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青藏高原东缘不同树种人工林对土壤养分及团聚体稳定性的影响

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摘要 为促进人工林树种选择及管理, 以次生落叶阔叶灌丛为对照, 3种人工林(云杉*Picea asperata*, 油松*Pinus tabulaeformis*, 连香树*Cercidiphyllum japonicum*)为研究对象, 比较不同树种人工林土壤理化特征以及土壤团聚体粒径组成和稳定性的变化。结果显示: 造林树种差异对土壤全氮(TN)、有机碳(SOC)、有效磷(AP)含量和含水量、pH有极显著影响, 对土壤微生物生物量无显著影响。云杉人工林和连香树人工林土壤TN、SOC、AP含量和含水量显著高于灌丛, 油松人工林的土壤TN、SOC、AP含量均显著低于灌丛。造林树种差异显著影响了土壤团聚体粒级分布和稳定性。与灌丛相比, 3种人工林更有利于提高表层土壤团聚体的稳定性, 其中以连香树人工林效果最好。不同林分类型的土壤养分含量均随土层的加深而降低。此外随土层的加深大团聚体数量逐渐减少, 表层土壤结构稳定性高于底层土。土壤SOC、TN、AP和微生物生物量碳氮(MBC、MBN)含量均与土壤团聚体稳定性呈极显著正相关关系。本研究表明连香树和云杉人工林能够更有效地改善土壤养分和促进土壤团聚体稳定性; 因此, 未来在该地区引入养分循环和凋落物分解更快的阔叶林和混交林, 有助于改善因纯林导致土壤退化的问题。(图3 表4 参63)

关键词 树种; 人工林; 土壤理化性质; 土壤团聚体; 团聚体稳定性

Effects of afforestation with different tree species on soil nutrients and aggregate stability in the eastern margin of the Qinghai-Xizang Plateau

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Abstract To comprehensively elucidate the mechanisms and interconnections governing soil nutrient cycling and stability within three plantations in western Sichuan, we investigated the distinctive features associated with soil nutrient cycling and stability in the aforementioned plantations. Here, soil physicochemical properties, aggregate composition, and stability characteristics of three plantations (*Picea asperata*, *Pinus tabulaeformis*, and *Cercidiphyllum japonicum*) were investigated. The results showed that variations in afforested species significantly affected soil total nitrogen (TN), soil organic carbon (SOC), available phosphorus (AP) content, water content, and pH. However, there was no significant impact on soil microbial biomass. Specifically, soils in *Picea asperata* and *Cercidiphyllum japonicum* plantations exhibited significantly higher TN, SOC, AP, and water content than shrub plantations. In contrast, soils in *Pinus tabulaeformis* plantations showed significantly lower TN, SOC, and AP contents than shrub plantations. Tree species diversity significantly influenced the distribution and stability of soil aggregate grain size. In comparison to shrubs, the three artificial plantation types were more conducive to enhancing the stability of surface soil aggregates. Meanwhile, *Cercidiphyllum japonicum* plantation had the most favorable impact. The nutrient contents of the different stand types decreased with increasing soil depth. Additionally, as the soil depth increased, the number of large aggregates gradually

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decreased as the structural stability of the topsoil surpassed that of the subsoil. Soil parameters, such as SOC, TN, AP, microbial biomass carbon (MBC), and microbial biomass nitrogen (MBN) contents, were significantly and positively correlated with the stability of soil aggregates. In conclusion, the *Cercidiphyllum japonicum* and *Picea asperata* plantations demonstrated a more effective capacity to improve soil nutrients and enhance the stability of soil aggregates than that of *Pinus tabulaeformis*. Consequently, introducing broadleaf and mixed forests with accelerated nutrient cycling and faster litter decomposition in the region may address the issue of soil degradation caused by monoculture forests in the future.

Keywords tree species; plantation; soil physical and chemical property; soil aggregate; aggregate stability

土壤团聚体是土壤结构的基本单元,是衡量土壤质量的重要指标^[1-2]。土壤团聚体稳定性越高,土壤固持有机碳和土壤养分的能力就越强,从而有利于降低土壤养分流失^[3-4]。土壤有机碳作为团聚体的重要胶结物质,在团聚体的形成和稳定过程中发挥重要作用^[5-6]。此外,土壤含水量、pH值、氧化还原电位、离子强度和机械压力等环境因子也会影响团聚体的稳定性和周转率^[7-8]。pH值越高,> 0.25 mm的风干大团聚体含量就越高^[9]。Coot等研究土壤抗侵蚀能力和稳定性发现,土壤大团聚体的稳定性随土壤含水量的增加而下降^[10]。崔媛媛研究发现,土壤含水量充足时有利于增加大团聚体含量,而水分缺乏时不利于微团聚体的积累^[11]。植被类型对土壤团聚体的形成和稳定性也具有一定影响^[12]。植被根系和菌丝可以通过渗出物和缠绕作用来促进团聚体的形成和发育^[13-14]。王小红等研究发现天然林转化为人工林会导致大团聚体数量减少,土壤结构稳定性降低^[15]。刘艳等研究发现,油松(*Pinus tabulaeformis*)林较高的土壤有机碳含量有利于促进大团聚体的形成,使得油松林的土壤稳定性高于栓皮栎^[16]。Wei等在研究由草地到次生林恢复过程中发现,植被恢复改善了土壤成分并促进了土壤大团聚体的形成^[17]。朱家琪等研究发现菌丝能通过缠绕作用促成大团聚体,而针叶林凋落物含有抑制细菌活动的物质,使得针叶林大团聚体含量低于阔叶林^[18]。

川西人工林作为我国西南森林的重要组成以及长江上游重要的水源涵养和水土保持公益林,是我国西部地区生态安全和可持续发展的“生态屏障”^[19]。但该地区自20世纪60年代以来原始森林被大量砍伐,森林生态系统受到严重破坏,导致水土流失,养分贫瘠。伴随着植被保护以及人工林植被恢复工程的实施,该地区已逐渐形成多种针、阔优势纯林。但人工林又存在结构单一、林分密度不合理、抗逆能力弱等问题,因此如何改善和提高该地区人工林养分循环、水土保持和水源涵养等能力引起广泛关注。

目前,虽然有较多学者对该地区的人工林进行研究,但主要集中在土壤养分、酶活性、根系特征^[20-23]等方面,不同树种人工林对土壤养分与团聚体稳定性的影响及其关系的研究还相对较少。因此,我们主要以川西地区的优势人工林树种云杉(*Picea asperata*)、油松、连香树(*Cercidiphyllum japonicum*)为研究对

象,并以次生落叶阔叶灌丛为对照,研究不同树种人工林对土壤养分和土壤团聚体稳定性的影响,为川西地区水土保持、人造林树种的选择以及林地的可持续经营管理提供科学依据。

1 材料与方法

1.1 研究区自然概况

本研究样地位于四川省阿坝藏族羌族自治州的中国科学院茂县山地生态系统定位研究站(103°90'E, 31°70'N, 海拔1 826 m)附近,地处青藏高原东缘、横断山系北段高山峡谷地带的岷江上游地区,是青藏高原东缘和长江上游生态环境十分脆弱的高山峡谷区典型代表^[24]。该区属高原性季风气候,局部气候复杂,日照充足,降水少,气候干燥,多风,昼夜温差和地区温差大。年均气温11.0℃,极端最低气温-11.6℃,极端最高气温32.2℃,无霜期200 d,年均日照1 549.4 h,年降水量486.3 mm,褐土和棕壤土是研究区的主要土壤类型^[20, 22],其中云杉人工林样地为棕壤土,灌丛、油松和连香树人工林为褐土。过去该地区的原始森林植被类型主要是云杉林和冷杉林(*Abies fabri*),过去50年经过大规模采伐后,通过人工造林和自然恢复形成了大量次生植被,人工林主要树种有云杉、连香树、油松、华山松(*Pinus armandi*)等,自然次生植被主要为槲栎(*Quercus aliena*)、川榛(*Corylus heterophylla* var. *sutchuanensis*)等落叶灌丛。

1.2 样地基本情况及设计

基于前期的背景调查,选择地形及土壤条件相似的3种优势人工林,分别为云杉(PA)、油松(PT)、连香树(CJ)为研究对象,以次生落叶阔叶灌丛(GC)为对照。在每一植被类型中选择典型地段布置3块10 m × 10 m的样地,对样地进行基本情况调查,结果详见表1。并在每个样方内按上、中、下坡位分别设3个样品采集点,采用土钻原状土柱法在每个取样点用直径5 cm的土钻进行表层土(0-20 cm)和底层土(40-60 cm)样品采集。土壤样品充分混合后去除细根和石块,过2 mm孔筛,一式两份,一份置于阴凉干燥通风处风干,用于土壤理化等指标的测定,另一份作为其他需要鲜土样品的指标测定。另外,在样地按“S”形取样,在每个采样点内清除表面凋落物,采用直径为10 cm的土钻对0-20 cm和40-60 cm层进行原状土取样,根据

表1 样地基本情况及林下植被

Table 1 Basic situation and understory vegetation of the sample plots

林分类型 Forest type	地理位置 Geographical position	海拔 Altitude (h/m)	林下植被 Understory vegetation
PA	103°89'E 31°70'N	2143	狗枣猕猴桃、川莓、川滇蕤草、金星蕨、深山堇菜、粗茎鳞毛蕨等 <i>Actinidia kolomikta</i> , <i>Rubus setchuenensis</i> , <i>Carex schneideri</i> , <i>Parathelypteris glanduligera</i> , <i>Viola selkirkii</i> , <i>Dryopteris crassirhizoma</i> et al.
PT	103°89'E 31°69'N	2099	川康栲子、六道木、深山堇菜、沿阶草、假升麻、金星蕨等 <i>Cotoneaster ambiguous</i> , <i>Zabelia biflora</i> , <i>V. selkirkii</i> , <i>Ophiopogon bodinieri</i> , <i>Aruncus sylvestris</i> , <i>P. glanduligera</i> et al.
CJ	103°89'E 31°69'N	2081	唐古特瑞香、川滇盘果菊、川滇蕤草、假升麻、深山堇菜、金星蕨等 <i>Daphne tangutica</i> , <i>Paraprenanthes melanantha</i> , <i>C. schneideri</i> , <i>A. sylvestris</i> , <i>V. selkirkii</i> , <i>P. glanduligera</i> et al.
GC	103°89'E 31°69'N	1971	榲桲、四川蜡瓣花、华西箭竹、单花小檗、沿阶草、金星蕨、川榛等 <i>Quercus aliena</i> , <i>Corylopsis willmottiae</i> , <i>Fargesia nitida</i> , <i>Berberis candidula</i> , <i>Ophiopogon bodinieri</i> , <i>P. glanduligera</i> , <i>Corylus heterophylla</i> et al.

PA: 云杉; PT: 油松; CJ: 连香树; GC: 灌丛.

PA: *Picea asperata*; PT: *Pinus tabuliformis*; CJ: *Cercidiphyllum japonicum*; GC: Shrub.

样地情况40-60 cm土层直接采样操作难度大, 因此还结合土壤剖面法进行采样(3钻混合土样), 并将周围受到挤压的土壤小心清除. 为避免土块遭到破坏, 编号后分别将其放入团聚体杯中, 土壤约为杯中容量的2/3即可, 密封后置于保温箱带回实验室用于后续土壤团聚体特征分析.

1.3 测定指标及方法

土壤pH测定采用酸度计; 土壤全氮(TN)和有机碳(SOC)测定利用元素分析仪(Vario Macro Analyzer, 德国); 土壤有效磷(AP)用50 mL氟化铵-盐酸溶液浸提振荡后用电感耦合等离子体发射光谱仪(ICP-AES)测定^[25]; 土壤微生物生物量碳氮磷(MBC、MBN、MBP)测定采用氯仿熏蒸法^[26]; 土壤团聚体分析采用湿筛法测定, 将风干土样过8 mm筛后, 取60 g放入湿筛仪套筛(2 000 μm、250 μm、53 μm)将土壤完全浸入去离子水中(套筛不完全浸入). 开启团聚体分析仪(振幅3 cm, 25 Hz, 2 min), 小心分离套筛上的土壤, 用于土壤团聚体比例测定^[27]. 土壤团聚体稳定性采用平均质量直径(MWD)和几何平均直径(GMD)进行表征, 其计算公式^[28]如下.

$$MWD = \sum (Ri \times Wi) / \sum Wi \quad (1)$$

$$GMD = \exp (\sum Wi \times \ln Ri / \sum Wi) \quad (2)$$

式(1)(2)中, Ri =某粒级团聚体平均直径, Wi =湿筛后某粒级团聚体的重量.

1.4 数据处理

首先利用Excel进行基础数据整理, 采用SPSS24统计分析软件进行数据的统计处理. 同一土层不同植被类型间采用单因素方差分析(one-way ANOVA), 并利用最小显著性差异法(LSD)进行差异性比较, 同一植被的不同土层间采用T检验. 采用双因素方差分析(two-way ANOVA)比较林型和土层间的差异及两者

的交互效应, 显著性水平设为 $P < 0.05$. 本研究出现的数据均为均值(mean)±标准误(SE). 理化性质、团聚体稳定性等指标的相关性分析采用Person相关分析法. 所有图均在Origin 9.0软件完成.

2 结果与分析

2.1 不同树种造林对土壤理化特征的影响

在表层土中, 云杉和连香树人工林的土壤含水量、TN、SOC、AP含量均显著高于灌丛, 而油松人工林的土壤TN、SOC、AP含量均显著低于灌丛(图1). 云杉人工林的土壤pH显著低于连香树人工林和灌丛. 在底层土中, 连香树人工林土壤TN和SOC含量最高, 且显著高于其他2种人工林和灌丛. 在底层土中, 灌丛的土壤AP含量均显著高于3种人工林, pH值显著高于云杉和油松人工林, 但土壤含水量显著低于云杉和连香树人工林. 3种人工林间的底层土壤AP含量无显著差异, 油松人工林的土壤含水量和pH均与连香树人工林无显著差异, 云杉人工林土壤含水量显著高于连香树人工林, 但pH显著低于连香树人工林. 各林分的土壤SOC、TN和AP含量均随土层深度的增加而降低, 而pH则随土层深度的增加而呈上升趋势; 云杉人工林土壤含水量随土层深度的增加而上升, 但其他树种则随土层深度的增加而降低. 双因素方差分析表明, 林分类型、土层以及林分类型与土层的交互作用均显著影响土壤TN、SOC和AP含量, 土层对土壤含水量未产生显著影响, 林分类型与土层的交互作用对土壤pH的影响不显著.

土壤微生物生物量结果如图2所示, 各林分的土壤MBN、MBC、MBP含量在表层土中均无显著差异. 在底层土中, 灌丛土壤MBC含量最高, 且显著高于油松和连香树人工林, MBN含量显著高于油松人工林,

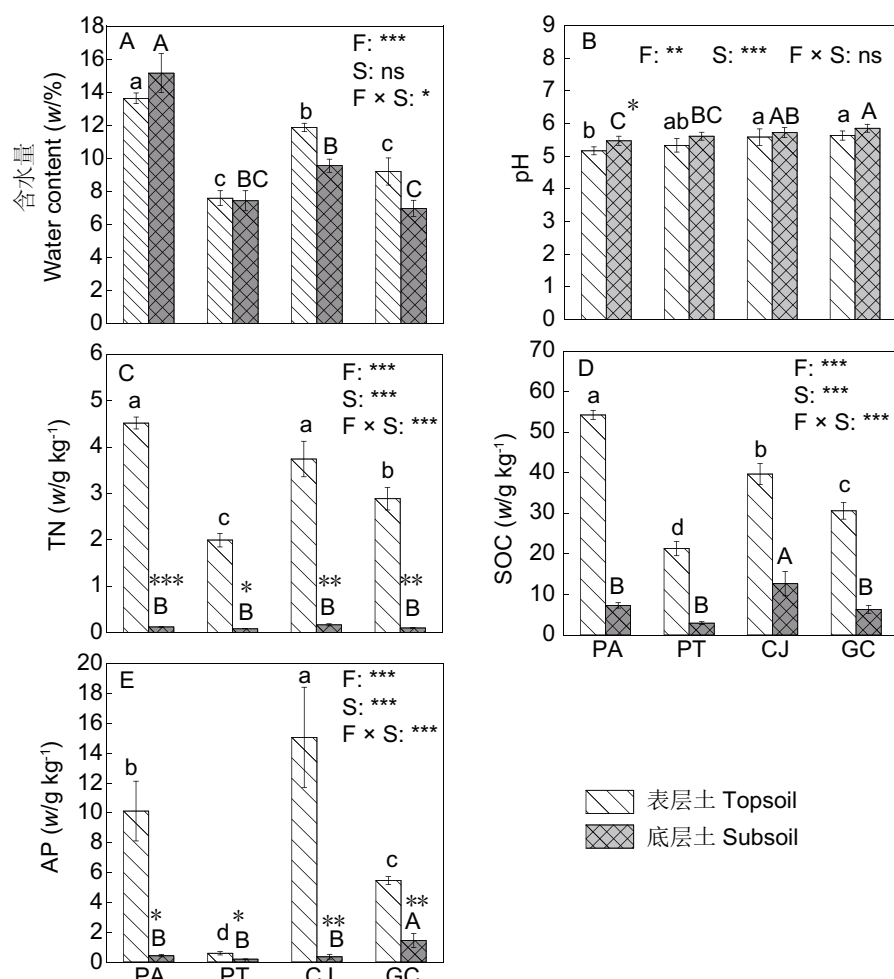


图1 不同林分类型土壤含水量(A)、pH(B)、全氮(TN, C)、有机碳(SOC, D)、有效磷(AP, E)。F: 林分类型; S: 土层; F × S: 林分类型与土层交互作用。PA: 云杉; PT: 油松; CJ: 连香树; GC: 灌丛。未出现相同小写字母表明不同林分类型表层土壤差异显著, 未出现相同大写字母表明不同林分类型底层土壤差异显著 ($P < 0.05$); 垂直竖线表示标准误差; 底层土大写字母上星号(*)表示同一林型不同土层差异显著; *** $P < 0.001$; ** $P < 0.01$; * $P < 0.05$ 。

Fig. 1 Soil water content (A), pH (B), total nitrogen (TN, C), organic carbon (SOC, D), and available phosphorus (AP, E) in different stand types. F: Forest type; S: Soil layer; F × S: Interaction between forest type and soil layer. PA: *Picea asperata*; PT: *Pinus tabulaeformis*; CJ: *Cercidiphyllum japonicum*; GC: Shrub. The absence of the same lowercase letters indicates significant differences in topsoil among different forest types and the absence of the same uppercase letters indicates significant differences in subsoil among different forest types ($P < 0.05$). The vertical lines represent the standard error; the uppercase letters with an asterisk (*) on the lower soil layer indicate significant differences among different soil layers within the same forest type. *** $P < 0.001$; ** $P < 0.01$; * $P < 0.05$.

与云杉和连香树人工林无显著差异。MBP含量在各林分的底层土中无显著差异。土壤MBN和MBC含量随着土层深度的增加而降低, 土壤MBP随土层的加深变化不显著。双因素方差结果显示, MBN和MBC含量仅受土层的显著影响, 而林分类型、土层、林分类型与土层交互作用均对MBP无显著影响。

2.2 不同树种造林对土壤团聚体组成及稳定性的影响

2.2.1 土壤水稳性团聚体粒级分布特征

在表层土中, 灌丛的> 2 mm粒级含量最低, 且与3种人工林间有显著差异, 而在0.25-2 mm粒级中, 灌丛的含量显著高于3种人工林, 而人工林之间均无显著差异。表层土中, 0.053-0.25 mm和< 0.053 mm粒级含量从大到小的顺序均为灌丛、油松人工林、云杉人工林、连香

树人工林, 其中0.053-0.25 mm粒级在各林分间分布具有显著差异。在底层土中, 灌丛的> 2 mm粒级的团聚体含量显著低于连香树人工林, 显著高于云杉人工林和油松人工林, 而在0.25-2 mm粒级中灌丛含量显著低于云杉人工林, 与其他两种人工林间无显著差异。在底层土中, 云杉人工林的0.053-0.25 mm粒级含量显著高于其他树种。底层土中, < 0.053 mm粒级含量从大到小的顺序为云杉人工林、油松人工林、连香树人工林、灌丛。由表2结果可知, 不同树种间表层土均主要以> 2 mm粒级的团聚体为主, 而底层土均主要以0.25-2 mm粒级的团聚体为主。随着土层的加深, > 2 mm粒级的团聚体呈逐渐降低的趋势, 而< 2 mm粒级

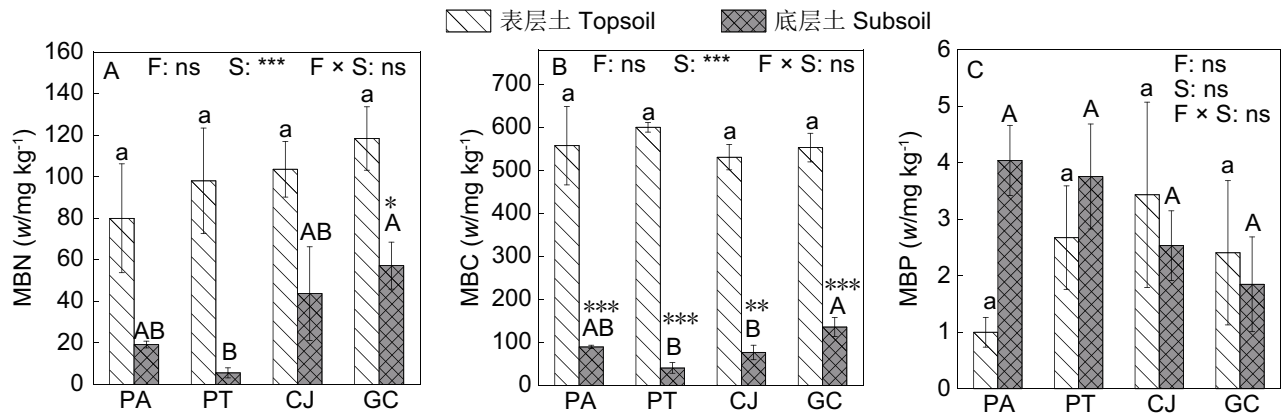


图2 不同林分类型土壤微生物生物量氮 (MBN, A)、微生物生物量碳 (MBC, B)、微生物生物量磷 (MBP, C)。F: 林分类型; S: 土层; F × S: 林分类型与土层交互作用。PA: 云杉; PT: 油松; CJ: 连香树; GC: 灌丛。未出现相同小写字母表明不同林分类型表层土壤差异显著, 未出现相同大写字母表明不同林分类型底层土壤差异显著 ($P < 0.05$); 垂直竖线表示标准误差; 底层土大写字母上星号 (*) 表示同一林型不同土层差异显著; *** $P < 0.001$; ** $P < 0.01$; * $P < 0.05$ 。

Fig. 2 Soil microbial biomass nitrogen (MBN, A), microbial biomass carbon (MBC, B), and microbial biomass phosphorus (MBP, C) in different stand types. F: Forest type; S: Soil layer; F × S: Interaction between forest type and soil layer. PA: *Picea asperata*; PT: *Pinus tabulaeformis*; CJ: *Cercidiphyllum japonicum*; GC: Shrub. The absence of the same lowercase letters indicates significant differences in topsoil among different forest types and the absence of the same uppercase letters indicates significant differences in subsoil among different forest types ($P < 0.05$). The vertical line represents the standard error; the uppercase letters with an asterisk (*) on the lower soil layer indicate significant differences among different soil layers within the same forest type. *** $P < 0.001$; ** $P < 0.01$; * $P < 0.05$.

的团聚体则呈逐渐增加的趋势。

林分类型仅对0.053-0.25 mm粒级的团聚体产生显著影响, 土层对团聚体粒级的分布都产生了极显著的影响 ($P < 0.001$), 林分类型与土层交互作用显著影响 > 2 mm、0.25-2 mm、0.053-0.25 mm等粒级的分布 ($P < 0.05$) (表3)。

2.2.2 土壤团聚体稳定性特征 如图3所示, 在表层土中, 不同林分类型的土壤团聚体MWD值和GMD值从大到小的顺序均为连香树人工林、云杉人工林、油松人工林、灌丛。云杉和连香树人工林的土壤团聚体MWD值和GMD值均显著高于灌丛, 油松人工林土壤团聚体GMD值显著高于灌丛。在底层土中, 连香树人工林土壤团聚体MWD值和GMD值最大, 显著高于灌丛; 云杉和油松人工林的土壤团聚体MWD值和GMD值最低, 均显著低于灌丛。各林分的土壤团聚体MWD和GMD均随土层的加深降低。双因素方差分析可知, 林分类型、土层以及林分类型与土层交互作用均对土壤团聚体的MWD值和GMD值产生极显著影响 ($P < 0.001$)。

2.3 土壤理化性质与土壤团聚体稳定性指标的相关性分析

土壤理化性质与土壤团聚体稳定性指标的相关性分析 (表4) 表明, 土壤TN、SOC、AP、MBN、MBC含量与土壤团聚体的MWD和GMD指标具有极显著正相关关系; 土壤pH与土壤团聚体的MWD和GMD指标呈极显著负相关关系; 土壤含水量、MBP含量与MWD、GMD无显著相关关系。

3 讨论

3.1 造林树种差异对土壤理化性质的影响

不同植被类型能通过影响根系结构、凋落物归还量、组成及分解速率来影响土壤养分循环和转化过程, 使土壤理化性质产生差异^[29-31]。LÜ等对毛乌素沙地的研究发现3种植被类型 (草地、天然蒙古岩黄芩林、柳树林) 对土壤理化性质有显著影响, 而植被的影响主要集中在表土层。秦嘉海等研究祁连山不同林分类型发现, 土壤含水量、SOM、TN含量均为灌木林 > 针叶林 > 阔叶林^[33]。本研究中, 造林树种差异对土壤含水量、pH、TN、SOC和AP含量具有显著影响。这可能与不同树种对土壤养分的吸收^[34]、归还能力^[35]和林下物种多样性^[36]等因素有关。有研究认为, 自然植被的土壤养分含量明显高于人工植被^[37]; 但也有研究认为人工植被有效改善了土壤理化性质, 效果优于自然植被^[38]。云杉和连香树人工林土壤含水量、TN、SOC、AP含量均显著高于灌丛表层土, 说明这两种人工林改善了表层土壤的理化性质。云杉土壤pH低于灌丛和连香树, 可能是由于针叶林凋落物在分解过程中会产生大量有机酸, 所以使得针叶林与阔叶林相比pH值更低^[39-40]。高伟等研究植被类型对土壤微生物生物量的影响发现, 植被类型对土壤微生物生物量有显著影响, 其中次生林各土层MBC和MBN含量均显著高于人工林, 不同人工林间MBN含量无显著差异^[41]。本研究表明树种差异对土壤微生物生物量并无显著影响。这与Ayres等研究的结果^[42]相似, 他们发现高海拔地

表2 不同林分类型土壤团聚体粒级分布

Table 2 Distribution of soil aggregate particle size in different stand types

土层 Soil layer	林分类型 Forest type	> 2 mm	0.25-2 mm	0.053-0.25 mm	< 0.053 mm
表层土 Topsoil	PA	75.19 ± 4.92ab	20.85 ± 4.44b	2.30 ± 0.78c	1.66 ± 0.06b
	PT	63.34 ± 3.02b	27.25 ± 1.23b	4.75 ± 0.39b	4.66 ± 0.85a
	CJ	78.61 ± 1.03a	18.44 ± 0.64b	1.72 ± 0.14d	1.23 ± 0.336b
	GC	43.43 ± 5.50c	41.38 ± 8.11a	7.82 ± 1.26a	7.37 ± 1.51a
底层土 Subsoil	PA	5.92 ± 0.35C	61.88 ± 2.54A	11.38 ± 3.37AB	20.98 ± 2.30A
	PT	12.36 ± 3.00C	49.41 ± 1.76B	17.25 ± 1.04A	20.82 ± 1.17A
	CJ	36.59 ± 0.92A	45.81 ± 1.00B	7.17 ± 1.16B	10.43 ± 1.41B
	GC	22.77 ± 3.56B	50.38 ± 5.05B	17.53 ± 0.66A	9.33 ± 1.58B

PA: 云杉; PT: 油松; CJ: 连香树; GC: 灌丛. 未出现相同小写字母表明不同林分类型表层土壤差异显著, 未出现相同大写字母表明不同林分类型底层土壤差异显著 ($P < 0.05$).

PA: *Picea asperata*; PT: *Pinus tabulformis*; CJ: *Cercidiphyllum japonicum*; GC: Shrub. The absence of the same lowercase letters indicates significant differences in topsoil among different forest types and the absence of the same uppercase letters indicates significant differences in subsoil among different forest types ($P < 0.05$).

表3 林分类型和土层深度对土壤团聚体粒级组成的影响

Table 3 Effects of stand type and soil depth on soil aggregate particle composition

粒径分级 Particle size classification	林分类型 Forest type		土层 Soil layer		林分类型×土层 Forest type × soil layer	
	F	P	F	P	F	P
> 2 mm	2.438	ns	34.599	***	4.770	*
0.25-2 mm	1.238	ns	22.725	***	3.902	*
0.053-0.25 mm	12.23	***	50.065	***	4.704	*
< 0.053 mm	2.416	ns	8.865	***	1.033	ns

显著性: *** $P < 0.001$; * $P < 0.05$; ns: 无显著差异 ($P > 0.05$).

Significance: *** $P < 0.001$; * $P < 0.05$; ns: No significant difference ($P > 0.05$).

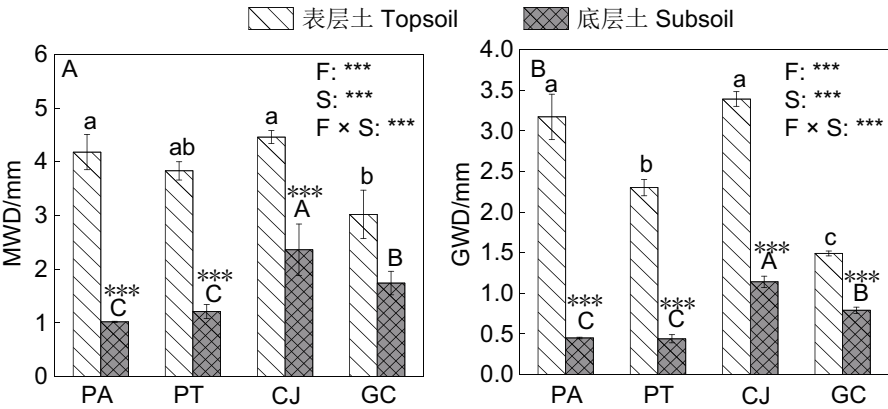


图3 不同林分类型土壤团聚体平均质量直径 (MWD, A) 和几何平均直径 (GMD, B) 特征. F: 林分类型; S: 土层; F × S: 林分类型与土层交互作用. PA: 云杉; PT: 油松; CJ: 连香树; GC: 灌丛. 未出现相同小写字母表明不同林分类型表层土壤差异显著, 未出现相同大写字母表明不同林分类型底层土壤差异显著 ($P < 0.05$); 垂直竖线表示标准误差; 底层土大写字母上星号 (*) 表示同一林型不同土层差异显著; *** $P < 0.001$; ** $P < 0.01$; * $P < 0.05$.

Fig. 3 Characteristics of mean mass diameter (MWD, A) and geometric mean diameter (GMD, B) of soil aggregates of different stand types. F: Forest type; S: Soil layer; F × S: Interaction between forest type and soil layer. PA: *Picea asperata*; PT: *Pinus tabulformis*; CJ: *Cercidiphyllum japonicum*; GC: Shrub. The absence of the same lowercase letters indicates significant differences in topsoil among different forest types and the absence of the same uppercase letters indicates significant differences in subsoil among different forest types ($P < 0.05$). The vertical line represents the standard error. The uppercase letters with an asterisk (*) on the lower soil layer indicate significant differences among different soil layers within the same forest type. *** $P < 0.001$; ** $P < 0.01$; * $P < 0.05$.

表4 土壤理化性质与团聚体稳定性相关性
Table 4 Correlation between soil physical and chemical properties and aggregate stability

指标 Index	MWD	GWD
含水量 Water content	0.266	-0.294
pH	-0.640**	-0.621**
全氮 Total nitrogen (TN)	-0.843**	-0.883**
有机碳 Soil organic carbon (SOC)	-0.860**	-0.900**
有效磷 Available phosphorus (AP)	-0.738**	-0.833**
微生物生物量氮 Microbial biomass nitrogen (MBN)	-0.651**	-0.600**
微生物生物量碳 Microbial biomass carbon (MBC)	-0.844**	-0.797**
微生物生物量磷 Microbial biomass phosphorus (MBP)	-0.205	-0.197

**为0.01水平上极显著相关。

** Significantly correlated at the 0.01 level.

区森林不同树种间土壤微生物生物量并无显著差异。

不同造林树种的pH、TN、SOC、AP、MBN、MBC含量均随土层的加深而降低。这与大多研究结果一致^[43-44]。土壤含水量在土层间变化不显著,可能是由于采样时间为2020年8月中旬,该地区正处于高温干旱时期,降水量少(该月降水量约53.2 mm),且采样前几天也无降雨,土壤相对干燥,从而可能使土壤含水量在土层间无显著变化。本研究中,不同林分类型土壤养分含量总体上表层土高于底层土,具有明显的“聚表”现象^[45]。这可能是由于凋落物的分解、根系残体和分泌物的积累为表层土壤提供了更丰富的有机质^[46]。

3.2 造林树种差异对土壤团聚体组成及稳定性的影响

土壤团聚体是土壤健康和生产力的关键,它们通过改善土壤结构、增强水分保持、促进养分循环和维护生物多样性,在生态环境保护中发挥着重要作用^[47]。本研究结果表明,不同造林树种差异显著影响了土壤团聚体粒级分布和稳定性。Zhang等研究发现造林显著提高了土壤团聚体的稳定性,大团聚体增加了土壤氮、碳、磷等养分循环功能^[48]。林立文等对南亚热带人工林的研究结果表明,杉木林与其他人工林相比土壤结构更稳定,更有利于提高土壤团聚体稳定性^[49]。本研究中3种人工林均显著提高了表层土> 2 mm粒径的团聚体数量、MWD和GMD值。相比于灌丛,人工林能有效提高土壤结构的稳定性,这与蔡琳等研究亚热带不同森林恢复方式时的结果^[50]一致。结合土壤理化性质与团聚体相关性(表4)可知,土壤SOC、TN、AP、MBC、MBN含量与土壤团聚体稳定性呈极显著正相关关系。这与先前研究的结论^[51-53]一致。不同树种因形态特征、凋落物以及根系分泌物的不同,导致土壤有机质输入、微生物活性和理化性质存在差异,从而影响团聚体的形成和稳定^[54]。李倩如等在研究灌木群落凋落物积累量时发现,乔木林凋落物的积累量明显高于灌丛^[55]。本研究中3种人工林促进了表层土壤团聚体的稳定性,这可能与以乔木为优势物种的人工林大量凋落物返还与分解,增加土壤SOC含量和土壤养分有助

于土壤团聚体形成和稳定有关^[56-57]。

油松林表层土的有机碳含量低于灌丛,但土壤GMD值显著高于灌丛,说明土壤团聚体稳定性可能还受到植被类型差异、根系特征、土壤微生物活动强度、土壤质地特征以及人为干扰等多种因素的影响^[58-59]。此外,不同树种的根系分泌物(如多糖、有机酸等)能够促进土壤微生物的活动,进而影响土壤团聚体的形成和稳定性。例如,松树的根系分泌物中含有较多的有机酸,这些有机酸能够与土壤中的矿物质结合,形成稳定的团聚体^[60]。而菌根真菌(如丛枝菌根真菌)通过与植物根系共生,能够分泌球囊霉素(glomalin)^[61],能够显著增强土壤团聚体的稳定性。不同树种与菌根真菌的共生关系不同,因此对土壤团聚体稳定性的影响也有所差异。

不同林分类型土壤大团聚体数量均随土层的加深而减少,而土壤微团聚体(< 0.25 mm)随土层的加深而增加。王兴等的研究也有类似的结果^[62],他们发现在长期撂荒恢复时相较于0-20 cm土层,40-60 cm土层土壤大团聚体数量较少而土壤微团聚体数量较多,表现出微团聚体在土壤深层普遍高于表层而大团聚体和中团聚体在土壤深层普遍低于表层的现象。本研究中,土壤团聚体稳定性在底层土壤中比表层土壤低,这可能与底层土壤中较低的土壤有机碳含量和根系质量密度有关^[63]。

4 结论

通过分析不同林分类型土壤理化特征、团聚体组成及其稳定性的关联性发现,树种差异对土壤养分特征及团聚体稳定性具有显著影响。不同树种的土壤TN、SOC、AP含量及pH、含水量等指标存在显著差异,但对土壤微生物生物量未产生显著影响。各林分类型土壤团聚体组成均以大团聚体为主导,其中人工林表层土壤团聚体稳定性显著优于底层土。土层深度对土壤特征具有显著调控作用。土壤TN、SOC、AP含量及微生物生物量均随土层加深呈显著递减趋势,同时团聚体稳定性降低。表层土壤结构稳定性与SOC含量呈显著正相关,表明有机质积累对维持土壤结构具有关键作用。人工林造林后显著改善了土壤质量。其中云杉和连香树人工林的表层土壤SOC含量及团聚体稳定性均有显著提升,通过促进有机质积累和团聚体形成增强了土壤结构功能,改良效果较好。但人工林对土壤微生物生物量的影响并不显著,表明土壤生物活性恢复可能需要更长的生态演替周期。本研究阐明了人工林对土壤质量的影响机制,为退化生态系统修复的树种选择提供了科学依据。然而,本研究尚未系统评估不同林分类型对土壤碳储量的长期累积效应,未来应结合多尺度空间分析与微生物功能研究,进一步为青藏高东缘地区人工林生态恢复提供指导依据。

参考文献 [References]

- Rabot E, Wiesmeier M, Schlüter S, Vogel HJ. Soil structure as an indicator of soil functions: a review [J]. *Geoderma*, 2018, **314**: 122-137
- Amézketa E. Soil aggregate stability: a review [J]. *J Sustain Agric*, 1999, **14** (2-3): 83-151
- Raine SR, So HB. An investigation of the relationships between dispersion, power, and mechanical energy using the end-over-end shaking and ultrasonic methods of aggregate stability assessment [J]. *Soil Res*, 1997, **35** (1): 41-54
- Six J, Elliott ET, Paustian K. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture [J]. *Soil Boil Biochem*, 2000, **32** (14): 2099-2103
- Situ G, Zhao Y, Zhang L, Yang XQ, Chen D, Li SH, Wu QF, Xu QF, Chen JH, Qin H. Linking the chemical nature of soil organic carbon and biological binding agent in aggregates to soil aggregate stability following biochar amendment in a rice paddy [J]. *Sci Total Environ*, 2022, **847**: 157460
- Xue B, Huang L, Huang Y, Zhou FL, Li F, Kubar KA, Li XK, Lu JW, Zhu J. Roles of soil organic carbon and iron oxides on aggregate formation and stability in two paddy soils [J]. *Soil Till Res*, 2019, **187**: 161-171
- Bronick CJ, Lal R. Soil structure and management: a review [J]. *Geoderma*, 2005, **124** (1/2): 3-22
- Haynes RJ, Swift RS. Stability of soil aggregates in relation to organic constituents and soil water content [J]. *J Soil Sci*, 1990, **41** (1): 73-83
- 胡琛, 贺云龙, 崔鸿侠, 黄金莲, 唐万鹏. 神农架4种典型人工林对土壤团聚体分布及稳定性的影响[J]. 中南林业科技大学学报, 2020, **40** (12): 125-133 [Hu C, He YL, Cui HX, Huang JL, Tang WP. [Effects of four typical plantations on the distribution and stability of soil aggregates in Shennongjia [J]. *J Centr S Univ For Technol*, 2020, **40** (12): 125-133]
- Coote DR, Malcolm-McGovern CA, Wall GJ, Dickinson WT, Rudra RP. Seasonal variation of erodibility indices based on shear strength and aggregate stability in some Ontario soils [J]. *Can J Soil Sci*, 1988, **68**: 405-416
- 崔媛媛. 降水量变化对荒漠草原土壤团聚体稳定性的影响[D]. 呼和浩特: 内蒙古农业大学, 2022 [Cui YY. Effect of precipitation change on the stability of soil aggregates in desert steppe [D]. Hohhot: Inner Mongolia Agricultural University, 2022]
- Cheng H, Che M, Hu W, Wu Q, Cheng Y, Hu X, Xiong S, Zheng J, Gong Y. Soil available nutrients associated with soil chemical and aggregate properties following vegetation restoration in western Sichuan, China [J]. *Forests*, 2023, **14** (2): 259
- 刘亚龙, 王萍, 汪景宽. 土壤团聚体的形成和稳定机制: 研究进展与展望[J]. 土壤学报, 2023, **60** (3): 627-643 [Liu YL, Wang P, Wang JK. The Formation and stabilization mechanisms of soil aggregates: research progress and prospects [J]. *Acta Pedol Sin*, 2023, **60** (3): 627-643]
- Poirier V, Roumet C, Munson AD. The root of the matter: Linking root traits and soil organic matter stabilization processes [J]. *Soil Boil Biochem*, 2018, **120**: 246-259
- 王小红, 杨智杰, 刘小飞, 杨玉盛, 吴君君, 付林池, 陈坦, 李伟. 天然林转换成人工林对土壤团聚体稳定性及有机碳分布的影响[J]. 水土保持学报, 2014, **28** (6): 177-182+189 [Wang XH, Yang ZJ, Liu XF, Yang YS, Wu JJ, Fu LC, Chen T, Li W. Effects of conversion from natural forest to plantation on soil aggregate stability and organic carbon distribution [J]. *J Soil Water Conserv*, 2014, **28** (6): 177-182+189]
- 刘艳, 查同刚, 王伊琨, 王高敏. 北京地区栓皮栎和油松人工林土壤团聚体稳定性及有机碳特征[J]. 应用生态学报, 2013, **24** (3): 607-613 [Liu Y, Cha TG, Wang YK, Wang GM. Soil aggregate stability and organic carbon characteristics of cork oak and *Pinus tabulaeformis* plantations in Beijing [J]. *Chin J Appl Ecol*, 2013, **24** (3): 607-613]
- Wei H, Deng Y, Lin L, Wang JY, Huang J. Improved soil composition promotes nutrient recovery during vegetation restoration in karst peak-cluster depressions [J]. *Catena*, 2023, **222**: 106769
- 朱家琪, 满秀玲, 王飞. 我国寒温带四种森林植被类型下土壤团聚体粒级组成及其稳定性比较研究[J]. 土壤通报, 2020, **51** (3): 606-613 [Zhu JQ, Man ZL, Wang F. Comparative study on soil aggregate particle composition and stability of four forest vegetation types in cold temperate zone in China [J]. *Chin J Soil Sci*, 2020, **51** (3): 606-613]
- 刘庆, 吴彦, 何海. 中国西南亚高山针叶林的生态学问题[J]. 世界科技研究与发展, 2001 (2): 63-69 [Liu Q, Wu Y, He H. Ecological problems of subalpine coniferous forests in Southwest China [J]. *World Sci-Technol Res Dev*, 2001 (2): 63-69]
- 舒媛媛, 黄俊胜, 赵高卷, 包维楷, 李根前, 庞学勇. 青藏高原东缘不同树种人工林对土壤酶活性及养分的影响[J]. 生态学报, 2016, **36** (2): 394-402 [Shu YY, Huang JS, Zhao GJ, Bao WK, Li GQ, Pang XY. Effects of different tree species on soil enzyme activities and nutrients in eastern margin of Tibetan Plateau [J]. *Acta Ecol Sin*, 2016, **36** (2): 394-402]
- Yang B, Qi K, Bhusal DB, Huang J, Chen W, Wu Q, Hussain A, Pang X. Soil microbial community and enzymatic activity in soil particle-size fractions of spruce plantation and secondary birch forest [J]. *Eur J Soil Biol*, 2020, **99**: 103196
- 陈文静, 祁凯斌, 黄俊胜, 杨婷惠, 包维楷, 庞学勇. 川西次生灌丛和不同类型人工林对土壤养分的影响[J]. 应用与环境生物学报, 2017, **23** (6): 1081-1088 [Chen WJ, Qi KB, Huang JS, Yang TH, Bao WK, Pang XY. Effects of secondary shrubland and different types of plantation on soil nutrients in western Sichuan [J]. *Chin J Appl Environ Biol*, 2017, **23** (6): 1081-1088]

- 23 Ding JX, Yin HJ, Kong DL, Liu Q, Zhang ZL, Wang QT, Guo WJ, Valverde-Barrantes OJ, Wang JJ. Precipitation, rather than temperature drives coordination of multidimensional root traits with ectomycorrhizal fungi in alpine coniferous forests [J]. *J Ecol*, 2023: DOI 10.1111/1365-2745.14151
- 24 肖群英, 尹春英, 濮晓珍, 乔明锋, 刘庆. 川西亚高山季节性冻土期针叶林主要树种叶片和细根的生态生理特征[J]. 植物生态学报, 2014, **38** (4): 343-354[Xiao QY, Yin CY, Pu XZ, Qiao MF, Liu Q. Ecological and physiological characteristics of leaves and fine roots of major tree species in coniferous forest during seasonal frozen soil period in western Sichuan [J]. *Chin J Plant Ecol*, 2014, **38** (4): 343-354]
- 25 何秀芬, 罗金辉, 韩丙军, 叶海辉. ICP-AES测定酸性土壤中有效磷的研究[J]. 热带农业科学, 2011, **31** (9): 37-39 [He XF, Luo JH, Han BJ, Ye HH. Determination of available phosphorus in acidic soil by ICP-AES [J]. *Chin J Trop Agric*, 2011, **31** (9): 37-39]
- 26 鲍士旦. 土壤农化分析[M]. 3版. 北京: 中国农业出版社, 2000 [Bao SD. Soil Agrochemical Analysis [M]. 3rd ed. Beijing: China Agricultural Press, 2000]
- 27 陈秋捷, 张楠楠, 仲波. 若尔盖高寒草地退化沙化过程中土壤养分与团聚体结构的变化特征[J]. 生态科学, 2019, **38** (4): 13-20 [Chen QJ, Zhang NN, Zhong B, Chen DM, Sun G, Liu M. Changes in soil nutrients and aggregate structure during the degradation and desertification process of Ruorgai alpine grassland [J]. *Ecol Sci*, 2019, **38** (4): 13-20]
- 28 郑子成, 李廷轩, 张锡洲, 王永东, 杨玉梅, 汪曦微. 不同土地利用方式下土壤团聚体的组成及稳定性研究[J]. 水土保持学报, 2009, **23** (5): 228-231+236 [Zheng ZC, Li TX, Zhang XZ, Wang YD, Yang YM, Wang XW. Study on the composition and stability of soil aggregates under different land use patterns [J]. *J Soil Water Conserv*, 2009, **23** (5): 228-231+236]
- 29 Aponte C, García LV, Marañón T. Tree species effects on nutrient cycling and soil biota: a feedback mechanism favouring species coexistence [J]. *For Ecol Manag*, 2013, **309**: 36-46
- 30 He YJ, Han XR, Wang XP, Wang LQ, Liang T. Long-term ecological effects of two artificial forests on soil properties and quality in the eastern Qinghai-Tibet Plateau [J]. *Sci Total Environ*, 2021, **796**: 148986
- 31 Yang X, Shao MA, Li TC, Zhang QY, Gan M, Chen MY, Bai X. Distribution of soil nutrients under typical artificial vegetation in the desert-loess transition zone [J]. *Catena*, 2021, **200**: 105165
- 32 Lǔ D, Liu Q, Xie T, Yang Y. Impacts of different types of vegetation restoration on the physicochemical properties of sandy soil [J]. *Forests*, 2023, **14** (9): 1740
- 33 秦嘉海, 金自学, 王进, 刘金荣, 谢晓蓉. 祁连山不同林地类型对土壤理化性质和水源涵养功能的影响[J]. 水土保持学报, 2007 (1): 92-94+139 [Qin JH, Jin ZX, Wang J, Liu JR, Xie XR. Effects of different forest types on soil physicochemical properties and water conservation function in Qilian Mountains [J]. *J Soil Water Conserv*, 2007 (1): 92-94+139]
- 34 Haghverdi K, Kooch Y. Effects of diversity of tree species on nutrient cycling and soil-related processes [J]. *Catena*, 2019, **178**: 335-344
- 35 管东生, 何坤志, 陈玉娟. 广州城市绿地土壤特征及其对树木生长的影响[J]. 环境科学研究, 1998 (4): 53-56 [Guan DS, He KZ, Chen YJ. Soil characteristics of urban green space and their effects on tree growth in Guangzhou [J]. *Res Environ Sci*, 1998 (4): 53-56]
- 36 冯嘉仪, 储双双, 王婧, 吴道铭, 莫其锋, 曾曙才. 华南地区5种典型林分类型土壤肥力综合评价[J]. 华南农业大学学报, 2018, **39** (3): 73-81 [Feng JY, Chu SS, Wang Q, Wu DM, Mo QF, Zen SC. Comprehensive evaluation of soil fertility of 5 typical stand types in South China [J]. *J South Chin Agric Univ*, 2018, **39** (3): 73-81]
- 37 王凯博, 时伟宇, 上官周平. 黄土丘陵区天然和人工植被类型对土壤理化性质的影响[J]. 农业工程学报, 2012, **28** (15): 80-86 [Wang KB, Shi WY, Shang Guan ZP. Effects of natural and artificial vegetation types on soil physicochemical properties in loess hilly region [J]. *Trans Chin Soc Agric Eng*, 2012, **28** (15): 80-86]
- 38 闫宝龙, 赵清格, 张波, 李雅璐, 赵鹏武, 张昊. 不同植被类型对土壤理化性质和土壤呼吸的影响[J]. 生态环境学报, 2017, **26** (2): 189-195 [Yan BL, Zhao QG, Zhang B, Li YL, Zhao PW, Zhang H. Effects of different vegetation types on soil physicochemical properties and soil respiration [J]. *Ecol Environ*, 2017, **26** (2): 189-195]
- 39 Kooch Y, Samadzadeh B, Hosseini SM. The effects of broad-leaved tree species on litter quality and soil properties in a plain forest stand [J]. *Catena*, 2017, **150**: 223-229
- 40 耿玉清, 余新晓, 孙向阳, 陈峻崎, 姚永刚. 北京八达岭地区油松与灌丛林土壤肥力特征的研究[J]. 北京林业大学学报, 2007 (2): 50-54 [Gen YQ, Yu XX, Shun XY, Chen JQ, Yao YG. Study on soil fertility characteristics of *Pinus tabulatus* and shrub in Badaling area of Beijing [J]. *J Beijing For Univ*, 2007 (2): 50-54]
- 41 高伟, 林媚媚, 黄雍容, 黄石德, 叶功富, 黄志群. 林分类型和环境因子对中国亚热带海岸沙地土壤微生物量的影响[J]. 资源与生态学报, 2020, **11** (5): 454-465 [Gao W, Lin MM, Huang YR, Huang SD, Ye GF, Huang ZQ. Effects of stand types and environmental factors on soil microbial biomass in sandy coastal areas of south subtropical China [J]. *J Resour Ecol*, 2020, **11** (5): 454-465]
- 42 AyresE, Steltze H, Berg S, Wallenstein MD, Simmons BL, Wall DH. Tree species traits influence soil physical, chemical, and biological properties in high elevation forests [J]. *PLoS ONE*, 2009, **4** (6): e5964
- 43 Chen X, Feng JG, Ding ZJ, Tang M, Zhu B. Changes in soil total, microbial and enzymatic CNP contents and stoichiometry with depth and latitude in forest ecosystems [J]. *Sci Total Environ*, 2022, **816**: 151583
- 44 Liu D, Huang YM, An SS, Sun HY, Bhople P, Chen ZW. Soil physicochemical and microbial characteristics of contrasting land-use types along soil depth gradients [J]. *Catena*, 2018, **162**: 345-353
- 45 张发会, 吴雪仙, 蔡小虎, 王琛. 川西亚高山3种不同林分

- 类型对土壤理化性质的影响[J]. 四川林业科技, 2015, **36** (3): 8-12 [Zhang FH, Wu XX, Cai XH, Wang C. Effects of three different stand types on soil physicochemical properties in western Sichuan subalpine region [J]. *J Shichuan For Sci Technol*, 2015, **36** (3): 8-12]
- 46 席丽, 李思瑶, 夏晓莹, 陈玉雯, 李林, 王杰, 马小龙, 米尔扎提·柯尼加里木阿丽耶·麦麦提, 王卫霞. 不同郁闭度天山云杉林土壤养分特征[J]. 新疆农业科学, 2023, **60** (9): 2216-2222 [Xi L, Li SY, Xia XY, Chen YW, Li L, Wang J, Ma XL, Maimaiti MK, Wang WX. Soil nutrient characteristics of spruce forest with different canopy density in Tianshan Mountains [J]. *Xinjiang Agric Sci*, 2023, **60** (9): 2216-2222]
- 47 Usharani KV, Roopashree KM, Naik D. Role of soil physical, chemical and biological properties for soil health improvement and sustainable agriculture [J]. *J Pharmacognosy*, 2019, **8** (5): 1256-1267
- 48 Zhang Q, Liu HY, Liang YY, Zhao YT, Wang ZC, Li YZ, Liu WC, Wang X, Yang GH, Ren CJ, Zhang W, Han XH. The multifunctionality of soil aggregates is related to the complexity of aggregate microbial community during afforestation [J]. *Elsevier*, 2024, **236**: 107737
- 49 林立文, 邓羽松, 王金悦, 杨钙仁, 蒋代华, 王玲. 南亚热带人工林种植对赤红壤团聚体分布及稳定性的影响[J]. 应用生态学报, 2020, **31** (11): 3647-3656 [Lin LW, Deng YS, Wang JY, Yang GR, Jiang DH, Wang L. Effects of plantation planting on the distribution and stability of aggregates in red and red soil in subtropical region [J]. *Chin J Appl Ecol*, 2020, **31** (11): 3647-3656]
- 50 蔡琳, 杨予静, 种玉洁, 袁义平, 曾翔宇, 姚和风, 陈初明, 李中强, 魏立飞, 余海燕. 亚热带退化森林不同恢复方式对土壤团聚体胶结物质及稳定性的影响[J]. 生态学报, 2023, **43** (9): 3689-3698 [Cai L, Yang YJ, Yuan YP, Zen XY, Yao HF, Chen CM, Li ZQ, Wei LF, Yu HY. Effects of different restoration methods on soil aggregate cementation and stability of subtropical degraded forests [J]. *Acta Ecol Sin*, 2023, **43** (9): 3689-3698]
- 51 Zhu G, Shang GZ, Deng L. Soil aggregate stability and aggregate-associated carbon and nitrogen in natural restoration grassland and Chinese red pine plantation on the Loess Plateau [J]. *Catena*, 2017, **149**: 253-260
- 52 Ma Y, Cheng XQ, Kang FF, Han HR. Dynamic characteristics of soil aggregate stability and related carbon and nitrogen pools at different developmental stages of plantations in northern China [J]. *J Environ Manag*, 2022, **316**: 115283
- 53 Xiao L, Huang YM, Zhao JF, Zhou JY, Abbas F. Effects of planting structure on soil water-stable aggregates, microbial biomass and enzyme activity in a catchment of Loess Plateau terraces, China [J]. *Appl Soil Ecol*, 2021, **159**: 103819
- 54 王冰, 张鹏杰, 张秋良. 不同林型兴安落叶松林土壤团聚体及其有机碳特征[J]. 南京林业大学学报(自然科学版), 2021, **45** (3): 15-24 [Wang B, Zhang PJ, Zhang QL. Soil aggregates and organic carbon characteristics of *Larix xingan* forest with different forest types [J]. *Nat Sci Ed*, 2021, **45** (3): 15-24]
- 55 李倩茹, 许中旗, 许晴, 黄选瑞, 纪晓林, 张兴锐, 习常新. 燕山西部山地灌木群落凋落物积累量及其持水性能研究[J]. 水土保持学报, 2009, **23** (2): 75-78 [Li QR, Xu ZQ, Xu Q, Huang XR, Ji XL, Zhang XR, Xi CX. Study on litter accumulation and water retention of shrub communities in western Yanshan Mountains [J]. *J Soil Water Conserv*, 2009, **23** (2): 75-78]
- 56 戴雯笑, 楼晨阳, 许大明, 张亚芬, 黄国栋, 骆争荣. 浙西南常绿阔叶林凋落物空间分布及其对土壤养分的影响[J]. 生态学报, 2021, **41** (2): 513-521 [Dai WX, Lou CY, Xu DM, Zhang YF, Huang GD, Luo ZR. Spatial distribution of litter and its effects on soil nutrients in evergreen broad-leaved forest in southwest Zhejiang Province [J]. *Acta Ecol Sin*, 2021, **41** (2): 513-521]
- 57 Shang WX, Jin C, Doug S, Detto M. Scale-dependent soil macronutrient heterogeneity reveals effects of litterfall in a tropical rainforest [J]. *Plant Soil*, 2015, **391**: 51-61
- 58 肖盛杨, 张蓝月, 陈敬忠, 陆祥, 李海波, 廖小锋, 谢元贵. 梵净山不同海拔土壤团聚体稳定性及影响因素[J]. 水土保持研究, 2024, **31** (3): 160-168 [Xiao SY, Zhang LY, Cheng JZ, Lu X, Li HB, Liao XF, Xie YG. Stability and influencing factors of soil aggregates at different altitudes in Fanjing Mountain [J]. *Res Soil Water Conserv*, 2024, **31** (3): 160-168]
- 59 吴际, 杨光, 韩雪莹, 温雅琴, 杨溢文, 李文龙, 刘一. 不同人工林对奈曼沙区土壤团聚体的影响[J]. 干旱区研究, 2022, **39** (6): 1832-1841 [Wu J, Yang G, Han XY, Wen YQ, Yang YW, Li WL, Liu Y. The effect of different artificial forests on soil aggregates in the Naiman sand area [J]. *Arid Zone Res*, 2022, **39** (6): 1832-1841]
- 60 陈龙池, 廖利平, 汪思龙, 肖复明. 根系分泌物生态学研究[J]. 生态杂志, 2002, **21** (6): 57-62 [Chen LC, Liao LP, Wangn SL, Xiao FM. Ecological research on root exudates [J]. *J Ecol Sci*, 2002, **21** (6): 57-62]
- 61 孙兴宇, 王庆贵. 砍伐干扰背景下的森林土壤球囊霉素动态研究进展[J]. 国际生态学期刊, 2021, **7** (15): 435 [Sun XY, Wang QG. Research progress on the dynamics of glomalin in forest soils under disturbance from logging. *Intern J Ecol*, 2021, **7** (15): 435]
- 62 王兴, 钟泽坤, 张欣怡, 吴少君, 卢绪巧, 杨改河, 任成杰, 韩新辉. 长期撂荒恢复土壤团聚体组成与有机碳分布关系[J]. 环境科学, 2020, **41** (5): 2416-2424 [Wang X, Zhong ZK, Zhang XY, Wu SJ, Lu XQ, Yang GH, Ren CJ, Han XH. Relationship between soil aggregate composition and organic carbon distribution after long-term abandonment [J]. *Environ Sci*, 2020, **41** (5): 2416-2424]
- 63 Bissonnais YL, Prieto I, Roumet C, Nespoulous J, Metayer J, Villatoro M, Stokes A. Soil aggregate stability in Mediterranean and tropical agro-ecosystems: effect of plant roots and soil characteristics [J]. *Plant Soil*, 2018, **424**: 303-317