学校编码：10384　　　　分类号______密级______

学　　号：21720080150394　　　　UDC______

厦门大学

博　士　学　位　论　文

沿海防护林短枝木麻黄单宁及其养分保存机制

Tannins and Nutrient Conservation Strategies *of* *Casuarina equisetifolia* in Coastal Protection Forest

张尚炬

指导教师姓名：林光辉　　教授

专 业 名 称：植　　物　　学

论文提交日期：2011 年 04 月

论文答辩时间：2011 年 06 月

学位授予日期：2011 年　　月

答辩委员会主席：____________

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2011 年　　月

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摘　要

短枝木麻黄是滨海沙地上重要的防护树种。本研究以福建东山和惠安沿海防护林短枝木麻黄为对象，解析了短枝木麻黄不同部位单宁的结构，系统探讨了两个群落类型（短枝木麻黄纯林和短枝木麻黄厚荚相思混交林）以及不同发育阶段短枝木麻黄养分保存策略的差异；在短枝木麻黄正常和衰败林中进行凋落小枝分解实验，阐明凋落小枝分解过程中单宁和养分水平的动态变化，并运用数学模型拟合凋落小枝的分解规律，分析了单宁与养分之间的关系。研究结果表明：

（1）运用高效液相色谱（HPLC）和 MALDI-TOF 质谱技术分析了短枝木麻黄小枝、树皮和细根单宁的组成成分，结果表明，短枝木麻黄小枝单宁主要由棓酸和鞣花酸组成，而树皮和细根提取物的组成成分主要由儿茶素、儿茶素衍生物、表儿茶素及表儿茶素衍生物组成；通过 MALDI-TOF 质谱分析树皮和细根缩合单宁黄烷-3-醇结构单元组成类型为原天竺葵定、原花青定及原翠雀定，但主要由原花青定构成，树皮和细根缩合单宁的链长分别为 DP3 到 DP13 和 DP3 到 DP15。

（2）以短枝木麻黄纯林和木麻黄厚荚相思混交林为对象，从单宁和养分内吸收相结合的角度，系统探讨纯林和混交林之间养分保存策略的差异。成熟小枝的总酚（TP）和缩合单宁（CT）含量在纯林和混交林之间的差异均不显著，两种林分类型短枝木麻黄成熟小枝可溶性缩合单宁（ECT）和纤维素结合缩合单宁（FBCT）在湿季的含量均低于干季，而蛋白质结合缩合单宁（PBCT）则表现为干季高于湿季；纯林中成熟小枝的氮磷含量均显著高于混交林；在纯林和混交林中，成熟小枝的 N:P 介于 16.32±0.42～28.23±0.97 之间，均高于 16，表现为磷限制；混交林中磷内吸收率高达 80%左右，显著高于纯林（50%左右），表明在磷限制生境中，相对于纯林，混交林具有更好的磷保存机制。

（3）探讨了不同发育阶段短枝木麻黄营养保存机制的差异。幼龄林（5a）成熟小枝中的 TP、ECT、总缩合单宁（TCT）含量及蛋白质结合能力（PPC）显著高于成熟林（21a）和衰老林（38a）；随着林分发育，成熟小枝中 N 含量显著升高，成熟小枝中的 P 含量变化呈现幼龄林≈成熟林>衰老林；成熟小枝中 N:P 也随着林分发育而升高，均大于 20，存在磷限制；不同发育阶段短枝木麻黄小枝氮内吸收率均在 50%左右，且衰老林显著低于幼龄林和成熟林，而磷内吸收率

均高于 70%，成熟林分中（78.08±1.96%）显著高于幼龄和衰老林，表明短枝木麻黄的养分保存机制随着林分发育阶段的变化而改变。

（4）从单宁与养分相结合的角度探讨细根和成熟小枝功能的差异性。短枝木麻黄成熟小枝的 TP 含量显著高于细根，各林龄短枝木麻黄成熟小枝 ECT、PBCT 和 TCT 的含量以及 PPC 均显著高于细根，而 FBCT 含量则显著低于细根；不同林龄短枝木麻黄成熟小枝 N 含量均显著高于细根，细根 P 含量随着林分发育而升高，但各林龄和季节的磷含量均显著低于成熟小枝。

（5）正常林和衰败林凋落小枝的分解规律相似。经过 12 个月的分解，其残留率均在 40%左右，但衰败林凋落小枝的年残留率显著低于正常林；TP 和 ECT 含量以及 PPC 在分解前期均下降了 85%以上，后趋于平缓，与此相反， FBCT 含量随着分解时间的推移而升高；正常林凋落小枝中氮含量从分解初期的 12.09±0.39 mg g^{-1} 上升到 20.76±0.51 mg g^{-1}，磷则从 0.20±0.01 mg g^{-1} 上升到 0.36±0.01 mg g^{-1}，而衰败林氮从分解初期的 11.78±0.18 mg g^{-1} 上升到 22.32±0.95 mg g^{-1}，磷则从 0.20±0.01 mg g^{-1} 上升到 0.63±0.02 mg g^{-1}。

（6）采用数学模型拟合了短枝木麻黄小枝分解失重率与各基质质量（特别是单宁）之间的关系，得到了最优回归模型，并分析了单宁与养分含量之间的相关关系。正常林和衰败林凋落小枝分解的半衰期分别为 0.78a 和 0.71a，分解 95%的时间分别为 3.36a 和 3.05a；采用修正的 Olson 指数衰减模型对正常林和衰败林中凋落小枝分解残留率和时间进行模拟，正常林和衰败林中凋落小枝的 Olson 指数衰减模型 R^2 分别为 0.9691 和 0.9838，均达到显著水平（$P<0.01$），说明该模型能够较好的预测凋落小枝的分解动态；通过探讨短枝木麻黄凋落小枝分解失重率与各基质质量之间的关系，建立了失重率与单宁和养分之间关系的最优回归模型（正常林：$y=-45.9493-1.4574x_1+0.1940x_3+1.2448x_4+0.6609x_5$，$P<0.001$；衰败林：$y=-15.1441-1.5551x_1-27.2372x_2+0.1858x_3+0.5761x_5+0.5169x_7$，$P<0.001$）；对凋落小枝分解过程中单宁和养分之间的关系的相关分析表明，在正常林中，磷含量与 TP 含量以及氮含量与 PBCT 含量之间具有显著相关性，而衰败林中碳氮比与 TP 含量具有显著正相关关系。

关键词：短枝木麻黄；单宁；凋落物分解；数学模型

Abstract

Casuarina equisetifolia is an important wind break shelter tree in coastal sandy areas. This study on *Casuarina equisetifolia* in Dongshan and Huian of Fujian province, discussed the differences of nutrient conservation strategies between two communities (mono-specie forests and mixed forests with *A. crassicarpa*) and among different development stages of *C. equisetifolia*. The changes in tannins and nutrient contents in litters of *C. equisetifolia* during decomposition in normal and decline forests were studied and then fitted wife mathematic models to discuss decomposition pattern of litters, as well as analyze the relationship between tannins and nutrients. The results showed as follows:

(1) The structures of condensed tannins in the branchlets, stem barks and fine roots of *Casuarina equisetifolia* were identified by MALDI-TOF MS and HPLC analyses for the first time. The tannins in the branchlets consist predominantly of gallic acid and ellagic acid, while the condensed tannins in the stem barks and fine roots were composed predominantly of catechin, catechin derivatives, epicatechin and epicatechin derivatives. The condensed tannins in the stem barks and fine roots consisted predominantly of procyanidin combined with prodelphinidin and propelargonidin, and the epicatechin was the main extension unit. The chain lengths of condensed tannins from stem barks and fine roots were from DP3 to DP13 and DP3 to DP15, respectively.

(2) The tannins and nutrient contents in mature branchlets were studied to compare the differences of nutrient conservation strategies between mono-specie and mixed forests with *Acacia crassicarpa*. The TP and CT contents in mature branchlets between mono-specie and mixed forests were significantly different. The ECT and FBCT contents in mature branchlets were significantly lower in wet season than in dry season both in two forest types, while the PBCT contents were significantly higher in wet season than in dry season. The N and P concentrations were

significantly higher in mono-specie forests than in mixed forests. N:P ratios of mature branchlets were > 16 (16.32±0.42～28.23±0.97), indicating both mono-specie and mixed forests were P-limited. PRE in mixed forests was about 80%, which was significantly higher than that in mono-specie forests around 50%, indicating that nutrient conservation strategies were more efficiency in mixed forests than in mono-specie forests under P limitation.

(3) The changes of nutrient conservation strategies of *C. equisetifolia* were discussed during stand development for the first time. TP, ECT, TCT contents and PPC of mature branchlets were significantly higher in juvenile forest (5a) than those in mature forest (21a) and senescent forest (38a). N concentrations in mature branchlets significantly increased during stand development. P concentrations in mature branchlets showed juvenile ≈ mature > senescent. N: P ratios of mature branchlets also significantly increased during stand development and were all above 20, indicated that 3 forest types of *C. equisetifolia* were all P-limited. NRE were about 50% in all forest types of *C. equisetifolia*, and the lowest was in senescent phase; PRE were >70% in all phases, and mature stage had the highest PRE (78.08±1.96%). The studies showed that nutrient conservation strategies of *C. equisetifolia* had changed during stand development.

(4) The tannins and nutrient contents were studied in conjunction to discuss the differences of functions between fine roots and mature branchlets for the first time. The TP contents in mature branchlets were significantly higher than those in fine roots. The ECT, PBCT, TCT contents and PPC of mature branchlets were significantly higher than fine roots in all forest types, while the FBCT contents increased during stand development. The N contents in mature branchlets were significantly higher than those in fine roots. The P contents in fine roots increased during stand development but all significantly lower than those in mature branchlets.

(5) The decomposition patterns of litters in normal forests were similar with decline forest. Retention rates were around 40% after 12 months decomposing, and the retention rate in decline forests were significantly lower than that in normal forests. The TP and ECT contents were dropped over 85% at the beginning of decomposition,

and then keep stable. In contrast, the FBCT contents increased during litter decomposition. During decomposition, N contents increased from 12.09±0.39 mg g^{-1} to 20.76±0.51 mg g^{-1}, and P contents from 0.20±0.01 mg g^{-1} to 0.36±0.01 mg g^{-1} (normal forests), while in decline forests, N contents increased from 11.78±0.18 mg g^{-1} to 22.32±0.95 mg g^{-1}, and P contents from 0.20±0.01 mg g^{-1} to 0.63±0.02 mg g^{-1} after 12months decomposition. N:P ratios of both normal and decline forests were significantly declined during decomposition.

(6) The lost weight rates of litters and various substrate contents (especially tannins) of *C. equisetifolia* were studied, fitted those utilizing mathematic models and got the optimum regression model for the first time. We also analysis the relationship between tannins and nutrient concentration during decomposition. Decomposition studies using litter bags suggested that the time required for the loss of half of the initial dry weight (t_{50}) in normal and decline forests were 0.78a and 0.71a; and t_{95} were 3.36a and 3.05a, respectively. The corrected models of exponential decay by Olson were used to imitate the time and retention rate of litters. In normal and decline forests R^2 were 0.9691 and 0.9838, respectively, both were at significant levels, indicated the models can forecast the decomposition dynamic well. The lost weight rates of litters and various substrate contents of *C. equisetifolia* were discussed relatively to set up a mathematical model of the best regression equation(normal forest: $y = -45.9493 - 1.4574x_1 + 0.1940x_3 + 1.2448x_4 + 0.6609x_5$, $P<0.001$; decline forest: $y = -15.1441 - 1.5551x_1 - 27.2372x_2 + 0.1858x_3 + 0.5761x_5 + 0.5169x_7$, $P<0.001$). Correlation analysis between tannins and nutrient contents during decomposing showed that there were significant correlations between P and TP contents as well as N and PBCT contents in normal forests, while in decline forests, C:N ratio had a significant positive relationship with TP contents.

Keywords: *Casuarina equisetifolia*; Tannin; Litter decomposition; Mathematical model

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