1965). To be specific, the composite soil specimens were soaked by the aqua destillata for 15 min, and afterwards were oscillated in the vertical direction for 15 min at the 1 s^{-1} oscillating rate and 5 cm amplitude. Consequently, we obtained 4 various sized aggregates, covering microaggregates (< 0.25 mm), fine (0.25-1 mm), medium (1-2 mm), and coarse (> 2 mm) macroaggregates. All of the aggregates were desiccated and weighted, and then aggregate-related OC and nutrients were detected.

2.5. Soil property analyses

Prior to the analyses of soil physical-chemical properties, soil specimens were subjected to atmospheric drying under indoor temperature condition. According to the cutting ring method (Lu, 2000), soil specimens were oven-dried at 105 °C to the stable weight in order to measure the bulk density. Soil clay was detected by the hydrometer (TM-85, Veichi, China) (Lu, 2000). Soil pH was detected by the glassy electrode (MT-5000, Ehsy, China), with the ratio of soil : water (mass : volume) as 1 : 2.5 (Lu, 2000). Soil OC and TN were identified via the acid dichromate wet oxidation method (Nelson and Sommers, 1996) and the micro-Kjeldahl method (Bremner, 1996), separately. Soil TP was identified via the molybdate blue colorimetry method (Bray and Kurtz, 1945). Soil exchangeable alkali cations (i.e., Ca^{2+} and Mg^{2+}) were abstracted by the ammonium acetate (CH_3COONH_4) (Thomas, 1982). In short, 2.5 g of every aggregate fraction was weighted into Erlenmeyer flask to blend with 50 mL 1 M CH_3COONH_4 (pH = 7.0). The extract liquid was agitated for 30 min under 150 rpm, and afterwards subjected to filtration via

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Whatman No. 2 V filtration paper (quantitative and ashfree). Soil available micronutrients (i.e., Fe^{2+} and Mn^{2+}) were abstracted by the diethylenetriamine pentaacetic acid (DTPA) (Lindsay and Norvell, 1978). In short, 10 g of every aggregate fraction was weighted into Erlenmeyer flask to blend with 20 mL 0.005 M DTPA + 0.01 M $CaCl_2$ + 0.1 M TEA (triethanolamine) (pH = 7.0). The extract liquid was agitated for 2 h under 180 rpm, and afterwards subjected to filtration. Entire extractable metallic cations were detected by the atomic absorption spectrometer (AAS, Shimadzu, Japan). In this study, 5 standard specimens (GBW-07401), 5 blank specimens, and 80 parallel specimens (accounted for 20% of the total soil specimens) were used to control quality, and the error is controlled in 5%.

2.6. Calculations and statistics

The mean weight diameter (MWD, mm) was utilized to indicate the stability of soil aggregates (Kemper and Chepil, 1965):

$$\mathrm{MWD} = \sum_{i=1}^{4} (\mathrm{X}_i \times \mathrm{M}_i),$$

in the formula, X_i indicates the i^{th} size aggregates' mean diameter (mm) and M_i indicates the i^{th} size aggregates' proportion (% in weight).

In the present study, since tea-planting age and soil depth serve as the two main factors, statistic analysis was conducted separately by aggregate size. SPSS 22.0 was used for statistic analysis (Table S1). One-way analysis of variance (ANOVA) was taken for exploring the effect of tea-planting age on the litterfall characteristics. Two-way ANOVA was taken for exploring the effects of tea-planting age and soil depth on the soil characteristics. Besides that, Pearson correlation analysis was utilized to test the relationships between pH and stoichiometric ratios (i.e., Ca/Mg and Fe/Mn ratios) in bulk soil during the process of tea planting.

3. Results

3.1. Composition and stability of soil aggregates

At the 0-10 and 10-20 cm soil depths, continuous planting of tea resulted in remarkable variations in the proportions of various sized aggregates, apart from the medium and fine macroaggregates (Figure 1). To be specific, the proportions of coarse macroaggregates remarkably rose within the first 17 years and afterwards remarkably dropped, whereas the proportions of microaggregates displayed an opposite trend over time. Meanwhile, the greatest value of soil MWD was identified in the tea plantations of 17 years (Figure 1). Notably, the role of tea-planting age in the aggregate composition and stability is limiting at the 20-40 and 40-60 cm soil depths. Across the 4 tea-planting ages, the coarse macroaggregates were prevailing at the 0-10 cm soil depth, which accounted for 32.60%-53.18% of bulk soil. However, at the 10-20, 20-40, and 40-60 cm soil depths, the microaggregates were dominant, which accounted for 33.80%-49.51%, 42.12%-48.24%, and 44.80%-49.45%, respectively. These results showed that the coarse macroaggregate proportions reduced while the microaggregate proportions elevated with increasing soil depth.

3.2. Contents of soil C, N, and P

At the aggregate scales, soil OC (Figure 2) and TN (Figure 3) contents increased with increasing aggregate size, but the distribution of soil TP (Figure 4) was even in various sized aggregates. In the tea-planting course (8-43 years), the aggregate-related OC and TN contents at the 0-10, 10-20, and 20-40 cm soil depths were significantly elevated by 22%-35% and 14%-24%, 11%-22% and 9%-17%, and 8%-18% and 9%-13%, respectively. Nevertheless, no remarkable variation existed in the aggregate-related TP content. Furthermore, at the 40-60 cm soil depth, the aggregate-related OC, TN, and TP contents did not show significant variations over time. Regardless of the tea-planting age, decreasing trend of the aggregate-related OC, TN, and TP contents was observed as the soil depth increased.

3.3. Stoichiometric ratios of soil C, N, and P

In this study, the increases in aggregate-related C/N (Table 2), C/P (Table 3), and N/P (Table 4) ratios were accompanied by the increasing aggregate size. At the 0-10, 10-20, and 20-40 cm soil depths, aggregate-related C/N ratio did not show remarkable variation while aggregate-related C/P and N/P ratios remarkably increased during the process of tea planting.

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Moreover, there was little role of tea-planting age in the aggregate-related C/N, C/P, and N/P ratios at the 40-60 cm soil depth. In different aged tea plantations, aggregate-related C/N, C/P, and N/P ratios dropped as the soil depth increased. For example, at the 0-10 cm soil depth, aggregate-related C/N, C/P, and N/P ratios across the 4 tea-planting ages fluctuated in 20.81-23.04, 28.81-37.07, and 1.31-1.67, respectively. Meanwhile, at the 40-60 cm soil depth, aggregate-related C/N, C/P, and N/P ratios fluctuated in 16.41-20.74, 13.44-22.88, and 0.84-1.08, respectively.

3.4. Contents of soil alkali cations and micronutrients

At the aggregate scales, soil exchangeable alkali cations (i.e., Ca^{2+} and Mg^{2+}) were mainly distributed in the microaggregates (Figures 5 and 6). However, soil available micronutrients (i.e., Fe^{2+} and Mn^{2+}) were mainly existed in the coarse macroaggregates (Figures 7 and 8). In the tea-planting course (8-43 years), the aggregate-related Ca^{2+} and Mg^{2+} contents at the 0-10, 10-20, and 20-40 cm soil depths were significantly reduced by 31%-38% and 10%-24%, 23%-27% and 9%-18%, and 10%-16% and 5%-8%, respectively. However, the aggregate-related Fe^{2+} and Mn^{2+} contents were significantly elevated by 16%-27% and 6%-9%, 11%-15% and 4%-7%, and 7%-12% and 3%-5%, respectively. In addition, at the 40-60 cm soil depth, the contents of aggregate-related exchangeable alkali cations and available micronutrients did not show significant variations over time. Irrespective of the tea-planting age, increasing trend of the aggregate-related Ca^{2+} and Mg^{2+} contents was observed with increasing soil depth, but the aggregate-related Fe^{2+} and Mn^{2+} contents showed an opposite trend.

3.5. Stoichiometric ratios of soil alkali cations and micronutrients

In this study, soil Ca/Mg (Table 5) and Fe/Mn (Table 6) ratios were evenly distributed in various sized aggregates. At the 0-10, 10-20, and 20-40 cm soil depths, aggregate-related Ca/Mg ratio remarkably decreased while aggregate-related Fe/Mn ratio remarkably increased in the tea-planting course. Moreover, there was little role of tea-planting age in the aggregate-related Ca/Mg and Fe/Mn ratios at the 40-60 cm soil depth. In different aged tea plantations, no

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variations were observed amongst different soil depths in aggregate-related Ca/Mg and Fe/Mn ratios. For example, at the 0-10 cm soil depth, aggregate-related Ca/Mg and Fe/Mn ratios across the 4 tea-planting ages ranged from 1.81 to 1.96 and 0.76 to 0.85, respectively. Meanwhile, at the 40-60 cm soil depth, aggregate-related Ca/Mg and Fe/Mn ratios ranged from 1.88 to 1.92 and 0.78 to 0.82, respectively.

4. Discussion

4.1. Composition and stability of soil aggregates

Tea-planting age significantly influenced the aggregate composition and stability at the 0-10 and 10-20 cm soil depths, whereas the effect at the 20-40 and 40-60 cm soil depths was quite limited (Figure 1). In the early (8-17 years) period, tea planting was beneficial for the transition from microaggregates to coarse macroaggregates at the 0-10 and 10-20 cm soil depths. By comparison, in the middle (17-25 years) and late (25-43 years) periods, tea planting induced coarse macroaggregate destruction and microaggregate release. According to the hierarchical concept of soil aggregates (Six et al., 2004), the quality of plant litterfall returning to the soil determines the distribution of decomposition products of litterfall in various sized aggregates, which ultimately impacts the aggregate composition. In the early period of tea planting, tea litterfall displayed greater availability (as indicated by the lower litterfall C/N ratio) (Table 1), revealing that the decomposition products of litterfall were easily combined into the coarse macroaggregates, hence fostering the formation of coarse macroaggregates (Tisdall and Oades, 1982). Reversely, in the middle and late periods of tea planting, tea plants naturally encountered aging processes and litterfall was progressively subjected to humification, which induced the decomposition of coarse macroaggregates into microaggregates (Six and Paustian, 2014). Moreover, the reduced litterfall amount and covering area after 17 years of tea planting (Table 1) enhanced the rainfall eluviation and artificial interferences (i.e., pruning of tea plants and application of fertilizers), which also caused the destruction of coarse macroaggregates. In the tea-planting course, variation in aggregate stability was indicated via the change of MWD value.

At the 0-10 and 10-20 cm soil depths, the MWD value was the greatest in the 17 years of tea planting (Figure 1), which was associated with the highest proportions of coarse macroaggregates in the 17-year tea plantations. These findings indicated that the 17-year tea plantations exhibited stronger aggregate stability in contrast to other plantations at the 0-10 and 10-20 cm soil depths.

Regardless of the tea-planting age, coarse macroaggregates were dominant in the topsoil (0-10 cm) while microaggregates were dominant in the subsoil (10-60 cm) (Figure 1), indicating transformation of aggregate composition from coarse macroaggregate-prevailing to microaggregate-prevailing with the increase in soil depth. Also, alike outcomes were corroborated by Li et al. (2015) and Zhu et al. (2017) from studies on tea plantations in the southwest Sichuan of China. In the present study, coarse macroaggregates were the prevailing fractions in the topsoil, not the subsoil, which was attributed to the surface cumulation of soil OC (Figure 2). As an essential cementing agent, soil OC could foster the formation of coarse macroaggregates (Al-Kaisi et al., 2014). Moreover, the reduced proportions of coarse macroaggregates as the soil depth increased were also because of the elevated soil compactness (as indicated by the bulk density) (Table 1). Soil densification could prevent the growth of plant roots, hence causing the activities of soil microorganisms decreased, especially soil fungi (Kurmi et al., 2020). Reduced activities of soil fungi could diminish the production of polysaccharose and glomalin-related soil protein (GRSP) from the fungal hyphae, hence inducing the proportions of soil macroaggregates decreased (Ji et al., 2019). Likewise, as per our past studies (Wang et al., 2017b; Zhu et al., 2019), soil microbial activities and GRSP content served as the vital effects in the formation and stabilisation of soil macroaggregates, and presented the higher levels in the topsoil compared with the subsoil in tea plantation ecosystems. With increasing soil depth, the decrease in MWD value (Figure 1) was mainly related to the change of soil aggregate composition, especially for the decomposition of coarse macroaggregates into microaggregates, implying that the topsoil exhibited stronger aggregate stability in contrast to the subsoil.

4.2. Contents of soil C, N, and P

In this study, more contents of soil OC and TN could be detected in coarse macroaggregates (Figures 2 and 3), which conformed to the findings of Six et al. (2004) that macroaggregates were comprised of microaggregates via temporary binding agents (i.e., microbe- and plant-originated polysaccharides, fungal mycelium, and plant roots); meanwhile, macroaggregates could provide the protection for the organic matters (OMs), hence causing the cumulation of OC and TN in macroaggregates. Unlike soil OC and TN, soil TP was evenly distributed in various sized aggregates (Figure 4). Moreover, Bhatnagar and Miller (1985) also detected alike outcomes from soil specimens subjected to fresh poultry manure treatments, and propelled the causal links influencing the TP distribution in soil aggregates. Specifically, (i) introduced P was firstly adsorbed by clay particulates in soil and clay particulates were discrepant in various sized aggregates, and (ii) introduced P had selective absorptive properties for various sized aggregates. According to our findings, stochasticity seems to be one probable mechanism that sheds light on the TP distribution in soil aggregates.

Continuous planting of tea could positively affect the cumulation of soil OC and TN, but such positive effects were more obvious at the 0-40 cm soil depth in contrast to the 40-60 cm soil depth (Figures 2 and 3). In this study, soil OC and TN contents exhibited a significant growing trend over time, which was possibly associated with the following mechanisms. First, many long-period tests had demonstrated the proactive roles of manure and chemical fertilizer applications in soil OM cumulation (Tong et al., 2009; Zhou et al., 2013). Similarly, in the tea-planting course, growing soil OC and TN contents were probably caused by the applications of substantial swine manure every year (12 Mg ha^{-1} year^{-1}) in this tea-planting region (Wang and Ye, 2020). Second, plants serve as the prime OM sources in soil via root exudates and litterfall remains (Franklin et al., 2020). In the tea-planting course, soil OC and TN cumulation probably occurred as a result of the growing root systems and the increasing amounts of aboveground litterfall attained from trimmed branches and leaves. Third, no tillage could provide physical protection for the OMs combined with soil aggregates, and then further improve soil OC and TN sequestration (Wulanningtyas et al., 2021). Notably, although the positive correlations of OC and TN contents with clay content in soil have been reported, the present study revealed that significant increases in the OC and TN contents were accompanied by no significant variation in the clay content during the process of tea planting (Table 1). Similarly, Li et al. (2015) and Wang et al. (2018) discovered as well that the changes of soil OC and TN contents were not influenced by the clay content over time in tea plantation ecosystems, mainly because soil OC and TN contents primarily depend on fertilization, tillage, root exudates, and litterfall remains, but soil clay content is mainly controlled by its parent material (Rakhsh et al., 2020). Unlike soil OC and TN, regardless of the soil depth, no remarkable difference existed in soil TP content amongst different aged tea plantations (Figure 4), which implied the resistance of soil TP content to the change of tea-planting age. Also, past studies verified that soil TP content was not related to the tea-planting age (Wu et al., 2018; Yan et al., 2018), as soil P primarily derives from the weathering release of soil minerals, instead of the short-period biology cycle (Cui et al., 2019).

In tea plantation ecosystems, the decreasing OC, TN, and TP contents with increasing soil depth (Figures 2, 3, and 4) coincided with some past findings in other ecosystems, such as tropic forests, bushlands, and grasslands (Stone and Plante, 2014; Yu et al., 2018; Qiao et al., 2020). In the present study, the higher contents of OC, TN, and TP in the topsoil were associated with the higher OM input, in which the soil OM contents in the topsoil were enriched by the input of surface tea litterfall, root debris and exudates, and swine manure.

4.3. Stoichiometric ratios of soil C, N, and P

Soil C/N, C/P, and N/P ratios act as vital indicators of soil health (Liu et al., 2018), which can be employed for exploring C circulation and guiding the equilibrium between N and P in soil ecosystems (Sardans et al., 2012). In this study, soil C/N ratio grew with growing aggregate size (Table 2), which indicated that the OMs in macroaggregates were younger and more unstable in contrast to microaggregates (Six et al., 2004). Meanwhile, the OMs associated with microaggregates experienced more degradation, resulting in the lower C/N ratio in the microaggregates (Xu et al., 2019). In different aged tea plantations, soil OC and TN were predominantly distributed in the coarse macroaggregates (Figures 2 and 3), but the TP was evenly distributed in various sized aggregates (Figure 4). As a result, the associations of C/P and N/P ratios to aggregate size primarily depended on the relationships of OC and TN contents with aggregate size (Tables 3 and 4). As far as we know, the changes of soil C/P and N/P ratios at the aggregate scales are rarely examined, although these kinds of knowledge are imperative because of the biogeochemical cycles of N and P being influenced by the dynamics of soil aggregates (Cui et al., 2021). Consequently, the impact generated by the aggregate size on the C/P and N/P ratios ought to be studied more for the accurate forecast of soil N and P cycling under natural or man-intervened ecosystems.

Irrespective of the soil depth, soil C/N ratio showed little significant variation in the tea-planting course (Table 2). Meanwhile, tea-planting age significantly affected soil C/P and N/P ratios at the 0-40 cm soil depth, not the 40-60 cm soil depth (Tables 3 and 4). Soil C/N ratio is generally treated as the critical indicator which affects the formation and degradation of soil OMs (Khan et al., 2016). Since response of soil TN content to soil environment change is almost the same as soil OC content (Wang et al., 2018), soil C/N ratio did not show significant difference amongst different aged tea plantations (Table 2). Likewise, Zhou et al. (2018) proved that no close correlation existed between soil C/N ratio and vegetation coverage, because C and N are structure elements and their cumulation and consumption in soil remain relative consistency. Soil C/P ratio is the indicator suggesting P effectiveness, and higher C/P ratio often denotes lower P effectiveness (Khan et al., 2016). In acidic soil (Table 1), available P was adsorbed on the surfaces of Fe/Al oxides and clay minerals in a preferential way, because Fe/Al oxides and clay minerals with greater surface areas could afford enough sites to available P adsorption (Wu et al., 2018). As the tea-planting age increased, therefore, soil acidification led to the decrease in P effectiveness (evidenced by the significant increase in soil C/P ratio) (Table 3).

Soil N and P are the prohibiting factors mostly seen during the process of plant growth, and thus, N/P ratio can be utilized as one efficient indicator that shows nutrient restriction (Khan et al., 2016). In this study, soil N/P ratio remarkably increased in the tea-planting course (Table 4), mainly because soil TN content experienced significant increase while no such significant change was found in TP content over time.

Soil C/N ratio decreased with increasing soil depth, regardless of the tea-planting age (Table 2), which coincided with the majority of studies (Cao et al., 2015; Feng and Bao, 2017, Yu et al., 2019). Batjes (1996) suggested that the decrease in soil C/N ratio as the soil depth increased was triggered by the stratification of humic substance in the soil profile. Moreover, in this study, the lower soil C/P and N/P ratios in the subsoil (Tables 3 and 4) backed the outcomes of past studies in terrestrial ecosystems of China, which were on the foundation of the data from both the 2nd soil investigation in China (Tian et al., 2010) and the Chinese Ecosystem Research Network (CERN) (Chai et al., 2015).

Across the 4 tea-planting ages, the mean contents of OC and TN in bulk soil (0-20 cm) were 16.70 and 0.77 g kg^{-1}, separately, which were below the mean contents of OC (21.30 g kg^{-1}) and TN (2.17 g kg^{-1}) in Chinese tea plantations (Sun et al., 2020; Xie et al., 2020). Moreover, in this tea-planting region, the mean content of TP in bulk soil (0-20 cm) was 0.57 g kg^{-1}, corresponding to the moderate level in Chinese tea plantations, where TP content varied in the range of 0.35-1.20 g kg^{-1} (Wu et al., 2018; Sun et al., 2020). Herein, soil C/N ratio is higher compared with other tea-planting regions in China, whereas soil C/P and N/P ratios are much lower (Sun et al., 2020). These findings are primarily associated with the lower contents of soil OC and TN, especially the TN. In general, N is the most limiting element in the net primary production of tea plantation ecosystems (Miner et al., 2018), and this phenomenon also appeared in the southern Guangxi of China.

4.4. Contents of soil alkali cations and micronutrients

According to the findings from Adesodun et al. (2007) and Emadi et al. (2009), the higher contents of exchangeable alkali cations (including Ca^{2+} and Mg^{2+}) were detected in both 2-4.76 and < 0.25 mm aggregates in the non-tillage soil. In the tillage course, however, the contents of these two cations decreased in the 2-4.76 mm aggregates and increased in the < 0.25 mm aggregates, revealing that the tillage practice could cause soil Ca^{2+} and Mg^{2+} to redistribute in various sized aggregates. In comparison, the present study exhibited that the distribution of soil Ca^{2+} and Mg^{2+} in aggregates was similar in different aged tea plantations (Figures 5 and 6), implying that the distribution of these two cations in aggregates was seldom influenced by the tea-planting age. To be specific, coarse macroaggregates had the lowest contents of Ca^{2+} and Mg^{2+}, whereas microaggregates exhibited the highest contents. These findings could be ascribed to the larger specific surface areas of microaggregates (Adesodun et al., 2007), which increased microaggregates' adsorption to Ca^{2+} and Mg^{2+} derived from root exudates, litterfall remains, and manure (Emadi et al., 2009). Unlike exchangeable alkali cations, the contents of soil available micronutrients (including Fe^{2+} and Mn^{2+}) usually correspond to the contents of soil OMs (Wang et al., 2017a), which are more abundant in macroaggregates (Six et al., 2004). Similarly, this study also found that the Fe^{2+} and Mn^{2+} had a similar distribution pattern with OC at the aggregate scales (Figures 7 and 8). Since the decomposition products of litterfall can be easily integrated to the coarse macroaggregates (Six et al., 2004), the nutrient cycling of plant-soil systems might lead to the higher contents of soil Fe^{2+} and Mn^{2+} in the coarse macroaggregates (Wang et al., 2017a).

At the 0-40 cm soil depth, the contents of soil Ca^{2+} and Mg^{2+} significantly decreased over time (Figures 5 and 6), which might be due to the applications of urea and NH_4^+-N fertilizer in the tea-planting course for increasing tea leaf outputs. Urea hydrolysis can promote the production of ammonium ions which are readily nitrified into nitrate, and the excessive proton produced by the nitrification can compete for the adsorption sites with Ca^{2+} and Mg^{2+} (Wang et al., 2017a). As a result, these cations were easy to lose from soil in the manner of leaching. Except at the 40-60 cm soil depth, continuous planting of tea led to the remarkable increases in soil Fe^{2+} and Mn^{2+} contents, which were elevated by 7%-27% and 3%-9% from 8 to 43 years of tea planting, separately (Figures 7 and 8). This phenomenon was possibly caused by the soil acidification (Table 1), which stimulates the release of soil Fe^{2+} and Mn^{2+} by mineralization and desorption from soil OMs and minerals (Wang et al., 2017a). Tea, as an aluminium (Al) cumulating crop, is able to cumulate Al in leaves (Li et al., 2016). Soil acidification in the tea-planting course was due to the substantial tea litterfall into the soil annually via trimmed branches and leaves (Li et al., 2016). At the same time, the rhizosphere deposition of massive organic acids (i.e., malate, lemon acid, and oxalate acid) around the tea roots could provoke localized acidification (Xue et al., 2006). In addition, for increasing the output of tea, tea plantations needed to apply N fertilizers (i.e., urea and NH_4^+-N), thus leading to soil acidification by the NH_4^+ nitration (Yang et al., 2018).

Across the 4 tea-planting ages, the contents of soil Fe^{2+} and Mn^{2+} were higher in the topsoil than the subsoil (Figures 7 and 8), primarily owing to the usage of swine manure and the inputs of tea litterfall and roots in the topsoil (Miner et al., 2018). Nevertheless, the contents of soil Ca^{2+} and Mg^{2+} showed an opposite trend as the soil depth increased (Figures 5 and 6), because soil Ca^{2+} and Mg^{2+} were easy to move from topsoil to subsoil in the manner of leaching (Hansen et al., 2017).

4.5. Stoichiometric ratios of soil alkali cations and micronutrients

Tea-planting age exerted a remarkable influence on the Ca/Mg and Fe/Mn ratios at the 0-40 cm soil depth, not the 40-60 cm soil depth (Tables 5 and 6). To be specific, a notable decline in the Ca/Mg ratio was found at the 0-40 cm soil depth over time (Table 5). From 8 to 43 years of tea planting, the contents of Ca^{2+} and Mg^{2+} at the 0-40 cm soil depth decreased by 10%-38% and 5%-24%, separately (Figures 5 and 6), which revealed that the role of tea-planting age in the content of soil Ca^{2+} was greater than that of soil Mg^{2+}. Lu et al. (2014) suggested that the selective losses of soil exchangeable alkali cations ($Ca^{2+} > Mg^{2+}$) could lead to the disequilibrium of soil metal ions in forest ecosystems. Similarly, in this study, the preferential loss of soil Ca^{2+} relative to Mg^{2+} was the prime cause of the notable decline in the soil Ca/Mg ratio in the tea-planting course. The depletion of soil exchangeable alkali cations (especially the Ca^{2+}) could lead to the decrease in soil buffering capacity and soil acidification (Hansen et al., 2017). Thus, the Ca/Mg ratio at the 0-40 cm soil depth was positively related ($P < 0.05$) to soil pH across the 4 tea-planting ages (Figure 9). Soil acidification accelerated the mineralization and desorption of soil available micronutrients from soil OMs and minerals (Wang et al., 2017a), conducive to the significant increases in Fe^{2+} and Mn^{2+} contents at the 0-40 cm soil depth, especially the Fe^{2+} (Figures 7 and 8). In a chronological sequence of tea plantations, the negative relationship ($P < 0.05$) of soil Fe/Mn ratio with soil pH in different soil depths (Figure 9) indicated more cumulation of soil Fe^{2+} relative to Mn^{2+} over time (Table 6). Moreover, the change of soil Fe/Mn ratio was also triggered by the antagonistic relationship between soil Fe^{2+} and Mn^{2+} during the process of tea plant uptake (Wang et al., 2017a). Tian et al. (2016) discovered that soil acidification could reduce Fe^{2+} absorption and enhance Mn^{2+} uptake by various plant species, thereby causing the increase in soil Fe/Mn ratio and threatening plant productivity.

5. Conclusions

Herein, soil OC, TN, and TP contents as well as C/N, C/P, and N/P ratios decreased as the soil depth increased. Moreover, soil Ca^{2+} and Mg^{2+} contents were lower in the topsoil than the subsoil, whereas soil Fe^{2+} and Mn^{2+} contents showed an opposite trend, and no differences were detected amongst different soil depths in soil Ca/Mg and Fe/Mn ratios. Tea-planting age could influence the variations in soil OC and nutrient contents and their stoichiometric ratios, but such effects were more obvious at the 0-40 cm soil depth in contrast to the 40-60 cm soil depth, thus supporting our hypothesis. At the 0-40 cm soil depth, continuous planting of tea was favorable to the cumulation of soil OC, TN, Fe^{2+}, and Mn^{2+}, whereas soil Ca^{2+} and Mg^{2+} were susceptible to leaching losses over time. Compared with other tea-planting regions in China, soil C/N ratio is higher in this tea-planting region, whereas soil C/P and N/P ratios are much lower, indicating that soil OC and TN contents in the present study were lower, especially the TN. Therefore, an appropriate increase in the amount of N fertilizer should be applied in this tea-planting region. In the tea-planting course, the losses of soil Ca^{2+} and Mg^{2+}, especially the Ca^{2+} (as indicated by the decrease in soil Ca/Mg ratio), could lead to the soil acidification. Soil acidification could reduce Fe^{2+} absorption and enhance Mn^{2+} uptake by tea plant (as indicated by the increase in soil Fe/Mn ratio), thereby causing the aggravation of Fe^{2+} insufficiency and the emergence of Mn^{2+} toxicity to tea plant. Overall, the present study improved the understanding of soil OC and nutrient dynamics in tea plantation ecosystems, and also provided supplementary information for soil ecological stoichiometry in global terrestrial ecosystems.

Data availability

The data supporting the discovered information here can be presented by the relevant author based on reasonable requests.

Author contribution

S.W. and S.Y. designed the experiments; L.M. carried out the experiments; S.W. and L.M. analyzed the experimental results; L.M., S.W. and S.Y. wrote and edited the manuscript.

Competing interests

The authors declare no conflict of interest.

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Table 1 Physical-chemical properties of litterfall and soil in different aged tea plantations.

Item	Soil depth	Tea-planting age			
		8 years	17 years	25 years	43 years
Litterfall amount (g m^{-2})		821 ± 21 B	974 ± 34 A	786 ± 28 C	648 ± 19 D
Litterfall C/N ratio		14.23 ± 1.61 C	12.68 ± 1.26 C	17.32 ± 2.24 B	21.37 ± 3.11 A
Soil bulk density (g cm^{-3})	0-10 cm	1.28 ± 0.02 Ab	1.20 ± 0.02 Bc	1.26 ± 0.01 Ad	1.31 ± 0.04 Ab
	10-20 cm	1.30 ± 0.03 Aab	1.22 ± 0.03 Bc	1.30 ± 0.03 Ac	1.29 ± 0.02 Ab
	20-40 cm	1.32 ± 0.04 Aab	1.31 ± 0.01 Ab	1.34 ± 0.01 Ab	1.33 ± 0.04 Ab
	40-60 cm	1.36 ± 0.01 Aa	1.37 ± 0.02 Aa	1.39 ± 0.02 Aa	1.38 ± 0.03 Aa
Soil clay (%)	0-10 cm	34.69 ± 3.21 Aa	35.91 ± 2.77 Aa	33.12 ± 2.46 Aa	35.08 ± 2.41 Aa
	10-20 cm	34.88 ± 2.08 Aa	32.59 ± 3.02 Aa	34.92 ± 3.67 Aa	32.35 ± 2.68 Aa
	20-40 cm	35.26 ± 1.45 Aa	34.57 ± 4.12 Aa	34.51 ± 3.21 Aa	34.29 ± 3.54 Aa
	40-60 cm	34.78 ± 3.66 Aa	36.89 ± 2.98 Aa	33.68 ± 1.91 Aa	35.81 ± 3.69 Aa
Soil pH	0-10 cm	4.57 ± 0.02 Aa	4.49 ± 0.01 Ba	4.31 ± 0.03 Ca	4.15 ± 0.02 Da
	10-20 cm	4.55 ± 0.03 Aa	4.50 ± 0.01 Aa	4.33 ± 0.02 Ba	4.17 ± 0.02 Ca
	20-40 cm	4.60 ± 0.04 Aa	4.53 ± 0.02 Ba	4.34 ± 0.04 Ca	4.19 ± 0.03 Da
	40-60 cm	4.58 ± 0.02 Aa	4.54 ± 0.03 Aa	4.32 ± 0.01 Ba	4.21 ± 0.01 Ca

Data represent the average of 5 replicates ± standard deviations. Different capital letters indicate significant differences ($P < 0.05$) among different tea-planting ages. Different lower case letters indicate significant differences ($P < 0.05$) among different soil depths.

Table 2 Effects of tea-planting age and soil depth on the soil C/N ratio in various sized aggregates.

Sample	Soil depth	Tea-planting age			
		8 years	17 years	25 years	43 years
Bulk soil	0-10 cm	22.21 ± 0.12 Aa	21.72 ± 0.11 Aa	22.06 ± 0.06 Aa	21.99 ± 0.07 Aa
	10-20 cm	21.73 ± 0.08 Aa	21.98 ± 0.08 Aa	21.10 ± 0.13 Aa	21.47 ± 0.11 Aa
	20-40 cm	18.86 ± 0.13 ABb	18.07 ± 0.09 ABb	17.52 ± 0.06 Bc	19.38 ± 0.08 Ab
	40-60 cm	18.48 ± 0.04 Ab	18.33 ± 0.09 Ab	19.40 ± 0.04 Ab	18.92 ± 0.05 Ab
	Mean	20.32	20.03	20.02	20.44
> 2 mm aggregates	0-10 cm	21.11 ± 0.13 Bab	22.19 ± 0.08 ABa	23.04 ± 0.10 Aa	22.24 ± 0.11 ABa
	10-20 cm	22.39 ± 0.04 Aa	22.97 ± 0.11 Aa	21.92 ± 0.07 Ab	21.83 ± 0.03 Aab
	20-40 cm	19.71 ± 0.12 Ab	20.21 ± 0.04 Ab	19.51 ± 0.14 Ac	20.40 ± 0.04 Ab
	40-60 cm	20.74 ± 0.07 Aab	19.61 ± 0.13 Ab	19.67 ± 0.08 Ac	20.51 ± 0.09 Ab
	Mean	20.99	21.24	21.03	21.24
1-2 mm aggregates	0-10 cm	22.53 ± 0.07 Aa	21.00 ± 0.12 Aa	21.31 ± 0.08 Aa	22.51 ± 0.07 Aa
	10-20 cm	22.09 ± 0.04 Aa	22.72 ± 0.09 Aa	22.69 ± 0.07 Aa	22.55 ± 0.08 Aa
	20-40 cm	19.05 ± 0.05 Ab	18.48 ± 0.11 Ab	19.29 ± 0.04 Ab	18.71 ± 0.10 Ab
	40-60 cm	17.47 ± 0.06 Ac	17.69 ± 0.10 Ab	16.94 ± 0.05 Ac	17.27 ± 0.06 Ab
	Mean	20.29	19.97	20.06	20.26
0.25-1 mm aggregates	0-10 cm	22.05 ± 0.08 Aa	21.70 ± 0.11 Aa	21.60 ± 0.09 Aa	21.61 ± 0.04 Aa
	10-20 cm	21.63 ± 0.09 Aa	22.56 ± 0.07 Aa	21.90 ± 0.04 Aa	21.89 ± 0.10 Aa
	20-40 cm	18.95 ± 0.12 Ab	18.27 ± 0.04 Ab	19.01 ± 0.07 Ab	18.03 ± 0.12 Ab
	40-60 cm	17.56 ± 0.13 Ab	17.08 ± 0.06 Ab	17.48 ± 0.06 Ac	17.22 ± 0.05 Ab
	Mean	20.05	19.90	20.00	19.69
< 0.25 mm aggregates	0-10 cm	21.89 ± 0.08 Aa	21.30 ± 0.07 Aa	20.81 ± 0.11 Aa	21.93 ± 0.09 Aa
	10-20 cm	21.51 ± 0.08 ABa	21.12 ± 0.03 ABa	20.27 ± 0.07 Ba	22.83 ± 0.06 Aa
	20-40 cm	17.78 ± 0.02 Ab	18.45 ± 0.13 Ab	17.46 ± 0.06 Ab	17.56 ± 0.04 Ab
	40-60 cm	16.52 ± 0.05 Ab	16.92 ± 0.07 Ac	17.03 ± 0.10 Ab	16.41 ± 0.08 Ab
	Mean	19.42	19.45	18.89	19.68

Data represent the average of 5 replicates ± standard deviations. Different capital letters indicate significant differences ($P < 0.05$) among different tea-planting ages. Different lower case letters indicate significant differences ($P < 0.05$) among different soil depths.

Table 3 Effects of tea-planting age and soil depth on the soil C/P ratio in various sized aggregates.

Sample	Soil depth	Tea-planting age			
		8 years	17 years	25 years	43 years
Bulk soil	0-10 cm	30.93 ± 1.02 Ba	31.63 ± 1.45 Ba	35.94 ± 1.41 Aa	34.50 ± 2.89 Aa
	10-20 cm	23.60 ± 0.85 Bb	24.18 ± 0.84 Bb	26.28 ± 1.21 Ab	26.56 ± 1.47 Ab
	20-40 cm	19.92 ± 0.48 Cc	20.13 ± 0.71 BCc	21.15 ± 0.89 Bc	24.41 ± 0.98 Ab
	40-60 cm	17.41 ± 0.69 Ac	17.21 ± 0.58 Ad	18.12 ± 0.24 Ad	17.59 ± 1.22 Ac
	Mean	22.97	23.29	25.37	25.76
> 2 mm aggregates	0-10 cm	32.04 ± 1.04 Ca	32.14 ± 0.98 Ca	35.54 ± 1.07 Ba	37.07 ± 0.38 Aa
	10-20 cm	25.93 ± 0.84 Cb	24.41 ± 1.07 Cb	27.21 ± 0.37 Bb	29.23 ± 0.98 Ab
	20-40 cm	22.13 ± 0.97 Bc	21.43 ± 1.12 Bc	26.33 ± 0.86 Ab	27.29 ± 1.24 Ab
	40-60 cm	22.40 ± 2.02 Ac	22.88 ± 0.87 Abc	22.67 ± 1.24 Ac	21.63 ± 1.56 Ac
	Mean	25.62	25.21	27.94	28.81
1-2 mm aggregates	0-10 cm	29.52 ± 1.01 Da	31.48 ± 0.47 Ca	33.54 ± 0.97 Ba	36.53 ± 0.81 Aa
	10-20 cm	24.76 ± 0.38 Bb	26.58 ± 0.58 Ab	27.55 ± 0.47 Ab	26.68 ± 0.97 Ab
	20-40 cm	20.68 ± 1.14 Bc	20.51 ± 1.48 Bc	21.95 ± 1.05 Bc	26.07 ± 0.78 Ab
	40-60 cm	16.78 ± 0.87 Bd	18.04 ± 0.98 Ac	16.63 ± 1.24 Bd	17.55 ± 1.05 ABc
	Mean	22.93	24.15	24.92	26.71
0.25-1 mm aggregates	0-10 cm	31.44 ± 1.27 Aa	30.46 ± 0.78 Aa	30.91 ± 1.08 Aa	30.62 ± 0.98 Aa
	10-20 cm	23.60 ± 0.27 Bb	25.38 ± 0.38 ABb	24.41 ± 1.14 ABb	26.41 ± 0.57 Ab
	20-40 cm	18.96 ± 1.47 Cc	21.62 ± 0.45 Bc	19.78 ± 0.87 Cc	25.60 ± 1.02 Ab
	40-60 cm	18.18 ± 0.87 Ac	17.40 ± 0.38 Ad	17.43 ± 0.91 Ac	17.92 ± 1.34 Ac
	Mean	23.05	23.71	23.13	25.14
< 0.25 mm aggregates	0-10 cm	28.81 ± 1.01 Ba	30.60 ± 1.07 Aa	29.78 ± 0.87 ABa	31.00 ± 0.38 Aa
	10-20 cm	19.39 ± 1.17 Cb	21.86 ± 0.68 Bb	22.36 ± 0.78 ABb	23.19 ± 0.98 Ab
	20-40 cm	15.22 ± 0.87 Bc	17.11 ± 1.14 Ac	17.46 ± 0.94 Ac	18.50 ± 0.75 Ac
	40-60 cm	13.73 ± 0.74 Ac	14.50 ± 0.74 Ad	13.44 ± 1.00 Ad	14.02 ± 0.91 Ad
	Mean	19.29	21.02	20.76	21.68

Data represent the average of 5 replicates ± standard deviations. Different capital letters indicate significant differences ($P < 0.05$) among different tea-planting ages. Different lower case letters indicate significant differences ($P < 0.05$) among different soil depths.

Table 4 Effects of tea-planting age and soil depth on the soil N/P ratio in various sized aggregates.

Sample	Soil depth	Tea-planting age			
		8 years	17 years	25 years	43 years
Bulk soil	0-10 cm	1.39 ± 0.04 Ba	1.46 ± 0.02 Ba	1.63 ± 0.04 Aa	1.57 ± 0.02 ABa
	10-20 cm	1.09 ± 0.01 Bb	1.10 ± 0.04 Bb	1.25 ± 0.08 Ab	1.24 ± 0.03 Ab
	20-40 cm	1.06 ± 0.02 Bb	1.11 ± 0.07 ABb	1.21 ± 0.02 Ab	1.26 ± 0.02 Ab
	40-60 cm	0.94 ± 0.06 Ab	0.99 ± 0.06 Ab	0.93 ± 0.01 Ac	0.98 ± 0.04 Ac
	Mean	1.12	1.17	1.25	1.26
> 2 mm aggregates	0-10 cm	1.52 ± 0.05 ABa	1.45 ± 0.01 Ba	1.54 ± 0.04 ABa	1.67 ± 0.02 Aa
	10-20 cm	1.16 ± 0.02 ABb	1.06 ± 0.02 Bc	1.24 ± 0.03 Ab	1.34 ± 0.01 Ab
	20-40 cm	1.11 ± 0.03 Bb	1.24 ± 0.02 ABb	1.25 ± 0.05 ABb	1.38 ± 0.04 Ab
	40-60 cm	1.08 ± 0.04 Ab	1.07 ± 0.03 Ac	1.00 ± 0.04 Ac	1.06 ± 0.03 Ac
	Mean	1.22	1.20	1.26	1.36
1-2 mm aggregates	0-10 cm	1.31 ± 0.03 Ba	1.50 ± 0.01 Aa	1.57 ± 0.02 Aa	1.62 ± 0.04 Aa
	10-20 cm	1.12 ± 0.04 Ab	1.17 ± 0.02 Ab	1.21 ± 0.03 Ab	1.18 ± 0.05 Abc
	20-40 cm	0.98 ± 0.01 Bc	1.05 ± 0.01 Bb	1.14 ± 0.04 ABbc	1.26 ± 0.02 Ab
	40-60 cm	0.96 ± 0.06 Ac	1.02 ± 0.03 Ab	0.98 ± 0.06 Ac	1.03 ± 0.03 Ac
	Mean	1.09	1.19	1.23	1.27
0.25-1 mm aggregates	0-10 cm	1.43 ± 0.02 Aa	1.40 ± 0.04 Aa	1.43 ± 0.02 Aa	1.42 ± 0.01 Aa
	10-20 cm	1.09 ± 0.02 Bb	1.13 ± 0.01 ABb	1.11 ± 0.01 ABb	1.21 ± 0.01 Ab
	20-40 cm	0.96 ± 0.06 Bb	1.02 ± 0.02 Bb	1.13 ± 0.04 ABb	1.29 ± 0.03 Ab
	40-60 cm	0.98 ± 0.04 Ab	1.02 ± 0.03 Ab	0.94 ± 0.02 Ac	1.04 ± 0.02 Ac
	Mean	1.11	1.14	1.15	1.24
< 0.25 mm aggregates	0-10 cm	1.32 ± 0.04 Ba	1.44 ± 0.03 Aa	1.43 ± 0.02 Aa	1.41 ± 0.04 Aa
	10-20 cm	0.90 ± 0.01 Bb	1.04 ± 0.02 ABb	1.10 ± 0.01 Ab	1.02 ± 0.03 ABb
	20-40 cm	0.91 ± 0.04 Bb	0.93 ± 0.02 Bbc	1.00 ± 0.03 Ab	1.05 ± 0.02 Ab
	40-60 cm	0.88 ± 0.03 Ab	0.86 ± 0.04 Ac	0.84 ± 0.02 Ac	0.85 ± 0.04 Ac
	Mean	1.00	1.06	1.09	1.08

Data represent the average of 5 replicates ± standard deviations. Different capital letters indicate significant differences ($P < 0.05$) among different tea-planting ages. Different lower case letters indicate significant differences ($P < 0.05$) among different soil depths.

Table 5 Effects of tea-planting age and soil depth on the soil Ca/Mg ratio in various sized aggregates.

Sample	Soil depth	Tea-planting age			
		8 years	17 years	25 years	43 years
Bulk soil	0-10 cm	1.94 ± 0.12 Aa	1.91 ± 0.05 Aa	1.86 ± 0.12 ABa	1.82 ± 0.07 Bab
	10-20 cm	1.93 ± 0.08 Aa	1.87 ± 0.07 ABa	1.87 ± 0.08 ABa	1.84 ± 0.12 Bab
	20-40 cm	1.96 ± 0.14 Aa	1.90 ± 0.14 Ba	1.88 ± 0.04 Ba	1.80 ± 0.14 Cb
	40-60 cm	1.91 ± 0.11 Aa	1.88 ± 0.09 Aa	1.90 ± 0.07 Aa	1.89 ± 0.06 Aa
	Mean	1.94	1.89	1.88	1.84
> 2 mm aggregates	0-10 cm	1.96 ± 0.17 Aa	1.89 ± 0.08 ABa	1.88 ± 0.16 ABa	1.83 ± 0.04 Bab
	10-20 cm	1.92 ± 0.14 Aa	1.87 ± 0.18 Ba	1.86 ± 0.06 Ba	1.88 ± 0.07 Bab
	20-40 cm	1.95 ± 0.08 Aa	1.88 ± 0.06 ABa	1.89 ± 0.07 ABa	1.81 ± 0.12 Bb
	40-60 cm	1.90 ± 0.11 Aa	1.91 ± 0.09 Aa	1.89 ± 0.11 Aa	1.90 ± 0.13 Aa
	Mean	1.93	1.89	1.88	1.86
1-2 mm aggregates	0-10 cm	1.94 ± 0.20 Aa	1.86 ± 0.17 Ba	1.85 ± 0.08 Ba	1.84 ± 0.14 Ba
	10-20 cm	1.95 ± 0.15 Aa	1.90 ± 0.16 Ba	1.88 ± 0.08 Ba	1.87 ± 0.10 Ba
	20-40 cm	1.92 ± 0.07 Aa	1.84 ± 0.05 Ba	1.86 ± 0.12 Ba	1.85 ± 0.08 Ba
	40-60 cm	1.90 ± 0.06 Aa	1.89 ± 0.06 Aa	1.88 ± 0.03 Aa	1.89 ± 0.09 Aa
	Mean	1.93	1.87	1.87	1.86
0.25-1 mm aggregates	0-10 cm	1.95 ± 0.14 Aa	1.88 ± 0.17 Ba	1.87 ± 0.06 Ba	1.81 ± 0.07 Cb
	10-20 cm	1.93 ± 0.11 Aa	1.90 ± 0.08 ABa	1.86 ± 0.07 ABa	1.84 ± 0.04 Bb
	20-40 cm	1.94 ± 0.12 Aa	1.86 ± 0.10 ABa	1.87 ± 0.03 ABa	1.82 ± 0.06 Bb
	40-60 cm	1.92 ± 0.07 Aa	1.90 ± 0.06 Aa	1.91 ± 0.05 Aa	1.89 ± 0.09 Aa
	Mean	1.94	1.89	1.88	1.84
< 0.25 mm aggregates	0-10 cm	1.92 ± 0.06 Aa	1.85 ± 0.04 Ba	1.83 ± 0.08 Ba	1.82 ± 0.12 Bb
	10-20 cm	1.94 ± 0.17 Aa	1.86 ± 0.12 Ba	1.87 ± 0.08 Ba	1.85 ± 0.07 Bab
	20-40 cm	1.91 ± 0.08 Aa	1.85 ± 0.07 Ba	1.84 ± 0.07 Ba	1.86 ± 0.04 Bab
	40-60 cm	1.92 ± 0.11 Aa	1.90 ± 0.03 Aa	1.89 ± 0.06 Aa	1.91 ± 0.13 Aa
	Mean	1.92	1.87	1.86	1.86

Data represent the average of 5 replicates ± standard deviations. Different capital letters indicate significant differences ($P < 0.05$) among different tea-planting ages. Different lower case letters indicate significant differences ($P < 0.05$) among different soil depths.

Table 6 Effects of tea-planting age and soil depth on the soil Fe/Mn ratio in various sized aggregates.

Sample	Soil depth	Tea-planting age			
		8 years	17 years	25 years	43 years
Bulk soil	0-10 cm	0.78 ± 0.04 Ba	0.82 ± 0.01 ABa	0.81 ± 0.04 ABa	0.84 ± 0.02 Aab
	10-20 cm	0.76 ± 0.02 Ba	0.81 ± 0.04 Aa	0.82 ± 0.01 Aa	0.83 ± 0.04 Aab
	20-40 cm	0.75 ± 0.03 Ca	0.80 ± 0.03 Ba	0.81 ± 0.05 Ba	0.85 ± 0.02 Aa
	40-60 cm	0.78 ± 0.05 Aa	0.80 ± 0.05 Aa	0.79 ± 0.03 Aa	0.81 ± 0.03 Ab
	Mean	0.77	0.81	0.81	0.83
> 2 mm aggregates	0-10 cm	0.77 ± 0.02 Ba	0.81 ± 0.01 ABa	0.81 ± 0.03 ABa	0.83 ± 0.02 Aab
	10-20 cm	0.75 ± 0.04 Ca	0.80 ± 0.04 Ba	0.79 ± 0.01 Ba	0.84 ± 0.02 Aa
	20-40 cm	0.77 ± 0.01 Ba	0.78 ± 0.01 Ba	0.82 ± 0.02 Aa	0.82 ± 0.03 Aab
	40-60 cm	0.78 ± 0.03 Aa	0.81 ± 0.02 Aa	0.79 ± 0.04 Aa	0.80 ± 0.01 Ab
	Mean	0.77	0.80	0.80	0.82
1-2 mm aggregates	0-10 cm	0.76 ± 0.01 Cab	0.82 ± 0.02 ABa	0.80 ± 0.01 Ba	0.85 ± 0.03 Aa
	10-20 cm	0.75 ± 0.02 Bb	0.81 ± 0.01 Aa	0.82 ± 0.02 Aa	0.84 ± 0.01 Aa
	20-40 cm	0.78 ± 0.02 Bab	0.80 ± 0.03 ABa	0.82 ± 0.01 ABa	0.85 ± 0.04 Aa
	40-60 cm	0.79 ± 0.01 Aa	0.82 ± 0.01 Aa	0.81 ± 0.03 Aa	0.82 ± 0.02 Aa
	Mean	0.77	0.81	0.81	0.84
0.25-1 mm aggregates	0-10 cm	0.78 ± 0.03 Bab	0.82 ± 0.02 ABa	0.82 ± 0.03 ABa	0.84 ± 0.01 Aab
	10-20 cm	0.77 ± 0.01 Bab	0.81 ± 0.01 ABab	0.82 ± 0.02 ABa	0.85 ± 0.02 Aa
	20-40 cm	0.75 ± 0.02 Bb	0.78 ± 0.04 ABb	0.81 ± 0.05 ABa	0.84 ± 0.01 Aab
	40-60 cm	0.80 ± 0.04 Aa	0.79 ± 0.02 Aab	0.80 ± 0.02 Aa	0.81 ± 0.03 Ab
	Mean	0.78	0.80	0.81	0.84
< 0.25 mm aggregates	0-10 cm	0.79 ± 0.02 Ba	0.81 ± 0.03 Ba	0.81 ± 0.03 Ba	0.85 ± 0.01 Aa
	10-20 cm	0.77 ± 0.01 Ba	0.82 ± 0.02 Aa	0.80 ± 0.01 ABa	0.83 ± 0.03 Aa
	20-40 cm	0.78 ± 0.03 Ba	0.80 ± 0.02 ABa	0.82 ± 0.02 ABa	0.83 ± 0.04 Aa
	40-60 cm	0.80 ± 0.01 Aa	0.81 ± 0.03 Aa	0.80 ± 0.04 Aa	0.82 ± 0.02 Aa
	Mean	0.79	0.81	0.81	0.83

Data represent the average of 5 replicates ± standard deviations. Different capital letters indicate significant differences ($P < 0.05$) among different tea-planting ages. Different lower case letters indicate significant differences ($P < 0.05$) among different soil depths.

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Figure 1 Effects of tea-planting age and soil depth on the composition and stability of soil aggregates. Data represent the average of 5 replicates and error bars represent the standard deviations. Different capital letters indicate significant differences ($P < 0.05$) among different tea-planting ages. Different lower case letters indicate significant differences ($P < 0.05$) among different soil depths.

Figure 2 Effects of tea-planting age and soil depth on the soil organic C content in various sized aggregates. Data represent the average of 5 replicates and error bars represent the standard deviations. Different capital letters indicate significant differences ($P < 0.05$) among different tea-planting ages. Different lower case letters indicate significant differences ($P < 0.05$) among different soil depths.

Figure 3 Effects of tea-planting age and soil depth on the soil total N content in various sized aggregates. Data represent the average of 5 replicates and error bars represent the standard deviations. Different capital letters indicate significant differences ($P < 0.05$) among different tea-planting ages. Different lower case letters indicate significant differences ($P < 0.05$) among different soil depths.

Figure 4 Effects of tea-planting age and soil depth on the soil total P content in various sized aggregates. Data represent the average of 5 replicates and error bars represent the standard deviations. Different capital letters indicate significant differences ($P < 0.05$) among different tea-planting ages. Different lower case letters indicate significant differences ($P < 0.05$) among different soil depths.

Figure 5 Effects of tea-planting age and soil depth on the soil exchangeable Ca^{2+} content in various sized aggregates. Data represent the average of 5 replicates and error bars represent the standard deviations. Different capital letters indicate significant differences ($P < 0.05$) among different tea-planting ages. Different lower case letters indicate significant differences ($P < 0.05$) among different soil depths.

Figure 6 Effects of tea-planting age and soil depth on the soil exchangeable Mg^{2+} content in various sized aggregates. Data represent the average of 5 replicates and error bars represent the standard deviations. Different capital letters indicate significant differences ($P < 0.05$) among different tea-planting ages. Different lower case letters indicate significant differences ($P < 0.05$) among different soil depths.

Figure 7 Effects of tea-planting age and soil depth on the soil available Fe^{2+} content in various sized aggregates. Data represent the average of 5 replicates and error bars represent the standard deviations. Different capital letters indicate significant differences ($P < 0.05$) among different tea-planting ages. Different lower case letters indicate significant differences ($P < 0.05$) among different soil depths.

Figure 8 Effects of tea-planting age and soil depth on the soil available Mn^{2+} content in various sized aggregates. Data represent the average of 5 replicates and error bars represent the standard deviations. Different capital letters indicate significant differences ($P < 0.05$) among different tea-planting ages. Different lower case letters indicate significant differences ($P < 0.05$) among different soil depths.

Figure 9 Relationships of soil Ca/Mg and Fe/Mn ratios with soil pH in different soil layers. ** indicates significant differences at $P < 0.01$.

Figure 1

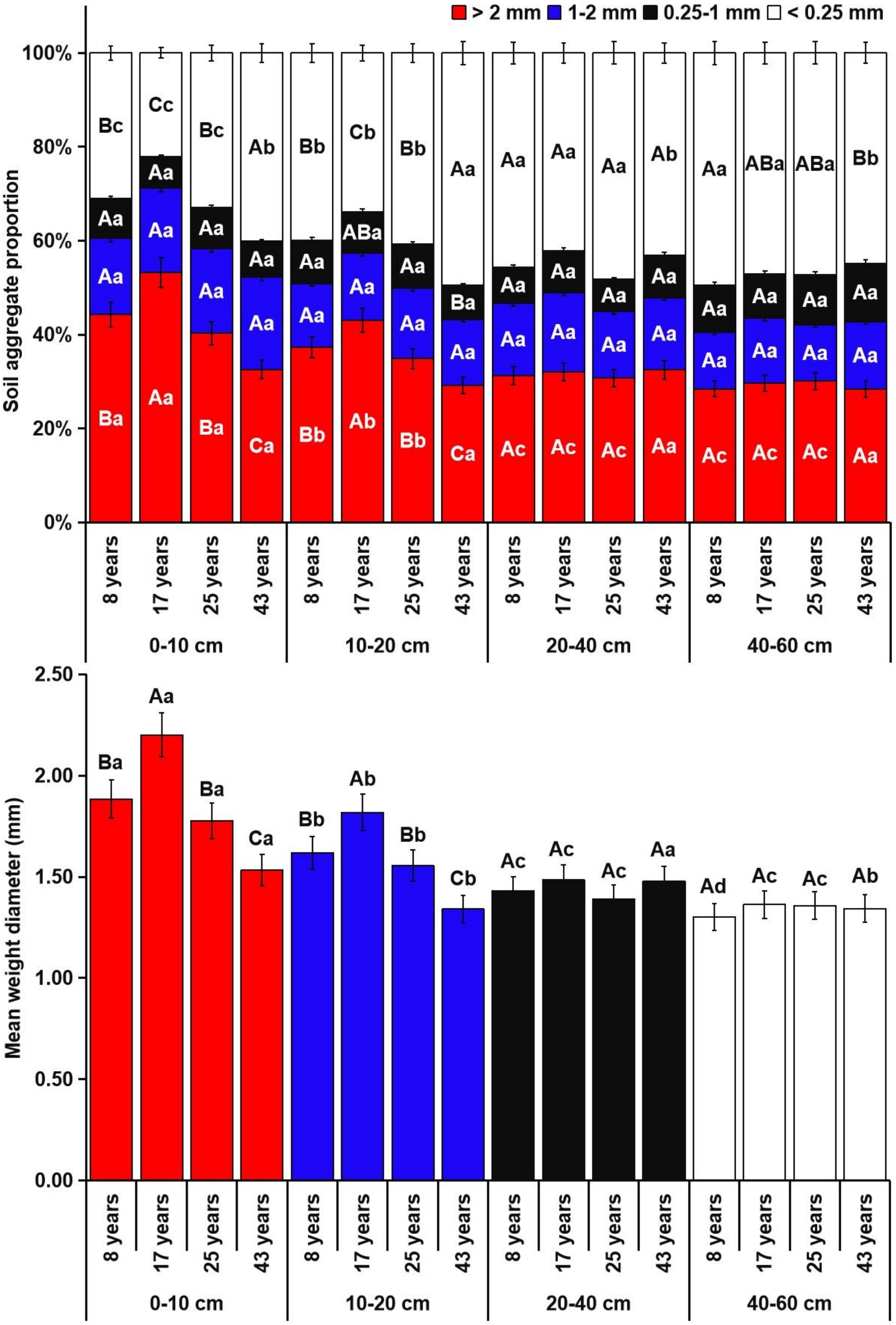
🟥 > 2 mm
🟦 1-2 mm
■ 0.25-1 mm
☐ < 0.25 mm
Soil aggregate proportion
100%
80%
60%
40%
20%
0%
Bc Aa Aa Ba
Cc Aa Aa Aa
Bc Aa Aa Ba
Ab Aa Aa Ca
Bb Aa Aa Bb
Cb ABa Aa Ab
Bb Aa Aa Bb
Aa Ba Aa Ca
Aa Aa Aa Ac
Aa Aa Aa Ac
Aa Aa Aa Ac
Ab Aa Aa Aa
Aa Aa Aa Ac
ABa Aa Aa Ac
ABa Aa Aa Ac
Bb Aa Aa Aa
8 years
17 years
25 years
43 years
0-10 cm
10-20 cm
20-40 cm
40-60 cm
Mean weight diameter (mm)
2.50
2.00
1.50
1.00
0.50
0.00
Ba
Aa
Ba
Ca
Bb
Ab
Bb
Cb
Ac
Ac
Ac
Aa
Ad
Ac
Ac
Ab
8 years
17 years
25 years
43 years
0-10 cm
10-20 cm
20-40 cm
40-60 cm

Figure 2

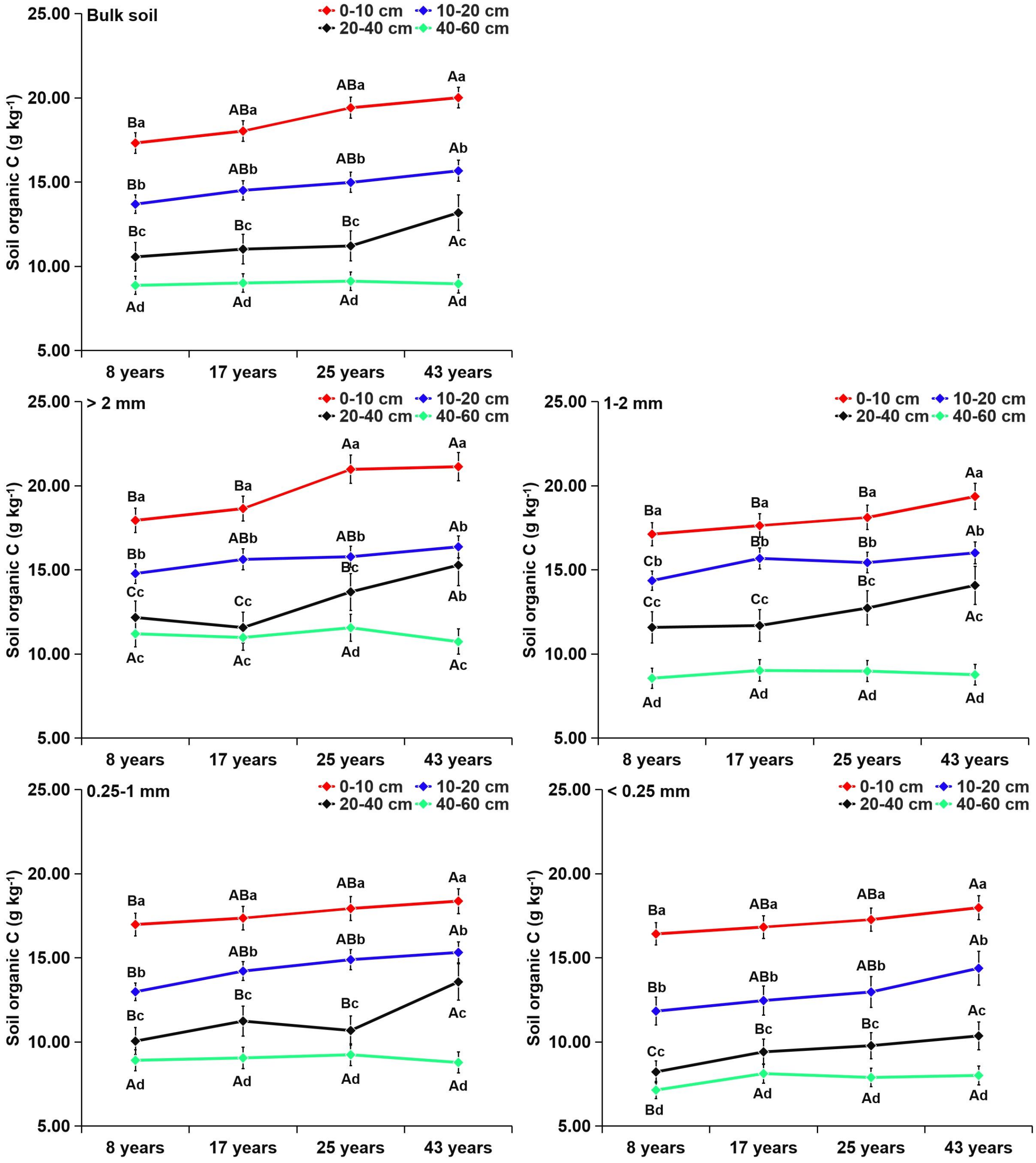
Bulk soil
> 2 mm
1-2 mm
0.25-1 mm
< 0.25 mm
0-10 cm
10-20 cm
20-40 cm
40-60 cm
Soil organic C (g kg^{-1})
25.00
20.00
15.00
10.00
5.00
8 years
17 years
25 years
43 years
Ba
ABa
ABa
Aa
Bb
ABb
ABb
Ab
Bc
Bc
Bc
Ac
Ad
Ad
Ad
Ad
Ba
Ba
Aa
Aa
Bb
ABb
ABb
Ab
Cc
Cc
Bc
Ab
Ac
Ac
Ad
Ac
Ba
Ba
Ba
Aa
Cb
Bb
Bb
Ab
Cc
Cc
Bc
Ac
Ad
Ad
Ad
Ad
Ba
ABa
ABa
Aa
Bb
ABb
ABb
Ab
Bc
Bc
Bc
Ac
Ad
Ad
Ad
Ad
Ba
ABa
ABa
Aa
Bb
ABb
ABb
Ab
Cc
Bc
Bc
Ac
Bd
Ad
Ad
Ad

Figure 3

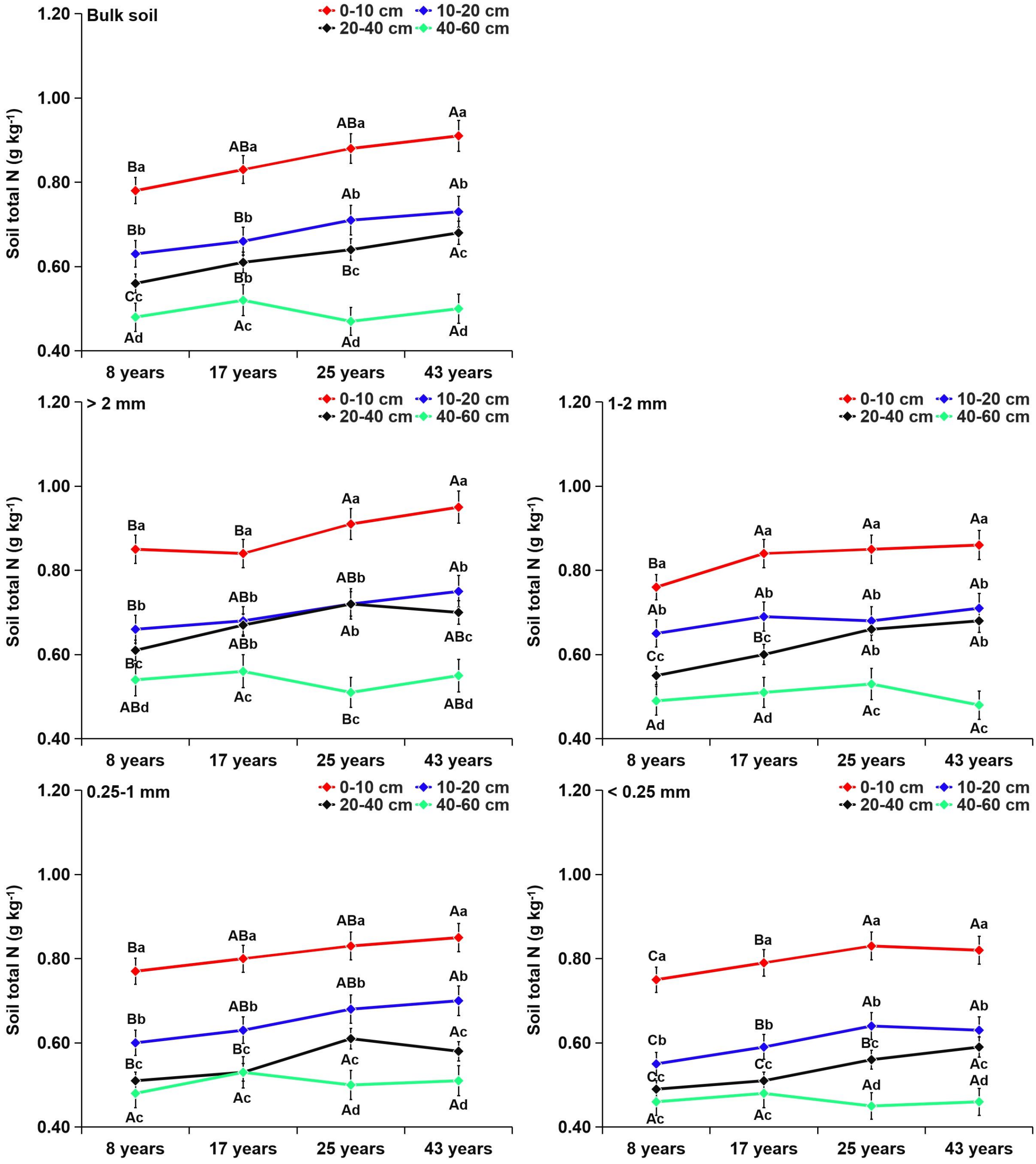
Bulk soil
0-10 cm
10-20 cm
20-40 cm
40-60 cm
Soil total N (g kg^{-1})
1.20
1.00
0.80
0.60
0.40
Ba
ABa
ABa
Aa
Bb
Bb
Ab
Ab
Cc
Bb
Bc
Ac
Ad
Ac
Ad
Ad
8 years
17 years
25 years
43 years
> 2 mm
Ba
Ba
Aa
Aa
Bb
ABb
ABb
Ab
Bc
ABb
Ab
ABc
ABd
Ac
Bc
ABd
1-2 mm
Ba
Aa
Aa
Aa
Ab
Ab
Ab
Ab
Cc
Bc
Ab
Ab
Ad
Ad
Ac
Ac
0.25-1 mm
Ba
ABa
ABa
Aa
Bb
ABb
ABb
Ab
Bc
Bc
Ac
Ac
Ac
Ac
Ad
Ad
< 0.25 mm
Ca
Ba
Aa
Aa
Cb
Bb
Ab
Ab
Cc
Cc
Bc
Ac
Ac
Ac
Ad
Ad

Figure 4

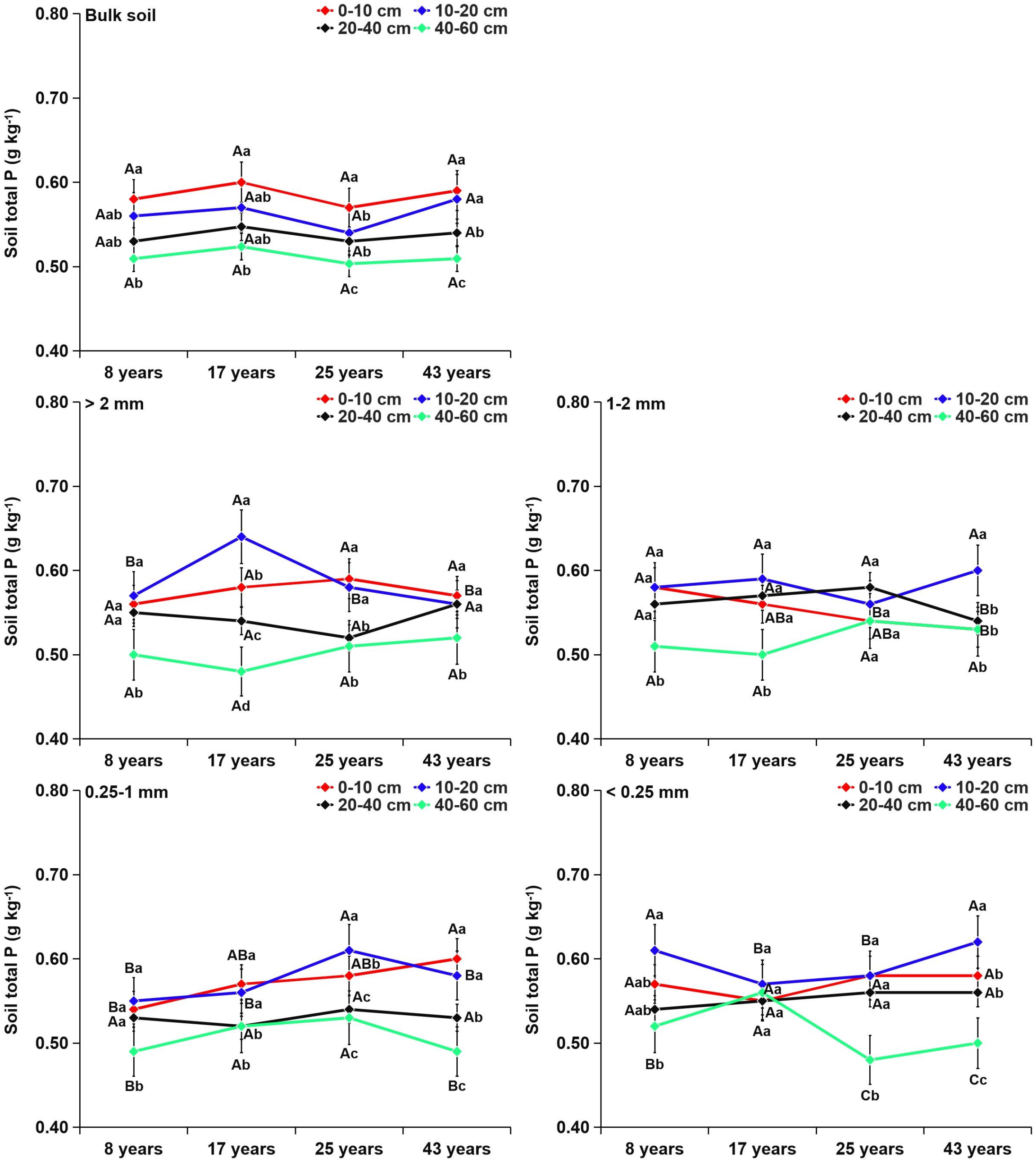
Bulk soil
> 2 mm
1-2 mm
0.25-1 mm
< 0.25 mm
0-10 cm
10-20 cm
20-40 cm
40-60 cm
Soil total P (g kg^{-1})
0.40
0.50
0.60
0.70
0.80
8 years
17 years
25 years
43 years
Aa
Aab
Aab
Ab
Aa
Aab
Aab
Ab
Aa
Ab
Ab
Ac
Aa
Aa
Ab
Ac
Ba
Aa
Aa
Ab
Aa
Ab
Ac
Ad
Aa
Ba
Ab
Ab
Aa
Ba
Aa
Ab
Aa
Aa
Aa
Ab
Aa
Aa
ABa
Ab
Aa
Ba
ABa
Aa
Aa
Bb
Bb
Ab
Ba
Ba
Aa
Bb
ABa
Ba
Ab
Ab
Aa
ABb
Ac
Ac
Aa
Ba
Ab
Bc
Aa
Aab
Aab
Bb
Ba
Aa
Aa
Aa
Ba
Aa
Aa
Cb
Aa
Ab
Ab
Cc

Figure 5

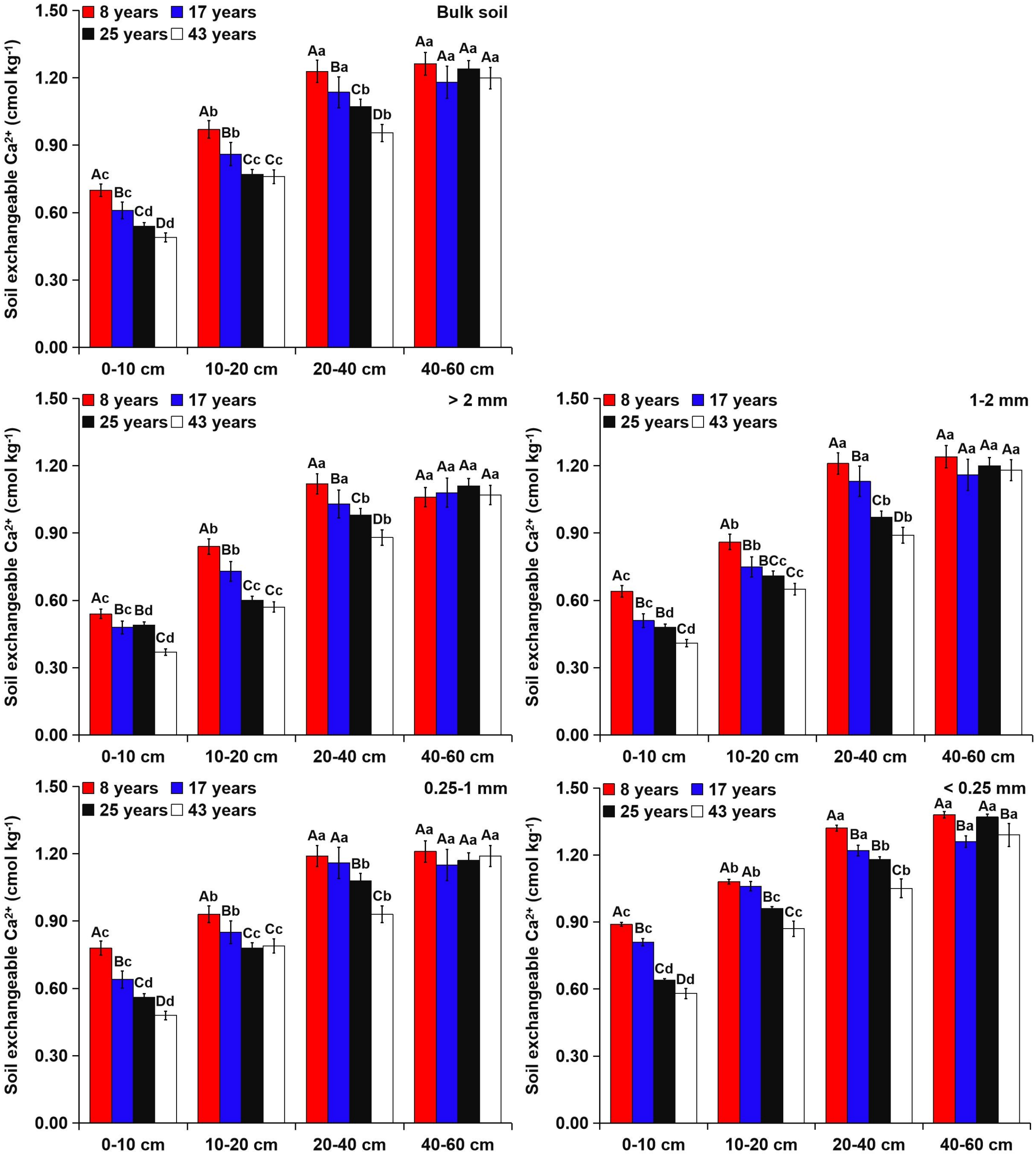
Bulk soil
> 2 mm
1-2 mm
0.25-1 mm
< 0.25 mm
🟥 8 years
🟦 17 years
■ 25 years
☐ 43 years
Soil exchangeable Ca^{2+} (cmol kg^{-1})
0.00
0.30
0.60
0.90
1.20
1.50
0-10 cm
10-20 cm
20-40 cm
40-60 cm
Ac Bc Cd Dd
Ab Bb Cc Cc
Aa Ba Cb Db
Aa Aa Aa Aa
Ac Bc Bd Cd
Ab Bb Cc Cc
Aa Ba Cb Db
Aa Aa Aa Aa
Ac Bc Bd Cd
Ab Bb BCc Cc
Aa Ba Cb Db
Aa Aa Aa Aa
Ac Bc Cd Dd
Ab Bb Cc Cc
Aa Aa Bb Cb
Aa Aa Aa Aa
Ac Bc Cd Dd
Ab Ab Bc Cc
Aa Ba Bb Cb
Aa Ba Aa Ba

Figure 6

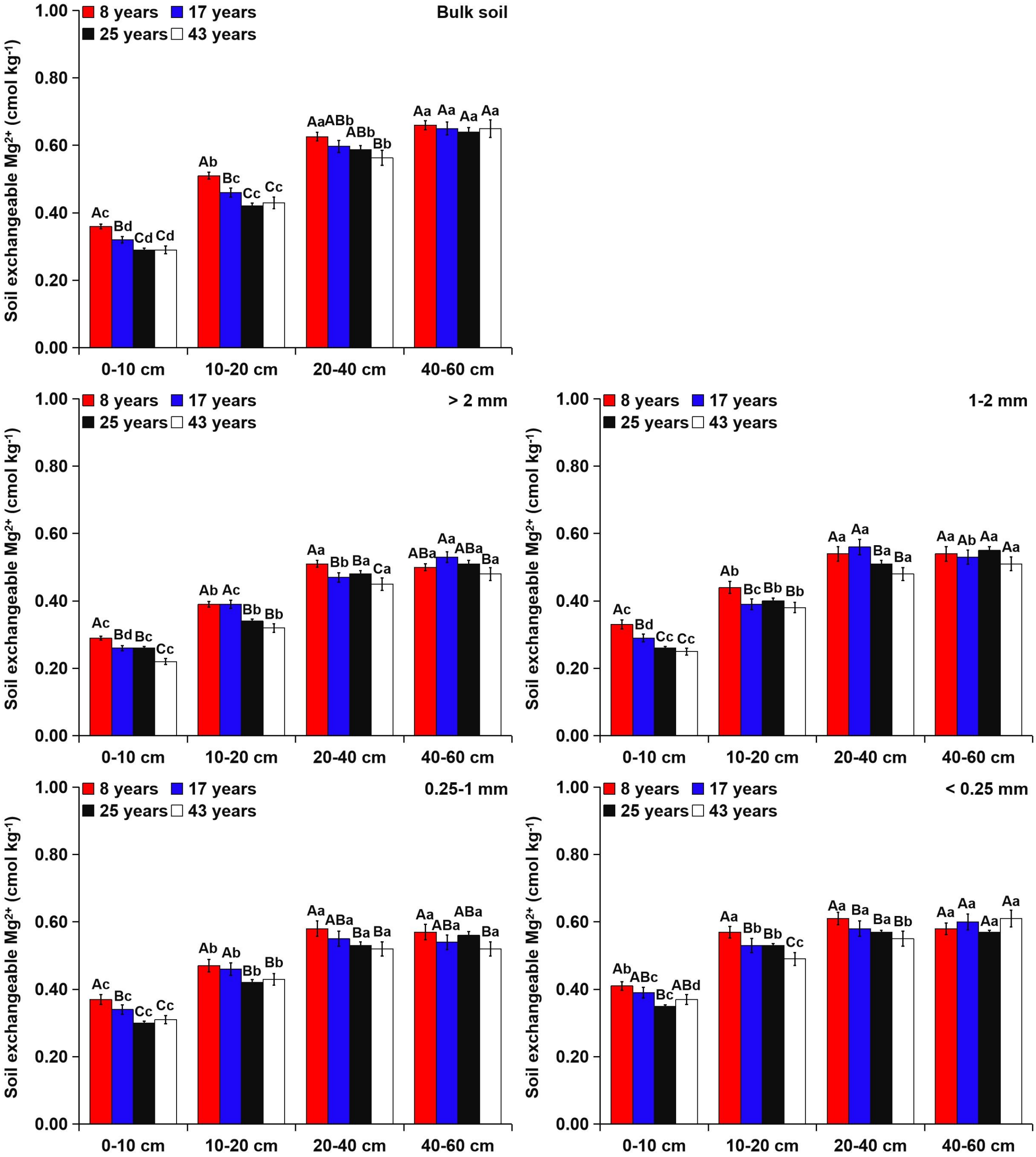
Bulk soil
> 2 mm
1-2 mm
0.25-1 mm
< 0.25 mm
■ 8 years ■ 17 years
■ 25 years □ 43 years
Soil exchangeable Mg²⁺ (cmol kg⁻¹)
0.00
0.20
0.40
0.60
0.80
1.00
0-10 cm
10-20 cm
20-40 cm
40-60 cm
Ac Bd Cd Cd
Ab Bc Cc Cc
Aa ABb ABb Bb
Aa Aa Aa Aa
Ac Bd Bc Cc
Ab Ac Bb Bb
Aa Bb Ba Ca
ABa Aa ABa Ba
Ac Bd Cc Cc
Ab Bc Bb Bb
Aa Aa Ba Ba
Aa Ab Aa Aa
Ac Bc Cc Cc
Ab Ab Bb Bb
Aa ABa Ba Ba
Aa ABa ABa Ba
Ab ABc Bc ABd
Aa Bb Bb Cc
Aa Ba Ba Bb
Aa Aa Aa Aa

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Figure 7

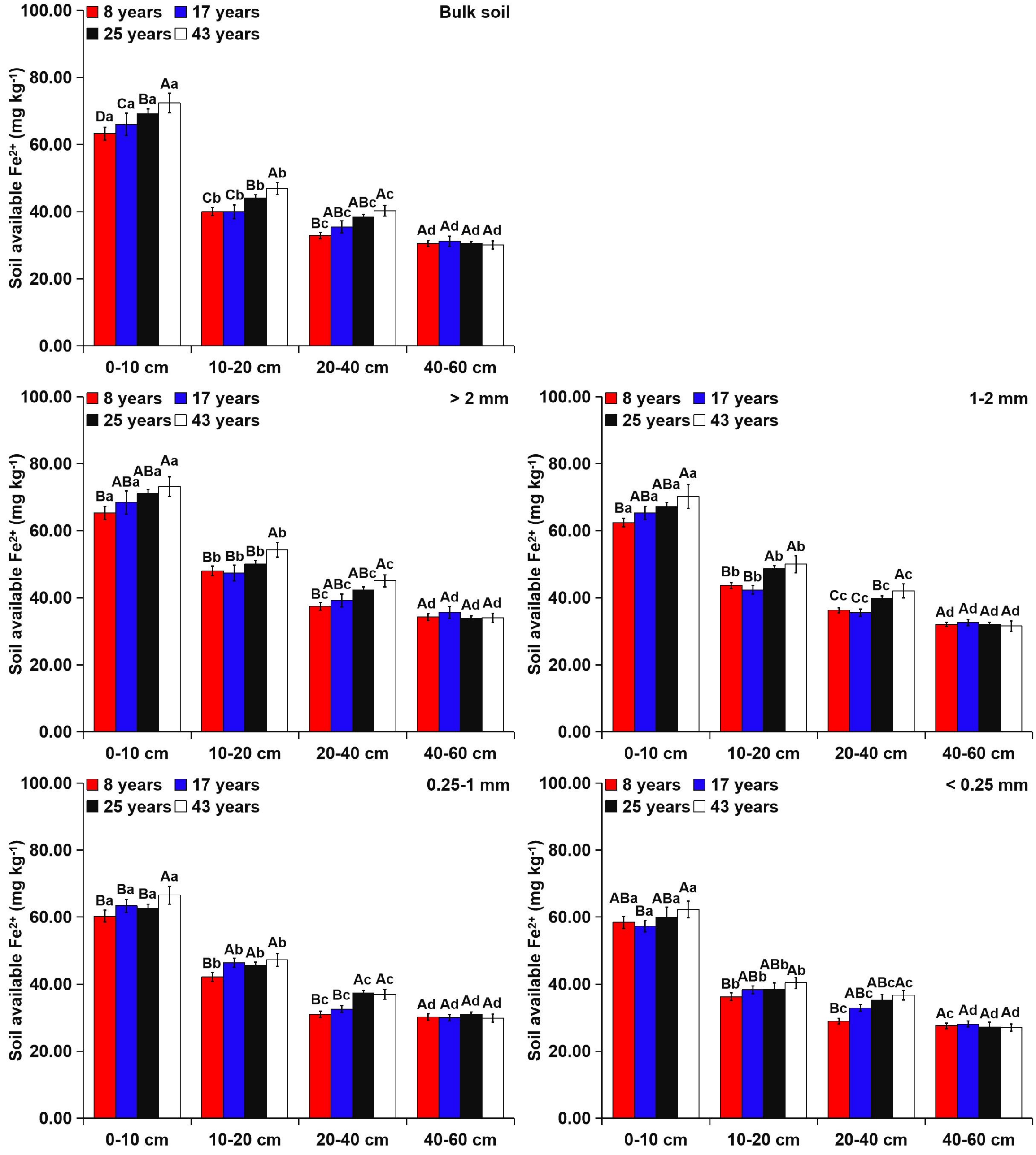


Figure 8

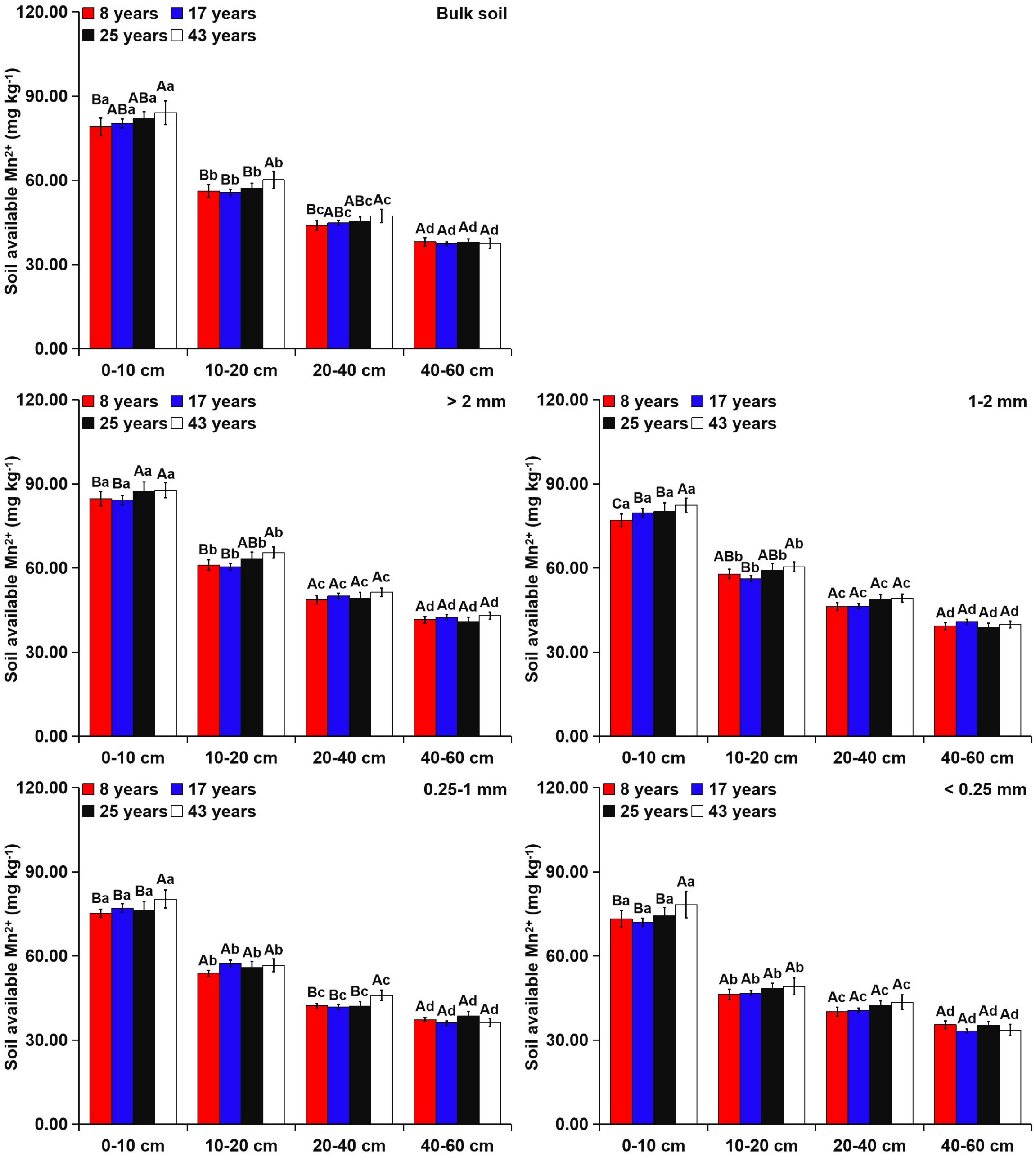
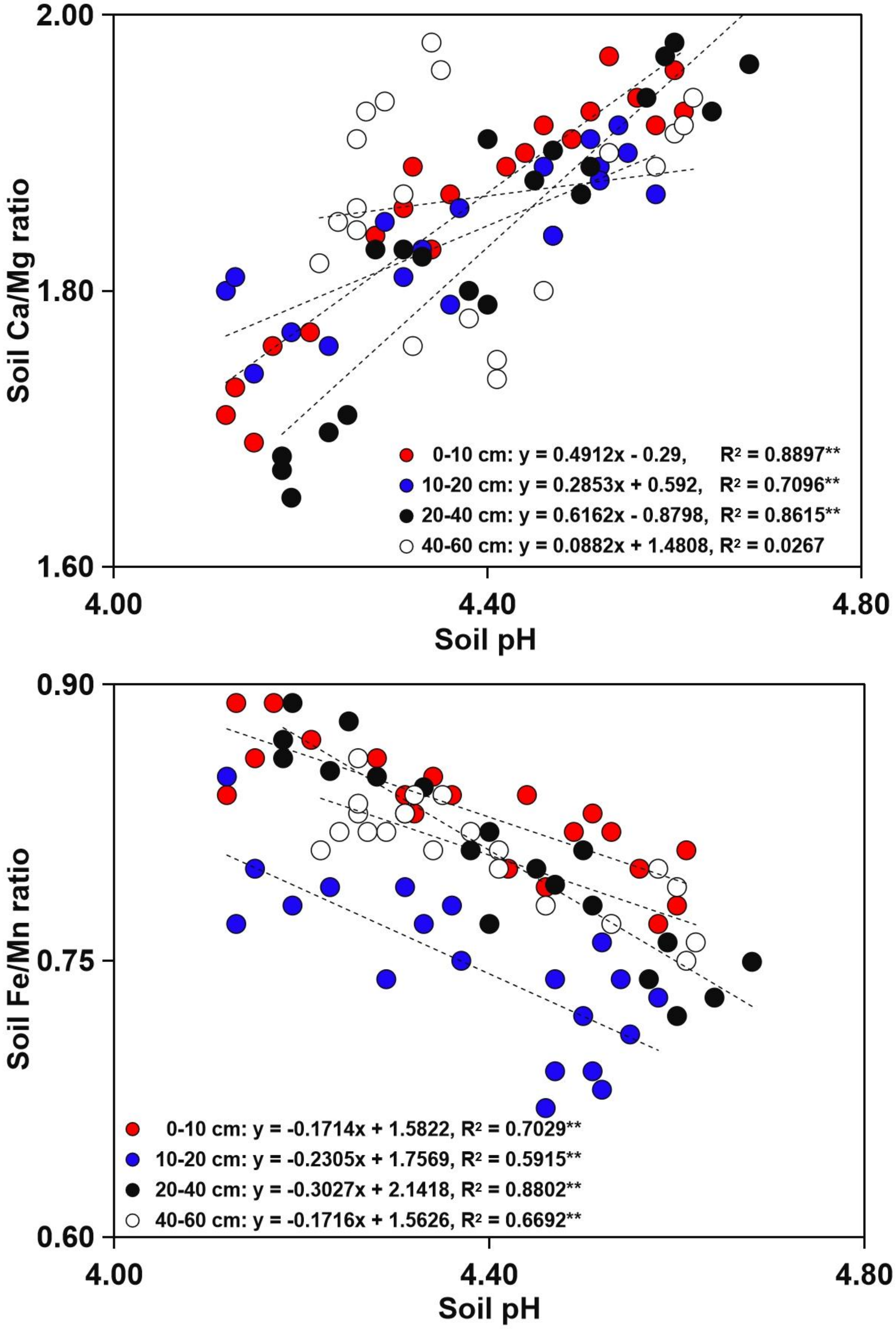

Bulk soil
> 2 mm
1-2 mm
0.25-1 mm
< 0.25 mm
🟥 8 years
🟦 17 years
■ 25 years
☐ 43 years
Soil available Mn²⁺ (mg kg⁻¹)
120.00
90.00
60.00
30.00
0.00
0-10 cm
10-20 cm
20-40 cm
40-60 cm
Ba ABa ABa Aa
Bb Bb Bb Ab
Bc ABc ABc Ac
Ad Ad Ad Ad
Ba Ba Aa Aa
Bb Bb ABb Ab
Ac Ac Ac Ac
Ad Ad Ad Ad
Ca Ba Ba Aa
ABb Bb ABb Ab
Ac Ac Ac Ac
Ad Ad Ad Ad
Ba Ba Ba Aa
Ab Ab Ab Ab
Bc Bc Bc Ac
Ad Ad Ad Ad
Ba Ba Ba Aa
Ab Ab Ab Ab
Ac Ac Ac Ac
Ad Ad Ad Ad

Figure 9


2.00
1.80
1.60
Soil Ca/Mg ratio
4.00
4.40
4.80
Soil pH
● 0-10 cm: y = 0.4912x - 0.29, R² = 0.8897**
● 10-20 cm: y = 0.2853x + 0.592, R² = 0.7096**
● 20-40 cm: y = 0.6162x - 0.8798, R² = 0.8615**
○ 40-60 cm: y = 0.0882x + 1.4808, R² = 0.0267
0.90
0.75
0.60
Soil Fe/Mn ratio
4.00
4.40
4.80
Soil pH
● 0-10 cm: y = -0.1714x + 1.5822, R² = 0.7029**
● 10-20 cm: y = -0.2305x + 1.7569, R² = 0.5915**
● 20-40 cm: y = -0.3027x + 2.1418, R² = 0.8802**
○ 40-60 cm: y = -0.1716x + 1.5626, R² = 0.6692**