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杉木（Cunninghamia lanceolata）连栽地力退化和杉阔混交林的土壤改良作用

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摘要 收集了有关杉木连栽的地力退化和连栽杉阔混交林的对比研究文献，并进行分析表明，杉阔混交林土壤容重平均比杉木纯林降低 5% 连栽杉木人工林随代数的增加呈现容重变大的趋势，2 代比 1 代平均增加 6% ，3 代比 2 代平均增加 9%。这种容重的变化使看似具有可比性的对比样地之间失去了可比性，可能导致对杉木连栽人工林地力退化和杉阔混交林的土壤改良作用的评价产生偏差。通过对这种容重变化产生的影响进行校正，对杉木连栽人工林地力退化和杉阔混交林的土壤改良作用进行了重新评估。结果表明，采用固定深度采样的杉阔混交林与对照的杉木纯林、多代连栽杉木人工林不同代次间土壤有机碳和全氮贮量的相对变化均出现不同程度的低估现象。固定深度采样时，与对照的纯林相比，杉阔混交林对土壤的改良作用被低估，土壤有机碳和全氮贮量的相对变化平均低估 6% 和 5% 杉木连栽引起的地力退化也被低估，土壤有机碳和全氮贮量从 1 代到 2 代分别低估 5% 和 7% ，从 2 代到 3 代分别低估 7% 和 8%。经 t-检验表明，杉阔混交林与对照的杉木纯林、多代连栽杉木人工林不同代次间土壤有机碳和全氮贮量的相对变化在土壤容重影响校正前后有明显差异（$p = 0.05$）。

关键词 容重影响 杉木 连栽 退化 混交

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The assessment of soil degradation in successive rotations of Chinese fir plantation and the soil amelioration of mixed plantation of Chinese fir and broad-leaved

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Abstract: Soil degradation in the successive rotations of Chinese fir（*Cunninghamia lanceolata*）and the soil improvement of the mixed plantations of Chinese fir and broad-leaved species have been widely reported. However, changes in soil bulk density are usually reported at the same times. We collected soil bulk density, soil organic carbon and nitrogen data from paired site studies of successive rotations of Chinese fir and mixed plantations. Our analyses found that soil bulk density of mixed plantation was 5% smaller than that of pure Chinese fir plantation, and the soil bulk density of Chinese fir plantation increased by 6% and 9% from the 1st rotation to the 2nd rotation, and from the 2nd rotation to 3rd rotation, respectively. The changes in soil bulk density may cause significant errors when assessing soil fertility among different rotations and

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planting models (pure versus mixed plantations), because the comparability of the paired sites was lost. In this paper, we tried to re-assess the changes in soil organic carbon and nitrogen among different successive rotations of Chinese fir plantations and mixed plantation of Chinese fir and broad-leaved trees, by eliminating the impacts of soil bulk density. Results showed that soil amelioration of mixed plantations and the soil degradation of successive rotations of Chinese fir plantation were underestimated. Comparing to Chinese fir pure plantation, relative changes of soil organic carbon and total nitrogen stocks in mixed plantations were underestimated by 6% and 5%, respectively. Relative changes of soil organic carbon and total nitrogen stocks were significantly underestimated by 5% and 7% from the first rotation to the second rotation, and 7% and 8% from the second rotation to the third rotation, respectively ($p = 0.05$).

Key Words: changes in soil bulk density; Chinese fir; successive rotation; soil degradation, mixed plantation

土壤中某元素的贮量通常采用单位面积或单位土体元素的量来表达，尤其是前者使用的较多。为此需要通过土壤容重将分析得到的元素含量转化为单位面积或单位土体元素的量。但是一些土地利用变化和林业活动会引起土壤容重的变化。如森林转化为农地和牧地平均使土壤容重分别增加 16.9% 和 9.5%[1]。这种变化给准确估计土壤中元素贮量带来较大的困难。如果对比样地之间容重有明显的差异，而采样深度相同，则土壤容重的变化，会使估计的元素的量被高估或低估，与其度量表达方式有关[1]。例如，如果土壤碳以单位面积碳贮量来表示，容重大的土壤的碳贮量将被高估，或者容重小的土壤的碳贮量将被低估，因为在同一土壤深度内，容重越大，包含的土壤质量越高。相反，如果以单位土体的碳贮量表示，容重大的土壤的碳量将被低估或容重小的土壤的碳量将被高估[2]。实际上，容重的变化使看似具有可比性的对比样地之间失去了可比性，即相同采样深度内的土体质量不同。

杉木（*Cunninghamia lanceolata* (Lamb.) Hook.）作为我国南方亚热带地区特有的优良速生乡土用材树种，面积达 1239.1 万 hm^2，占全国人工林面积 26.55%[3]。过去几十年来，对杉木人工林林地养分循环及其与管理措施的关系进行了大量的研究报道，如杉阔混交林与杉木纯林土壤肥力的比较、杉木连栽人工林地力衰退等，而且均采用固定深度的采样方式，忽视了土壤容重的变化对土壤碳氮贮量的影响及影响程度[4~6]。为此，本文通过对土壤容重的影响进行校正，以土壤有机碳和全氮贮量的变化为例，研究分析容重的影响程度。

1　数据来源

收集已发表或公开出版的杉木人工混交林及多代连栽人工林土壤采样深度、土壤容重、土壤有机质（或有机碳）含量和全氮含量的数据。对收集的数据精心筛选，本研究分析只采用来自对比样地（同立地条件、同树种、同林龄）的测定数据，包括杉木人工混交林对比研究文献 53 篇共 90 组数据[4~56]，不同代数杉木人工林对比研究文献 15 篇共 20 组数据[57~71]。

2　校正方法

2.1　土壤有机碳和全氮贮量的计算

土壤有机碳贮量利用采样深度、土壤容重和有机质含量来计算[72]：

$$SOC = \frac{\sum_{i=1}^{n} SOM_i \cdot D_i \cdot BD_i}{1.724} \tag{1}$$

式中，SOC 为土壤有机碳贮量（t·hm^{-2}）；n 为采样层数，SOM_i 为第 i 层土壤有机质含量（%）；D_i 为第 i 层土壤厚度（cm）；BD_i 为第 i 层土壤平均容重（g·cm^{-3}）；1.724 为土壤有机质含量转化成有机碳的换算系数。土壤全氮贮量亦采用上式形式进行计算，将土壤有机质含量换成全氮含量，同时去掉换算系数。

不同土壤的元素含量存在着差异，采样深度与采样方法也不尽相同，所以很难比较根据不同文献研究数据计算出的元素贮量的绝对变化。因此，本文采用对比样地间元素贮量的相对变化来分析校正前后土壤元素贮量的变化。

2.2　土壤容重影响的校正方法

采用 Gifford 等[3]的计算同等质量下土壤元素贮量的方法，即首先计算每一层的土体质量（t·hm^{-2}）和土壤元素贮量（t·hm^{-2}），确定最大的累积土体质量（标准土体质量），则对累积土体质量较小的样地，做累积土体质量与累积土壤元素贮量的相关曲线，然后外推至标准土重时的土壤元素贮量。

当采样层数较少时，累积土体质量（$\sum M$）与累积元素贮量（$\sum Stock$）成线性关系：

$$\sum stock = a + b \cdot \sum M \quad (1)$$

式中，a 和 b 为参数。然而，随着采样层数的增加，累积土重与累积元素贮量的关系可能会呈现明显的非线性关系，则可以通过对累积元素贮量取对数的方式降低曲线的曲率，再用上述方法外推得到标准土体质量时的土壤某种元素的贮量。

对分层采样得到的每层土壤容重，采用整个采样剖面的加权平均容重（即以每个采样层的厚度为权）来比较对比样地间容重的相对变化。

3　校正前后杉木人工林碳氮贮量的变化

3.1　杉木混交林

3.1.1　土壤容重的变化

杉阔混交林的平均土壤容重总体上比杉木纯林的要低，少部分数据（$n = 12$）出现反常，杉阔混交林容重平均比杉木纯林降低 5.16% ±1.34%（$n = 90$）（图 1）。

3.1.2　碳氮贮量的变化

校正前杉阔混交林土壤有机碳和全氮贮量分别比杉木纯林提高 12.32% ±7.96%（$n = 56$）和 9.14% ±5.44%（$n = 56$）；剔除容重的影响后分别提高 18.02% ±8.75%（$n = 56$）和 13.88% ±5.58%（$n = 56$）。因此，固定深度采样时，与纯林对照样地相比，杉阔混交林对土壤的改良作用被低估，土壤有机碳和全氮贮量的相对变化平均低估了 5.70% ±2.17%（$n = 56$）和 4.75% ±2.25%（$n = 56$）（图 2）。

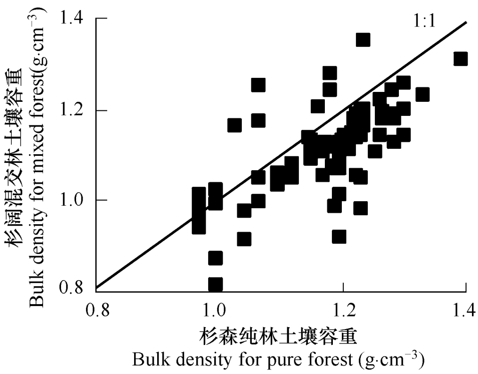

图 1　杉阔混交林和杉木纯林土壤容重的变化

Fig. 1　Changes in bulk density for Chinese fir pure and mixed plantations

采用配对数据的 t-检验表明，单侧 P 值均小于显著性水平 α（0.05），为此拒绝 H_0，即容重影响校正前后杉阔混交林和纯林土壤有机碳和全氮贮量的相对变化有明显差异（表 1）。

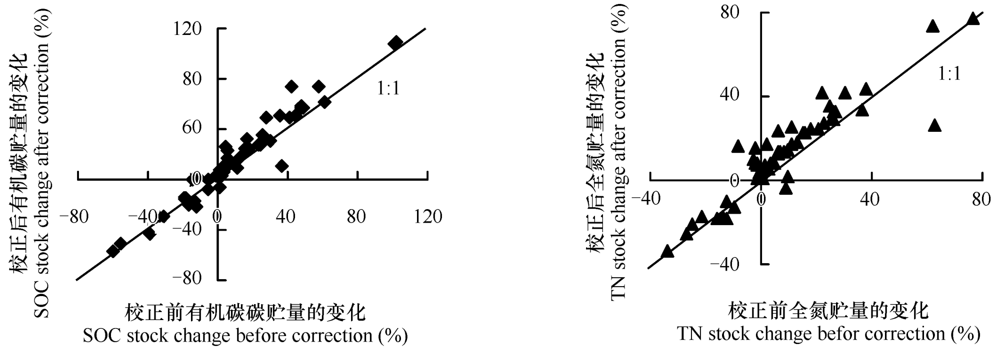

图 2　校正前后杉阔混交林和杉木纯林土壤有机碳和全氮贮量的变化

Fig. 2　Changes in soil organic carbon（SOC）and total nitrogen（TN）stocks for Chinese fir mixed and pure plantations before and after soil bulk density correction

3.2 多代连栽杉木人工林

3.2.1 土壤容重的变化

随着连栽代数的增加，土壤容重出现不同程度的增加，2 代比 1 代平均增加 6.42% ±5.62% (n = 19)，3 代比 2 代平均增加 8.83% ±5.81% (n = 12)（图 3）。

表 1 校正前后土壤有机碳和全氮贮量变化的差异性检验

Table 1 Significance tests of changes in SOC and TN stocks before and after correction

项目 Item		平均数 Mean	方差 Variance	零假设 H_0 Null hypothesis	自由度 Degree of freedom	t 统计量 Test statistic	单侧 P 值 One-sided P value	显著性水平 α Significance level
SOC	校正后 After correction	18.02	1116.26	0	55	5.1631	0.000	0.05
	校正前 Before correction	12.32	923.75					
TN	校正后 After correction	13.88	454.26	0	55	4.1371	0.000	0.05
	校正前 Before correction	9.14	431.66					

3.2.2 碳氮贮量的变化

校正前 2 代土壤有机碳和全氮贮量分别比 1 代低 6.33% ±5.76% (n = 17) 和 2.03% ±4.26% (n = 16)，3 代分别比 2 代低 11.15% ±15.69% (n = 9) 和 14.72% ±11.67% (n = 8)。校正后 2 代土壤有机碳和全氮贮量分别比 1 代低 11.01% ±4.73% (n = 17) 和 8.57% ±4.17% (n = 16)，3 代分别比 2 代低 17.90% ±12.80% (n = 9) 和 23.03% ±8.54% (n = 8)。所以，固定深度采样时，杉木连栽土壤有机碳和全氮贮量的降低程度被低估，即连栽引起的地力退化被低估，其中从 1 代到 2 代分别低估了 4.68% ±2.24% (n = 17) 和 6.54% ±2.69% (n = 16)，从 2 代到 3 代分别低估了 6.75% ±5.30% (n = 9) 和 8.32% ±5.78% (n = 8)（图 4）。

采用 t-检验表明，单侧 P 值均小于显著性水平 α (0.05)，为此拒绝 H_0，即容重影响校正前后多代连栽杉木人工林土壤有机碳和全氮贮量的相对变化有明显差异（表 2）。

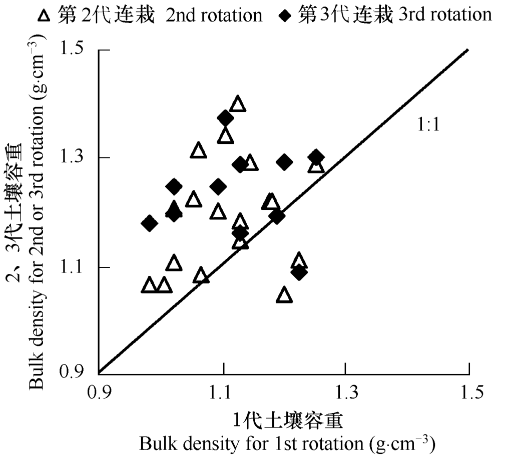

图 3 多代连栽杉木人工林土壤容重的变化

Fig. 3 Changes in soil bulk density for successive rotations of Chinese fir plantations

4 结论与讨论

杉阔混交林林地的平均土壤容重平均比杉木纯林降低 5.16% ±1.34%；随着连栽代数的增加，土壤容重出现不同程度的增加，2 代比 1 代平均增加 6.42% ±5.62%，3 代比 2 代平均增加 8.83% ±5.81%。利用上述土壤容重影响的校正法，消除土壤容重的影响后，结果表明，采用固定深度采样的杉阔混交林和对照的杉木纯林、多代连栽杉木人工林不同代次间土壤有机碳和全氮贮量的相对变化均出现不同程度的低估现象。固定深度采样时，与对照的纯林相比，杉阔混交林对土壤的改良作用被低估，土壤有机碳和全氮贮量的相对变化平均低估 5.70% ±2.17% 和 4.75% ±2.25%；杉木连栽引起的地力退化也被低估，土壤有机碳和全氮贮量从 1 代到 2 代分别低估 4.68% ±2.24% 和 6.54% ±2.69%，从 2 代到 3 代分别低估 6.75% ±5.30% 和 8.32% ±5.78%。经 t-检验，杉阔混交林和对照的杉木纯林、多代连栽杉木人工林不同代次间土壤有机碳和全氮贮量的相对变化在土壤容重影响校正前后有明显差异 (P = 0.05)。

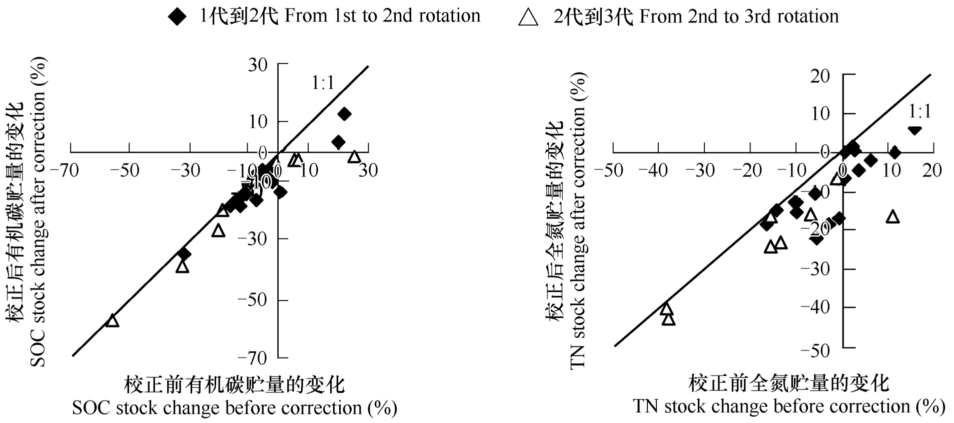

图 4　校正前后多代连栽杉木人工林土壤有机碳和全氮贮量的变化

Fig. 4　Changes in SOC and TN stocks for successive rotations of Chinese fir plantations before and after correction

表 2　校正前后土壤有机碳和全氮贮量变化的差异性检验

Table 2　Significance tests of changes in SOC and TN stocks before and after correction

项目 Item			**平均数** Mean	**方差** Variance	**零假设** H_0 Null hypothesis	**自由度** Degree of freedom	t **统计量** Test statistic	**单侧** P **值** One-sided P value	**显著性水平** α Significance level
SOC	**从 1 代到 2 代** From 1st rotation to 2nd	**校正后** After correction	−11.01	98.81	0	17	−4.2248	0.000	0.05
		校正前 Before correction	−6.33	146.73					
	从 2 代到 3 代 From 2nd rotation to 3rd	**校正后** After correction	−17.90	383.86	0	8	−2.4979	0.019	0.05
		校正前 Before correction	−11.15	576.82					
TN	**从 1 代到 2 代** From 1st rotation to 2nd	**校正后** After correction	−8.57	72.57	0	16	−4.9168	0.000	0.05
		校正前 Before correction	−2.03	75.61					
	从 2 代到 3 代 From 2nd rotation to 3rd	**校正后** After correction	−23.03	152.03	0	7	−2.8217	0.013	0.05
		校正前 Before correction	−14.72	283.76					

目前，土壤采样方法可分为两类，一是依据土体质量决定采样深度的思想进行土壤采样[4,75]，即累计质量坐标法（Cumulative Mass Coordinate）[3,76~81]，二是按某一固定深度进行采样，其中以后一种采样方法的应用较广，主要因为这种采样方法比较现实可行，操作方便，但也会由于对比样地间土壤容重的变化导致计算的结果被高估或低估。与固定深度采样相比，累计质量坐标法操作步骤比较繁琐，实际应用有一定的困难。因此，可对固定深度采样的结果进行修正[82]，消除土壤容重的影响，增加某一固定深度内对比样地土壤元素贮量的可比性，以期更准确的反映对比样地某一深度内元素贮量的变化。这种做法与对比样地在某一固定采样

深度内土壤元素贮量变化的比较一致。

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