Stoichiometric characteristics drive the soil aggregate stability rather than microbial community characteristics and soil nutrients after 5 years of vegetation restoration in China

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Abstract

Soil physical and chemical properties and aggregate stability can be significantly affected by vegetation restoration in degraded land. However, it is not known how the aggregate stability is related to soil stoichiometric characteristics under different vegetation restorations. A 5-year in situ experiment was conducted to investigate the effects of vegetation restoration on the structure, stability and stoichiometric properties of soil aggregates. In the northwest part of Beijing, *Bromus inermis* Leyss. and *Medicago sativa* L. were planted in a typical area of desertification land, and natural succession grassland was used as control. Boosted regression trees (BRTs) were applied to partition the factors that control aggregate stability. The results showed that the mean weight diameter (MWD) of soil water-stable aggregates under natural restoration (CK) and in the alfalfa sowing treatments (AF) was significantly higher than that under the restoration of the smooth brome sowing treatments (SB). Compared with CK, AF significantly increased the geometric mean aggregate diameter (GMD) of soil water stability, while SB showed the opposite result. AF significantly increased the proportion of soil aggregates > 2 mm particle sizes, MWD and GMD at 20–30 cm. AF can improve the stability of soil aggregates by increasing the content of large aggregates. For the stoichiometric characteristics of the aggregates, AF improved significantly the value of C/P in 0.053 – 0.125mm particle size aggregates. The MBC/MBN ratio of 0-10cm and 10-20cm was also significantly increased in the treatment of AF. The BRTs indicated that stoichiometric ratio is the main factor driving the stability of soil aggregates rather than microbial community characteristics and soil nutrients. The C/P is the main driving factor affecting the MWD, in which the overall stoichiometric influence accounts for 46%, followed by the microbial influence of 36%. For the GMD, MBC/MBN is the main driving factor, and the stoichiometric influence accounts for 94%. Our finding indicates that AF is beneficial to the stability of deep soil aggregates, and the stoichiometric characteristics of soil are the key factors affecting the stability of soil aggregates.

1. Introduction

A growing number of ecosystems are experiencing large-scale degradation due to the increasing impact of climate change and unsustainable land use (Mao et al. 2018, Xie et al. 2020, Bardgett et al. 2021). Land degradation poses a serious threat to biodiversity loss, land desertification, human living environment and sustainable development of social and economic systems (Solomun et al. 2018, Winslow et al. 2011). Vegetation restoration can speed up the restoration process and is one of the common and effective ways to restore degraded land and ecosystem functions (Chen et al. 2005, Hu et al. 2022, Klopf et al. 2017).The purpose of vegetation restoration is not only to improve biodiversity, but also to improve soil health, including soil structure, soil nutrient and soil quality (Vaverkova et al. 2018, Xu et al. 2021, Zhao et al. 2020).

As the basic unit of soil structure formation, soil aggregates play an important role in soil structure and fertility (Pérès et al. 2013, Yao et al. 2019, Liu et al. 2023). Soil aggregate stability is one of the relevant indexes of soil stability, which refers to the ability of soil aggregates to resist damage when applying destructive force (water, wind), and is a good indicator of soil sensitivity to erosion (Barthes & Roose

2002, Oztas & Fayetorbay 2003). Soil mean weight diameter (MWD) and geometric mean diameter (GMD) is an important index to evaluate the stability of aggregates, and the larger the value of MWD and GMD, the stronger the stability and aggregation ability of aggregates (Padbhushan et al. 2016, Schaller & Stockinger 1953). Soil aggregation is a complex process, which is regulated by vegetation type (Duchicela et al. 2012, Dou et al. 2020), fertilization (Eviner & Chapin 2002) and management measures (Du et al. 2022, Ren et al. 2022), etc. For example, the distances between alfalfa and jujube at 0.5 m can significantly increase the amounts of macro-aggregates, and improved soil mechanical properties and aggregate stability among the other treatments in herbage-fruit tree intercropping systems (Chen et al. 2023). Long-term fertilization for 26 years significantly increased MWD and GMD, which meant that the stability of soil aggregates was improved (Mustafa et al. 2020). Previous studies have shown microbial changes driven by the change of soil nutrient might be the major factor affecting soil surface aggregate stability in the process of degradation succession in typical grassland (Ren et al. 2022). In addition, in the process of vegetation restoration, the selection of different plants has different effects on soil aggregates. For example, studies have shown that the effects of vegetation restoration measures on the stability of soil aggregates were different and the MWD and GMD were both highest in two soil layers only under the natural shrub restoration on the Loess Plateau, China (Dou et al. 2020). Conversely, a previous study showed that natural pasture restoration improved soil physical properties and water stable aggregate stability better than planting species (Wang et al. 2012). In northern China, *Medicago sativa L.* (alfalfa) and *Bromus inermis Leyss.* (smooth brome) are often used a community building species for degraded land restoration. Unlike the fibrous roots of smooth brome, alfalfa is a premium perennial leguminous plant that may be an improvement in texture and nutrients in deeper soils (Hafner & Kuzyakov 2016). Our previous studies indicated that short-term alfalfa planting could enhance surface soil fertility (Xu et al. 2022a). However, in the process of vegetation restoration, there are few reports on the influence of different herbaceous restoration methods on the soil aggregate stability and its driving factors (microbial community characteristics, stoichiometric characteristics and soil nutrients) in degraded land.

Soil carbon (C), nitrogen (N) and phosphorus (P) stoichiometry has been extensively studied around the world in recent decades (Bai et al. 2012, Cleveland & Liptzin 2007, Sun et al. 2022, Wang et al. 2022). Soil aggregate stability and its stoichiometric characteristics are the effective ways to evaluate the effect of soil restoration and various sized aggregates play different roles in the supply and transport of soil C, N, and P (Chen et al. 2021, Tang & Wang 2022). Therefore, in order to better understand the effects of different vegetation restoration on soil structure and function, it is necessary to study the stoichiometric characteristics of soil C, N and P at the aggregate scale (Smith et al. 2019, Zhao et al. 2015, Xu et al. 2022c). In recent years, some studies have investigated the distribution of soil stoichiometric characteristics in aggregates. For example, the increases in soil C:N, C:P, and N:P ratios were accompanied by the decreasing aggregate size in Chinese fir plantations (Tang & Wang 2022). The vegetation restoration only significantly reduced the value of N:P and C:P in different particle size aggregates and had no significant effect on the C:N in all particle size aggregates (Xu et al. 2022c).

However, it is not known how the stability of soil aggregates is related to oil stoichiometric characteristics under different vegetation restorations.

The effects of planting alfalfa and brome after five years on soil aggregate composition, stoichiometry and stability in degraded wastelands in North China Plain were studied. The objectives of this study were to (1) analyze the influence of different restoration methods on the soil aggregate stability, (2) evaluate the changes of soil aggregate composition and structure after five years of vegetation restoration, (3) measure the stoichiometric characteristics of soil aggregate, and (4) explore the key driving factors (microbial community characteristics, stoichiometric characteristics and soil nutrients) affecting the soil aggregate stability.

2. Materials and Methods

2.1 Site Description

The experiment was conducted at the Long-term Ecological Research Station of Degraded Land in Yanqing District, Beijing. The study site is located at 115°50'23" E and 40°27'53" N, with an elevation of 492 meters above sea level (Figure S1). The area receives an average annual precipitation of approximately 600 mm, which primarily falls between June and September. The soil at the site is classified as intermediate between sandy soil and loam. The dominant plant species observed during the experiment were *Pennisetum centrasiaticum* Tzvel. (55%), *Artemisia capillaris* Thunb (18%), and *Melica scabrosa* Trin. (15%).

2.2 Experimental design

In 2015, we conducted a randomized field experiment utilizing 12 plots in total. Each plot had an area of 100 m^2, and we planted three different species: Medicago sativa (AF) in four plots, Bromus inermis Leyss (SB) in four plots, and natural recovery (CK) in the remaining four plots. The seeds were sown without plowing in May 2015 at a density of 200 seeds per m^2 for each species. Once the vegetation had become established, the area was fenced off.

2.3 Soil Sampling and aggregate separation

During the 2020 growing season, soil samples were collected at depths of 0–10 cm, 10–20 cm, and 20–30 cm. The samples were passed through a 5 mm sieve to remove plant roots and rocks, and then air-dried. 100g of the air-dried soil samples were utilized for wet sieving. The distribution of different particle size aggregates was determined using a nested sieve consisting of three sieve sizes with apertures of 2 mm, 0.25 mm, and 0.053 mm (Pohl et al. 2012, Cates et al. 2016). By utilizing wet sieving (Tang & Wang 2022), four different size classes of soil aggregates were separated: i) > 2000 μm (macro-aggregates), ii) 250–2000 μm (macro-aggregates), iii) 53–250 μm (micro-aggregates), and iv) < 53 μm (silt + clay particles). After wet sieving, all of the separated aggregates were dried at 65 °C and weighed. The particle size distribution of soil aggregates is determined by calculating the weight percentage of each aggregate size class relative to the total weight of all aggregates.

2.4 Soil properties analysis and soil microbial community

The total organic carbon (TC) was measured with a TOC analyzer (Rapid CS Cube, Elementar, Langenselbold, Germany). The total nitrogen (TN) was measured with a C/N analyzer (Rapid CS Cube, Elementar, Langenselbold, Germany). Soil pH was detected through the glass electrode. Soil P content was measured by the approach of molybdenum blue colorimetric (Xu et al. 2022c). Microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) were quantified by comparing sets of chloroform-fumigated and non-fumigated soil samples (Xu et al. 2022b). The coefficients giving the extractable part of MBC and MBN were set at 0.45 and 0.54, respectively (Jaeger III et al. 1999). The microbial community's genomic DNA was extracted from 0.25 g of moist soil using the PowerSoil DNA Isolation Kit (MO BIO laboratories, Carlsbad, CA, USA) following a standardized protocol. High throughput sequencing was used to calculate the diversity of soil microbial, bacterial and fungal communities (Xu et al. 2022b).

2.5 Calculations

Soil mean weight diameter (MWD, mm) value and geometric mean diameter (GMD, mm) were obtained by this formula:

$$MWD = \sum_{i=1}^{n} (\bar{X_i} \cdot W_i)$$

$$GMD = \exp\left\{\sum_{i=1}^{n} (W_i \cdot \ln \bar{X_i})\right\}$$

In the formula, $\bar{x}_i$ (mm) indicates the average diameter associated with the i^{th} size aggregates, and Wi (% in weight) represents the proportion associated with the i^{th} size aggregates.

2.6 Statistical analysis

One-way analysis of variance (ANOVA) was conducted for detecting how different restoration methods affected soil aggregate composition, stoichiometry and stability in R 3.5.2 (R Development Core Team, Vienna, Austria, 2015). The Bray-Curtis method was used to further verify the effects of different vegetation restoration on bacterial and fungal community structure by non-metric multidimensional scaling (NMDS). Duncan new repolarization difference method was used for difference significance analysis, and the significance level was $P < 0.05$. We used boosted regression trees (BRTs) to partition independent influences of microbial characteristic (α diversity and β diversity of bacteria and fungi, MBC and MBN), stoichiometric characteristics (C/N, N/P, C/P, MBC/MBN) and soil conditions (TC, TP, TN, pH) on MWD and GMD. The parameter combination returning the highest cross- validated model fit was selected, with a tree complexity of one, a learning rate of .001 and a bag fraction of .8. BRTs were fitted in R, using the dismo package (Elith et al. 2008, Guo et al. 2021).

3. Results

3.1 Soil aggregate stability and soil aggregate composition

The MWD of soil water-stable aggregates under natural restoration (CK) and reseeding of AF was significantly higher than reseeding of SB (Fig. 1a; $P < 0.001$). The GWD of soil water-stable aggregates was significantly increased by reseeding of AF, but the effect was opposite by reseeding of SB (Fig. 1b; $P < 0.001$). Through the analysis of the MWD of water-stable aggregates in different soil layers, AF significantly increased the MWD of water-stable aggregates in 20–30 cm soil layers (Fig. 1c; $P < 0.05$). Through the analysis of the GWD of soil water-stable aggregates in different soil layers, it was found that the GWD of soil water-stable aggregates in 10–20 cm and 20–30 cm was significantly reduced by reseeding of SB (Fig. 1d; $P < 0.01$). AF significantly increased the GWD of soil water-stable aggregates at 20–30 cm (Fig. 1d; $P < 0.01$). By analyzing the composition of soil aggregates in the 0–10 cm, 10-20cm and 20-30cm soil layer, it was found that AF significantly increased the soil aggregate mass fraction of grain size > 2 mm (Fig. 2).

3.2 Nutrient characteristics of soil aggregates in different soil layers

In the 0–10 cm soil layer, different restoration methods had different effects on TN in soil aggregates under different particle sizes (Fig. 3; $P < 0.05$). SB significantly increased TN content of soil with diameter of > 2 mm. SB and AF significantly increased soil TN content of soil with diameter of 0.250-1 mm (Fig. 3; $P < 0.05$). SB and AF significantly increased soil TC content in aggregates of all particle sizes. For soil total phosphorus, vegetation restoration significantly increased. SB and AF significantly increased soil TP content of soil with diameter of > 2 mm and 0.053–0.250 mm. Both restoration methods were significantly improved the MBC content of > 2 mm, 1 ~ 2 mm, 0.053 ~ 0.250 mm diameter. Only at 0.053–0.250 mm particle size, SB significantly improved the MBN content (Fig. 3; $P < 0.05$).

In the 10–20 cm soil layer, SB significantly increased TN content of > 2 mm grain size (Fig. 3; $P < 0.05$). SB and AF significantly increased TC content in aggregates of all particle sizes. Vegetation restoration had no significant difference in soil total phosphorus content under all particle sizes. Both restoration methods improved significantly MBC content of > 2 mm, 1 ~ 2 mm, 0.250-1 mm diameter. The MBN of SB was significantly higher than that of other treatments only at the size of 1–2 mm (Fig. 3; $P < 0.05$).

In the 20–30 cm soil layer, there was no significant difference in TN among different particle sizes (Fig. 3; $P < 0.05$). SB and AF significantly increased soil TC content. For soil TP, AF significantly increased the soil TP content at 1 ~ 2 mm and 0.250-1 mm grain size (Fig. 3; $P < 0.05$). Both restoration methods were significantly improved MBC content of > 2 mm, 0.250-1 mm, 0.053–0.250 mm particle size. The content of MBN of AF was significantly higher than that of other treatments only at 0.250-1 mm diameter (Fig. 3; $P < 0.05$).

3.3 Stoichiometric characteristics of soil aggregates

In the 0–10 cm soil layer, AF and SB had significantly improved the C/N ratio of 0.053-0.1235mm particle size (Fig. 4; $P < 0.05$). Vegetation restoration had no significant effect on N/P in any soil layer and particle size. At 0-10cm, the C/P ratio of 0.125-1mm and 0.053-0.125mm was significantly increased by AF. The C/P ratio of 0.053-0.0125mm in soil layers of 10-20cm and 20-30cm was also significantly increased by AF and SB (Fig. 4; $P < 0.05$). AF significantly increased the MBC/MBN of all particle sizes 0-10cm and 10-20cm (Fig. 5; $P < 0.05$). AF significantly increased the stoichiometric ratio of MBC/MBN of > 2 mm particle size, while SB significantly increased the stoichiometric ratio of MBC/MBN of 0.125-1mm (Fig. 5; $P < 0.05$).

3.4 key factors driving aggregate stability

All indexes were divided into microorganisms (α diversity and β diversity of bacteria and fungi, microbial biomass carbon and nitrogen), stoichiometry (C/N, N/P, C/P, MBC/MBN) and soil physicochemical properties (TC, P, N, pH). Through enhanced regression tree analysis, the results show that C/P is the main driving factor affecting the MWD, in which the overall stoichiometric influence accounts for 46%, followed by the microbial influence of 36%. For the GMD, MBC/MBN is the main driving factor, and the stoichiometric influence accounts for 94%.

4. Discussion

4.1 Soil aggregate stability and composition

A previous study showed that the stability of aggregates at 0.15m of soil surface varies with different plant species, and that the stability of aggregates at 0.15-0.45m is not affected by plant species (Eviner & Chapin 2002). In this study, different plant types have different effects on the stability of deep soil aggregates. The MWD and GMD of water-stable aggregate were significantly reduced after 5 years of reseeding SB, but AF significantly increased GMD by 15.1% compared with CK treatment (Fig. 1a and b). This was mainly because AF significantly increased the MWD and GMD in 20–30 cm (Fig. 1d). On the other hand, AF can improve the stability of soil aggregates by increasing the content of large aggregates (> 2mm) in all soil layers (Fig. 2). The higher the content of soil water-stable macroaggregates, the more stable soil aggregates, and the better the structural stability of soil (Xu et al. 2022c, Celik 2005). This indicates that AF planting in degraded land can improve soil aggregate structure and enhance aggregate stability within 0–30 cm. However, SB had no significant effect on large aggregates, but significantly increased the proportion aggregates of 0.053-0.125mm size at 0-10cm (Fig. 2). A previous study showed that the stability of soil aggregates in the surface layer was higher than that in the subsoil layer (An et al. 2008), which could indirectly support our results. This may be because, unlike the deep roots of AF (Clement et al. 2022, Song et al. 2022, Wang et al. 2023), the traversing rhizomes of SB affect aggregate structure only in shallow soil. This could also explain the decrease the GMD of 10-20cm and 20-30cm in SB. The results of this study also showed that the proportion of > 2mm particle size of soil aggregates was a good index to evaluate the effect of vegetation restoration on soil aggregates (Huang et al. 2010). Therefore, AF has important potential as a recovery plant for restoring degraded land from the perspective of soil aggregate stability and soil quality improvement.

4.2 Stoichiometric characteristics of soil aggregates

The C and N are structural elements of organic matter, so the distribution of C and N contents in aggregates will affect the change of soil organic matter content (Cooper et al. 2020). Vegetation restoration can promote the accumulation of organic carbon through biomass input, thus promoting the stability of soil aggregates (Tang et al. 2010). On the other hand, vegetation restoration reduced nutrient loss in soil aggregates and leads to a greater ability to collect organic matter (Zhang & Marschner 2018). It has been found that the content of C and N varies with different particle sizes, and < 0.25mm particle size aggregates had higher C and N content (Egan, Crawley, & Fornara, 2018; L. Tang & Wang, 2022; S. Q. Wang, Li, & Zheng, 2018), but C and N content were evenly distributed in various sized aggregates in our study. In addition, in our present research, both vegetation restoration measures significantly increased the TC content in all soil layers (Fig. 3). Different from the increasing trend of carbon, only the TN content of large aggregates in 0-10cm and 10-20cm soil layers was increased under the treatment of AF seeding (Fig. 3). This indicates that different restoration methods have different degrees of influence on TC and TN content in different particle sizes and soil layers, which will significantly affect the C/N of different aggregates. Previous research has shown that the C/N ratio of soil aggregates was relatively stable in both Chinese fir forest restoration (Tang & Wang 2022) and herbaceous plant restoration (Xu et al. 2022c). Unlike our results, only in the size of 0.053-0.125mm, vegetation restoration significantly increased soil TC content, but there was no significant difference in TN content among different treatments, which resulted in a significant increase in C/N by vegetation restoration in 20-30cm soil layer (Fig. 4). This indicated that the two vegetation restoration methods had insufficient ability to improve the nitrogen content of deep soil microaggregates (0.053-0.125mm). N/P ratio is an effective indicator of nutrient restriction, because soil N and P are the most common limiting factors in plant growth (Khan et al. 2016). In our study, there was no significant difference in N/P ratio between different aggregates and soil depth (Fig. 4). However, vegetation restoration significantly reduced the value of N:P in different particle size aggregates in a typical acid rain area in south China (Xu et al. 2022c). This is because the average P content in this area is about 0.19g/kg (the P content in our study site was about 0.6g/kg), and the soil aggregates were obviously limited by the P element. This indicated that the effect of vegetation restoration on soil N/P ratio was influenced by the P content in the background soil before restoration. Different from the study results that vegetation restoration significantly reduced C/P ratio under different aggregate sizes (Xu et al. 2022c), our study showed that AF significantly increased the C/P of small aggregates. The main reason is that different vegetation restoration has no significant effect on the P content in small aggregates, while the C content increases significantly (Fig. 3). This differential response leads to a significant increase in C/P ratio. The MBC/MBN in soil strongly determines the adjustment of terrestrial ecosystem C and N cycling, which is very important for the stoichiometric balance of resources

(Mooshammer et al., 2014). In general, the distribution of microbial biomass in soil aggregates is closely related to TC content, which is similar to the present study (Six et al. 2004). The TC and MBC content of aggregate particle size and soil depth were significantly increased by both planting restoration methods (Fig. 3 and Fig. 5). This may be because alfalfa has higher aboveground biomass (Figure S2 a), which leads to more litter input (Figure S2 b), and the increase of exogenous organic matter increases microbial biomass carbon.

4.3 key factors driving aggregate stability

Previous studies have shown that soil aggregate stability is positively correlated with the content of MBC, MBN, OC and TN in forest ecosystems (Mao et al. 2021, Zhong et al. 2017, Xiao et al. 2019). This may be because organic matter plays a critical role in the cementing agents of soil aggregation, and it has an impact on soil aggregation stabilization (TISDALL & OADES 1982). In addition, soil OC and TN contents have a significant positive correlation with soil aggregate stability (Mao et al. 2021, Zhong et al. 2017). TN had a positive effect on the stability of soil aggregates by affecting plant yield and root growth (Liu et al. 2019). Thus, the soil C/N ratio is considered the best predictor of soil aggregate stability, and the impacts of the soil C/N ratio on soil aggregate stability have been reported (He et al. 2023). For example, the C/N ratio of large-size macroaggregates had an important influence on the MWD of aggregates in a woodland system (Haidong Xu, Yuan, Yu, & Cheng, 2020) and in subtropical China (He et al., 2023). Soil stoichiometry was a balanced coupling mechanism between soil organic carbon, nitrogen and phosphorus. The changes in the MBC:MBN strongly determined the adjustment of microbial N use efficiency (NUE) and C use efficiency (CUE), which are important for carbon (C) and nitrogen (N) cycling (Mooshammer et al. 2014). Previous research has also found that soil nutrient-driven microbial changes might be the dominant factor that caused the changes in the stability of the soil surface soil aggregate in typical grasslands (Ren et al. 2022). We found that vegetation restoration significantly changed the bacterial and fungal community structure, and SB significantly reduced the bacterial and fungal community diversity in soil surface (Figure S3).

However, through enhanced regression tree analysis, the results show that C/P is the main driving factor affecting the MWD, in which the overall stoichiometric influence accounts for 46%, followed by the microbial influence of 36%. For the GMD, MBC/MBN ratio is the main driving factor, and the stoichiometric influence accounts for 94% (Fig. 6). The indicated that stoichiometric ratio is the main factor driving the stability of soil aggregates rather than microbial community characteristics and soil nutrients in the restoration of vegetation after five years.

5. Conclusions

After five years of vegetation restoration, alfalfa planting significantly improved the structure of large aggregates and thus improved the stability of soil aggregates. The value of C/P ratio have a greater influence on the MWD, while MBC/MBN ratio have a greater influence on the GMD. Our finding indicates that alfalfa is beneficial to the stability of deep soil aggregates, and the stoichiometric characteristics of soil are the key factors affecting the stability of soil aggregates. Therefore, soil stoichiometry can be regulated and soil aggregates can be improved by planting legumes, which has potential application value to rehabilitate degraded land. Also, it provided additional information on the relationship between global soil ecological stoichiometry and soil aggregates in terrestrial ecosystems.

Declarations

Declaration of Competing Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Figures

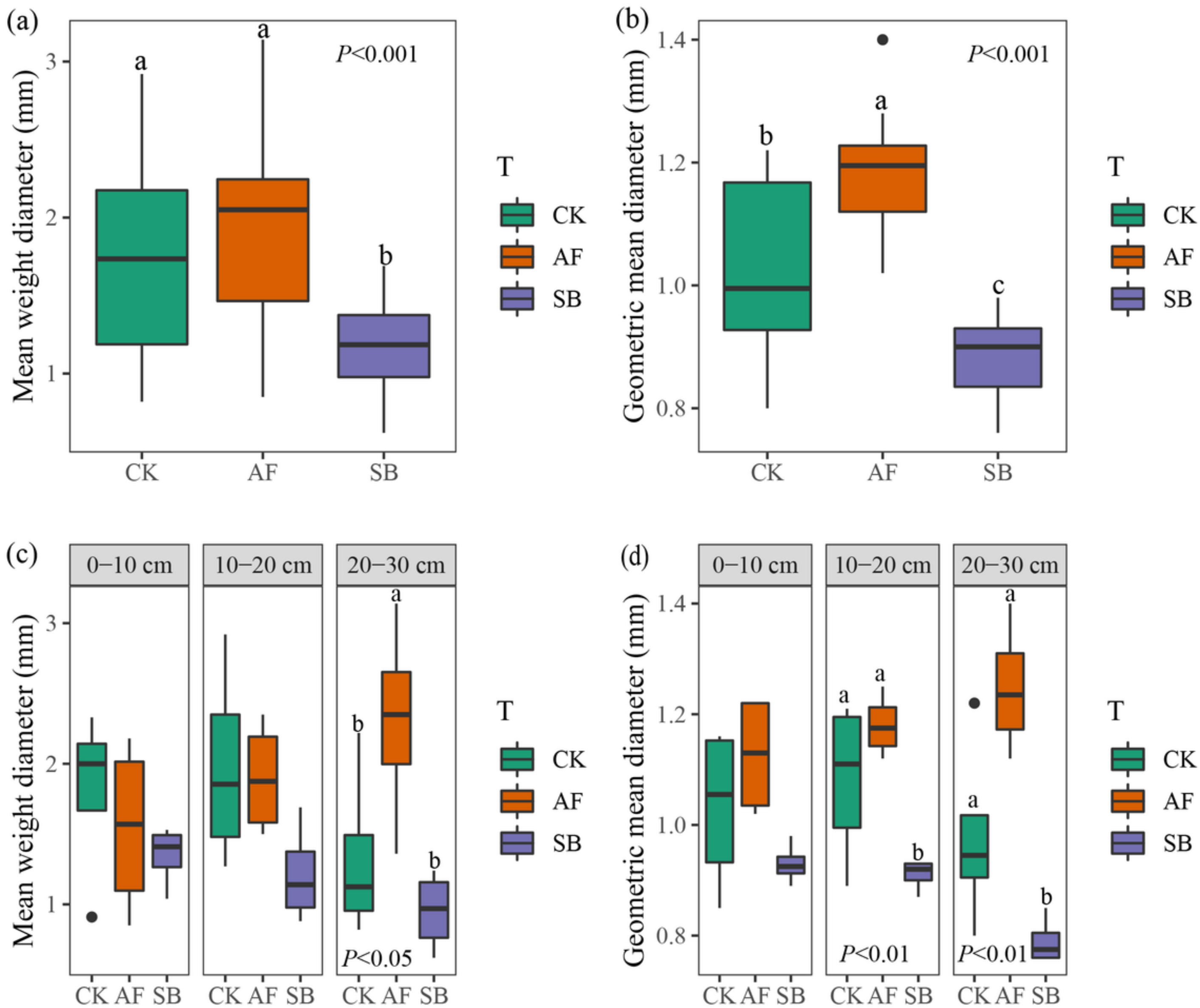

Figure 1

Effects of different restoration measures on soil mean weight diameter (a) and geometric mean diameter (b). soil mean weight diameter (c) and geometric mean diameter (d) response at different soil depth. CK, natural recovery; AF, *Medicago sativa* L sowing; and SB, *Bromus inermis*

Leyss sowing.

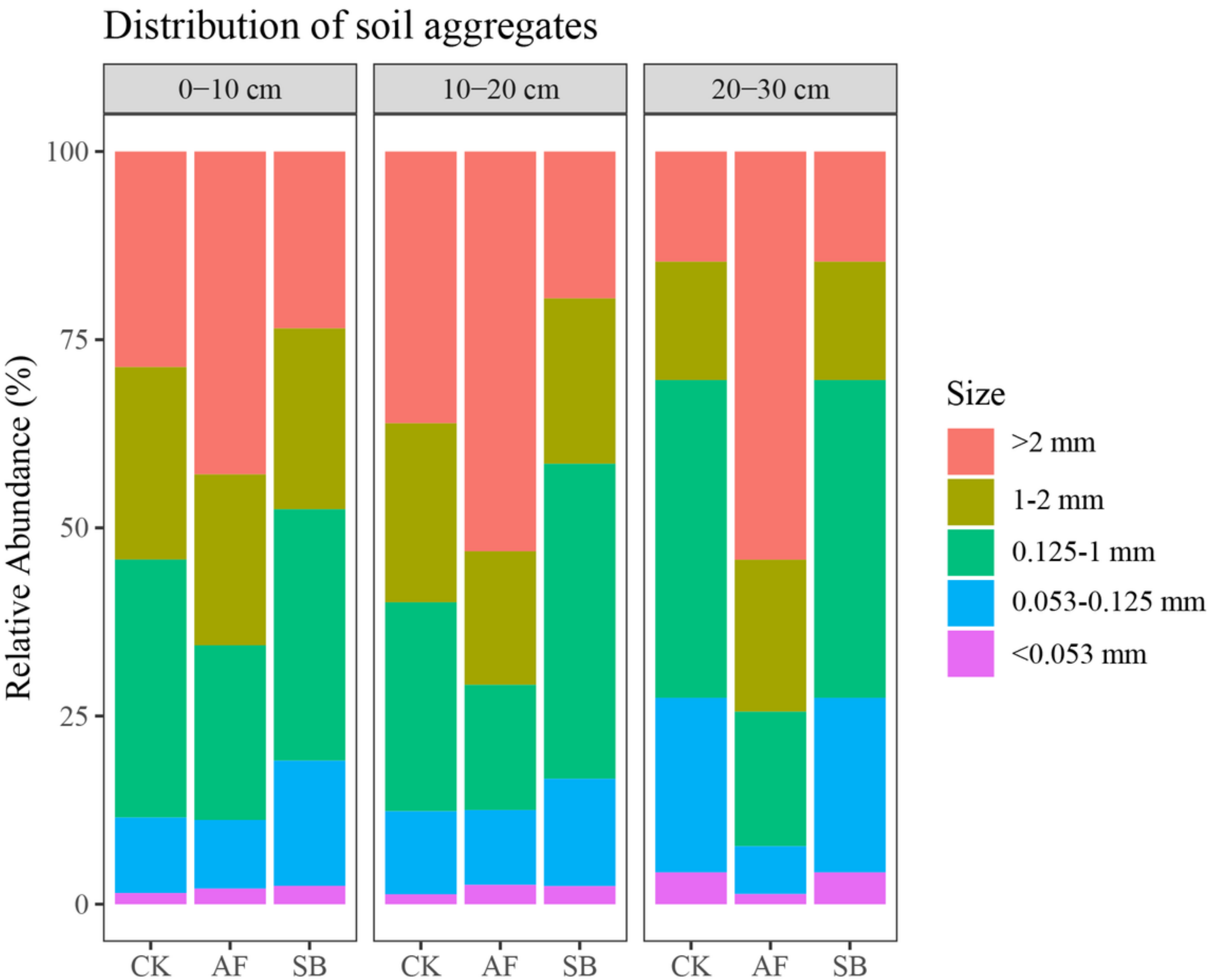

Figure 2

Effects of different restoration methods on soil aggregate composition. CK, natural recovery; AF, *Medicago sativa* L sowing; and SB, *Bromus inermis* Leyss sowing.

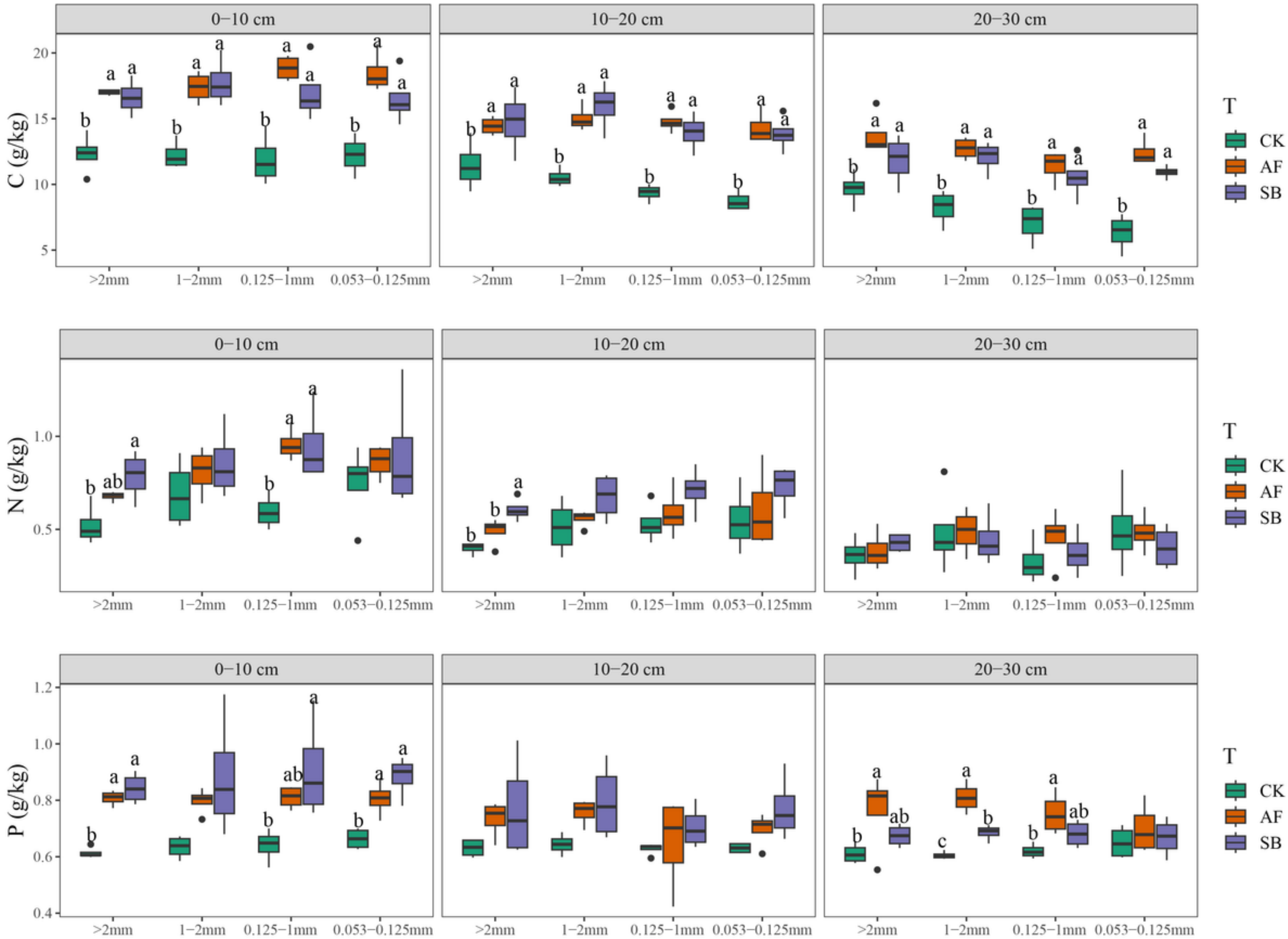

Figure 3

Soil carbon, nitrogen and phosphorus content characteristics under different soil depth and aggregate particle size. CK, natural recovery; AF, *Medicago sativa*L sowing; and SB, *Bromus inermis* Leyss sowing.

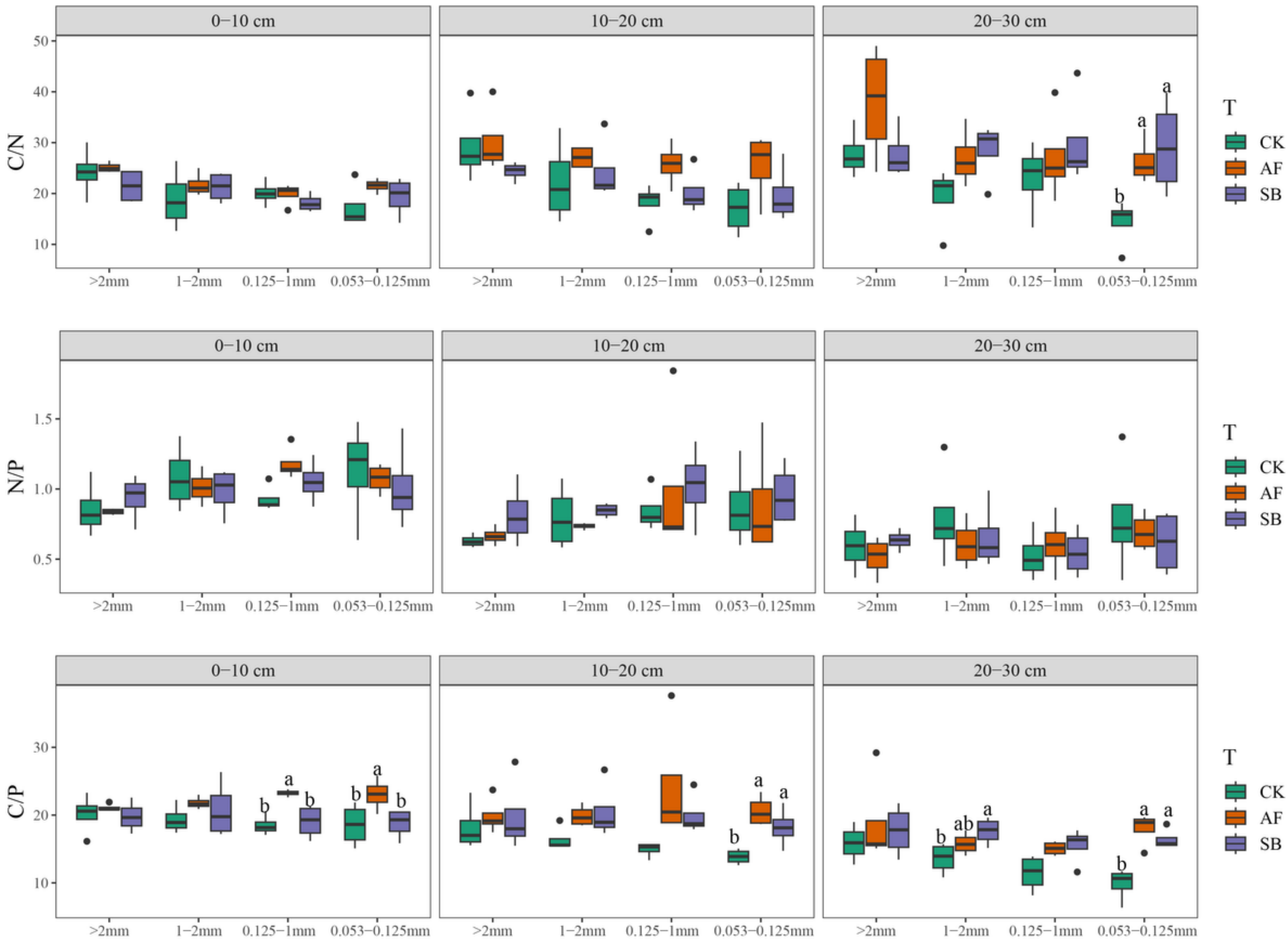

Figure 4

Soil C/N, N/P and C/P under different soil depth and aggregate particle size. CK, natural recovery; AF, *Medicago sativa* L sowing; and SB, *Bromus inermis* Leyss sowing. C/P: the ratio of carbon to phosphorus; C/N: the ratio of carbon to nitrogen; N/P: the ratio of nitrogen to phosphorus.

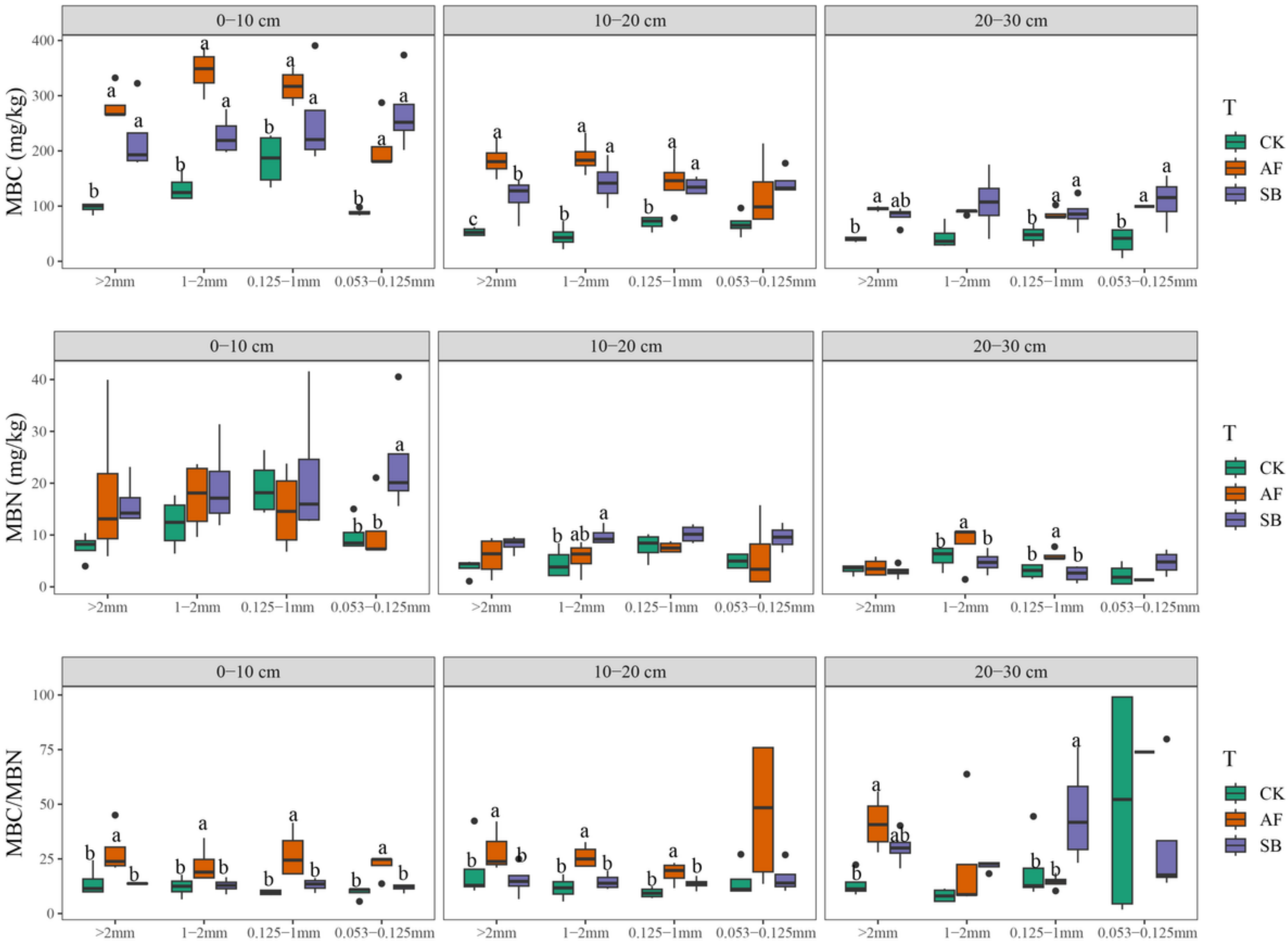

Figure 5

The effects of different vegetation restoration on microbial biomass carbon (MBC), microbial biomass nitrogen (MBN) and microbial biomass carbon nitrogen ratio (MBC/MBN) under different soil depth and different aggregate particle size. CK, natural recovery; AF, *Medicago sativa* L sowing; and SB, *Bromus inermis* Leyss sowing.

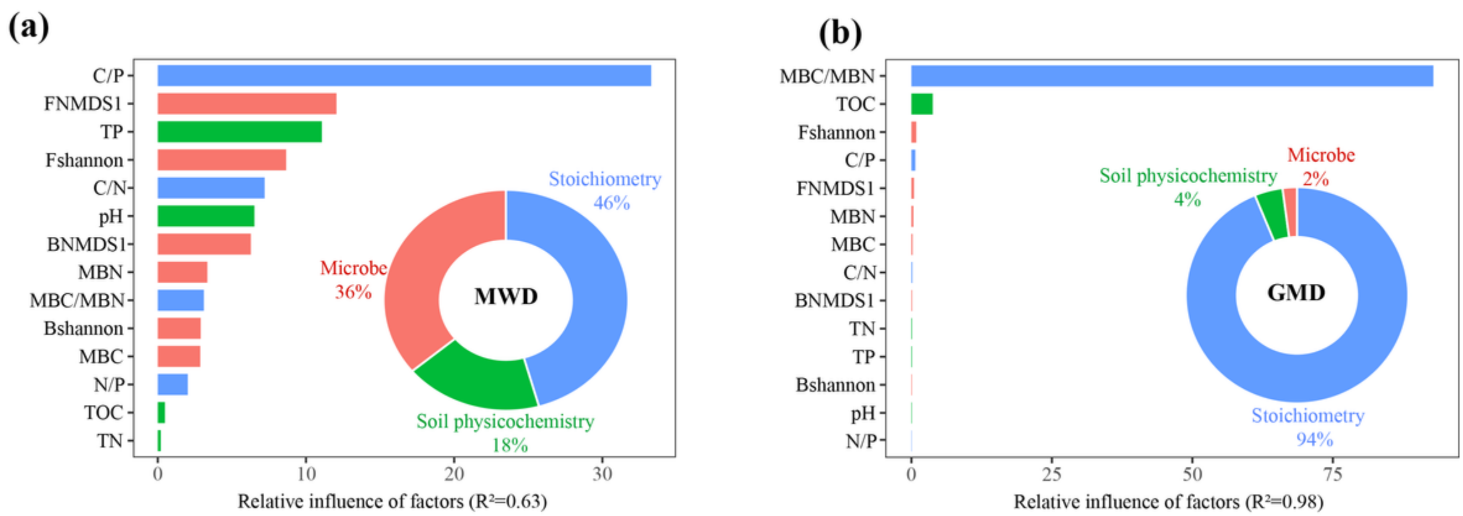

Figure 6

Relative influence of different factors on decomposition of (a) soil mean weight diameter (MWD) and (b) geometric mean diameter (GMD). Barplots and donut charts indicate the relative influence of microbe (α diversity and β diversity of bacteria and fungi, MBC and MBN), stoichiometry (C/N, N/P, C/P, MBC/MBN) and soil physicochemical properties (TOC, TP, TN, pH) on MWD and GMD. FNMDS1: NMDS1 of fungi; BNMDS1: NMDS1 of bacteria; Fshannon: The Shannon index of fungi; Bshannon: The Shannon index of bacteria. TOC: organic carbon; TP: soil total phosphorus; TN: soil total nitrogen; C/P: the ratio of carbon to phosphorus; C/N: the ratio of carbon to nitrogen; N/P: the ratio of nitrogen to phosphorus; MBC: microbial biomass carbon; MBN: microbial biomass nitrogen; MBC/MBN: the ratio of MBC to MBN; pH: pH value.

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