STUDY ON THEORETICAL GROWTH EQUATION AND DIAMETER STRUCTURE MODEL

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内 容 简 介

本书系统阐述了理论生长方程与林分直径结构模型的研究及其进展。本书共分 6 章，围绕杉木人工林林分直径结构模拟和预测、优势高生长模拟及其多形地位指数方程的研制、Fuzzy 分布函数的应用、直径动态变化规律和密度效应的关系等进行了论述，从方程-林分匹配性这一全新角度，揭示了理论生长方程的解析性质和林分结构的实质特点，以期进一步推动理论生长方程及林分直径结构模拟和预测的研究，为杉木人工林的定向培育提供了科学可靠的理论和实践依据。

本书可供林学工作者和高校相关专业的师生学习、使用。

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前　言

森林是地球生态系统的主体，也是人类利用木材的唯一来源，森林的可持续发展决定着人类社会和林业的可持续发展。当前，人类面临着环境与发展两大问题，环境的日益恶化严重阻碍了社会、经济的发展，保护天然林资源已成为全人类共同的心愿和行动。但是，这里有个问题，天然林得到保护，必然导致人类木材需求来源的大量减少，如何解决这一问题，使自然资源保护与木材利用兼顾、协调起来，人们已把希望的目光越来越多地投向了迅速发展的人工林事业。

我国出于保护环境、实现可持续发展的目的，在21世纪伊始，启动了耗资巨大的天然林保护工程。与此同时，为保证工程的顺利实施和积极解决我国木材市场供需存在的巨大缺口，国家林业局在整合后的六大林业重点工程中提出重点地区以速生丰产用材林为主的林业产业基地建设工程。人工林的大力发展可谓大势所趋。

杉木[*Cunninghamia lanceolata*(Lamb.) Hook.]是7500万年前遗留的活化石，它是我国亚热带温暖湿润地区特有的优良速生针叶树种，素以分布广、生长快、繁殖易、病虫害少、材质好、产量高、栽培历史悠久而闻名中外。在我国，杉木在速生丰产用材林中比重极大。据1987年统计，全国杉木人工林面积有11 929.6万亩，蓄积量达27 069.8万立方米，占全国造林面积的1/10。杉木为我国主要用材林树种，杉木人工林的发展有其重要的战略意义。建国以来，由于立地评价、良种选育、密度控制等方面研究成果的广泛推广应用，有力地推动了杉木人工林栽培技术的进步。

20世纪80年代以来，有关杉木造林经营技术的科学研究工作成绩卓著。“六五”、“七五”、“八五”、“九五”期间，中国林业科学研究院主持的“杉木产区区划、立地类型划分及立地评价的研究”、“杉木人工林集约栽培技术研究”、“杉木建筑材优化栽培模式研究”和“杉木建筑材树种遗传改良及大中径材培育技术研究”等国家攻关专题项目，在江西、福建等地建立了规模较大的试验林，这些试验林按照我国杉木主要产区设立，分别代表东部的武夷山区、南部的南岭山地、西部的雪峰山区及中北部的武功山区。这些试验林由于设计合理、保存较好且经过连续而长期的观测，拥有无比珍贵的研究价值，值得不断探索利用。本书的编写就是以这些固定试验地数据资料以及所收集整理的更早期杉木临时样地调查资料为基础撰写而成。

人工林经营的目的就是要达到定向、速生、丰产、优质、稳定及高效，而要实现这一目的，就必须清楚地了解人工林树种的生长特性及生长过程。目前国际

上对此方面研究的一个重要方向是利用模型描述复杂的林木群体生长规律，通过模拟探索多变条件下的林分生长动态，从而预测林分生长及经营措施对林木生长的影响，制定优化经营方案，实现林分的最优经营管理。林分直径结构是林分结构的基本规律之一，是估算林分材种出材量、确定合理经营周期和准确评定生产力的基础，具有其重要的理论和实践意义，精确地模拟和预测林分直径结构是进行营林效果评价的前提，利用理论生长方程构建林分直径结构模型是现代森林经营的先进手段。本书共分 6 章，重点论述了理论生长方程和林分直径结构模型的研究进展、杉木人工林优势高生长模拟及其多形地位指数方程的研制、杉木人工林林分直径结构模拟和预测、Fuzzy 分布函数在杉木人工林林分直径结构上之应用研究、林分密度对杉木人工林直径结构动态变化的影响等方面的研究内容，旨在推动理论生长方程及林分直径结构模拟和预测的研究，并为杉木人工林的定向培育提供科学可靠的理论及实践依据。本书的编写得到了中国林业科学研究院林业研究所童书振先生的关心和指点，谨于付梓之际表示深深的感谢！

限于作者的水平，书中肯定有不少错误和不当之处，敬请读者和同行批评指正。

张建国　段爱国

2003 年 12 月

Abstract

Chapter 1

Theoretical equations can scientifically and reasonably describe the growth and distribution of forest. This chapter relatively and comprehensively elaborates the origin, present situation of application and development, complicated relationship among theoretical equations, in order to make people have a clear knowledge of theoretical equations and scientifically use them, and make application fields wide to promote the further development of theoretical equations. The modeling and prediction of stand diameter structure are of important value in theoretical and practical study, have broadly applied prospects in the field of forest management and forest resource, and even are the nucleus of stand growth model. This chapter, from two aspects, relatively and thoroughly discussed the internal and external study situation about the modeling and prediction of stand diameter structure model, summarily indicated that the study on stand diameter structure model is unfolded around two methods—parametric approach and nonparametric approach, mainly introduced a few main modeling and prediction methods such as theoretical equation method and *k*-nearest neighbor estimation method, and a few common evaluation and prediction methods such as percentile method and regression method.

Chapter 2

The study on polymorphic dominant height models and polymorphic site index equations is always the emphasis and difficulty in the field of forest growth model. This chapter adopted difference methods first to build the polymorphic site index equations based on six theoretical growth equations such as Korf, and then proceed to explore their polymorphic meaning and analyse their modeling qualities, finally reach several main conclusions: ① Based on theoretical growth equations, through difference methods the polymorphic dominant equations can be built on a good biological basis; ② The inflection points of theoretical growth equations have most important effect on their modeling precision of dominant height growth; ③ Difference equations have better modeling effect on the Statistics at a wider range of region; ④ The polymorphic

dominant height equations, such as the two-parameter polymorphic forms of Korf, Richards, Weibull and three-parameter polymorphic form of Sloboda, show higher modeling precision; ⑤ The entirely reasonable polymorphic site index equations can be built when excellent polymorphic dominant height growth models are adopted.

Chapter 3

It is analysed and explored that the mathematical characteristics of six growth equations and their theoretical basis are applied to modeling of stand diameter structure. The long-term observation data of permanent sample plots of China fir are sorted. The six equations are applied to modeling of stand cumulative diameter distribution in order to master modeling parameters and properties of every growth equation in the field of diameter structure. The results show that Richards at most time presents a kind of Logistic, and Weibull has its inflection point. Except for Mitscherlich function, modeling precision of every growth function is very high. The optimum rate of Richards, Weibull, Logistic, Gompertz, Mitscherlich and Korf successively decrease. The whole precision of Richards, Logistic, Weibull, Gompertz, Korf and Mitscherlich successively decrease. The relative growth rate of functions with index of variable has the higher precision than those with power of variable. Equations with three parameters have the higher precision than those with two.

For growth equations, it is significant to explore the sense of their parameters. With the highest precision in the above-mentioned equations, Richards was selected to develop this study. The results of stepwise regression show that parameter k is affected by age, site index, average diameter and density remarkably, and their affection decreases in turn. The stand factors that remarkably affect parameter m in turn are age, average height, average diameter and density, and the relative coefficient of regression is smaller than the former. Parameter b is affected remarkably by stand factors such as average height, average diameter and density in turn, and its relative coefficient of regression is very small. Parameter k and m have remarkably negative linear or nonlinear relations with age and average diameter, and nonlinear relation is stronger. Parameter k has the stronger relations with them than m in either linear or nonlinear form, the relation between the two parameters(k and m) and age is affected by site index, density and thinning intensity. Parameter k and m have remarkably positive relativity with density. Parameter k and m respectively present the tendency of descent with the increase of site index and average height, both of them present remarkably linear relativity.

The application of theoretical growth equations in the field of stand diameter structure plays an important role in both theory and practice. In order to look for the inside and outside mechanism, and distinguish and use theoretical growth equations correctly, this chapter in view of stands and equations makes further studies and discussions. The results show that factors such as age, site index, density and thinning intensity have no distinct impact on modeling precision of the six growth equations mentioned above, but the difference of modeling precision is obvious among the equations. The inflection points of curve of stand cumulative diameter distribution range from 0.4 to 0.6, the distribution of inflection point value of growth equations has deep relations with modeling precision of functions, the wider the range of effective inflection points of the fittest equation curve is, and the higher the precision of inflection points is, the more obvious the validity of inflection points is, and the higher the modeling precision of equations is.

Chapter 4

According to the fuzziness of stand *DBH* distribution of China fir plantations, this chapter introduces Fuzzy distribution functions into modeling . It takes good effect. This chapter discusses the adaptability of Fuzzy distributions and the reasons that make modeling precision of them discrepant, and draws main conclusions as follows: ① The modeling precision of nine kinds of functions is shown as Fuzzy-Γ_5> Logistic> Fuzzy-Γ_3> Fuzzy-Γ_4> Fuzzy-C> Fuzzy-Γ_2> Gompertz> Korf> Fuzzy-Γ_1, among them, the Fuzzy-Γ_5 distribution of development type has the best modeling properties. Parameters of Fuzzy-Γ_3 are closely correlated with stand age and density. ② For different stands, initial planting density has larger influence on diameter cumulative distribution, but for the same stand, age plays main role. ③ Stand diameter cumulative distribution has inflection point, the size of which negatively correlates to stand age and initial planting density. The main range of inflection point of diameter cumulative distribution is 0.4~0.6, and there is a central distribution point about 0.5. For average precision of samples, when inflection point of distribution function lies in the main range, its modeling precision is higher, and the closer it nears 0.5, the higher its precision is. ④The stand age and initial planting density have different influences on modeling precision of every distribution form. Fuzzy-Γ_5, Fuzzy-Γ_3 and Logistic have stable and good modeling properties.

Chapter 5

The prediction of stand diameter structure can provide theoretical foundation for scientifically engaging in direct silviculture of plantations. This Chapter, from four aspects such as growth equations and so on, discusses the reason that influences prediction effects of the stand diameter structure of China fir plantations, compares parametric prediction method with parametric recovery one, and makes a thorough study on the reason that influences adaptation degree of test in the view of stand factors. The results are as follows: The influences of different recovery models, different modeling materials, different test materials and different growth equations on adaptation degree of test are respectively greatly obvious, sometimes obvious, obvious or greatly obvious and not obvious. When recovery model adopts the simplest power function, the adaptation degrees are all over 50%. The prediction effect of Richards is better, and there is only one adaptation degree under 60% in six cases. Parametric prediction methods and parametric recovery methods both have higher adaptation degrees of test in prediction, superiority and inferiority, and well applied prospects. Stand initial planting density is different from factors such as age, site index and thinning, etc., its adaptation degrees of prediction in different cases have a certain regulation in general, which has obvious influence on adaptation degree, and such a prominent effect of density should be considered while making classified prediction.

Chapter 6

Using data from permanent plots, this chapter studies the dynamics of diameter structure of China fir plantations and influence of density on it. Some criterions are adopted, such as skewness, kurtosis, variance coefficient, cumulative diameter distribution curves and frequency distribution, etc. The results show: ①At age of 6~20, the value of skewness changes from negative to positive, the absolute value of skewness first gets small, then big. At any time, high-density stands have the bigger skewness, and the higher the density of stands is, the earlier the skewness varies from negative to positive. ②The law of kurtosis varying with age is not obvious. Kurtosis of low-density stands is bigger than that of high-density ones, and both their values of kurtosis tend towards 0 at last. ③The *CV* of diameter shows weakly increasing tendency with age on the whole, and declines at an earlier stage, then increases after canopy closure. Non-evenness of high-density stands is bigger, and the higher the density is, the earlier the *variance* coefficient of diameter shows increasing tendency. ④At any range of cumulative frequency distribution, the smaller the density is, the bigger the middle value of diameter class is. It benefits the formation of middle and big wood. The tree distribution of diameter class testifies these conclusions.

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1 理论生长方程及林分直径结构模型研究概述

研制森林生长与收获预估模型始终是森林学研究的中心任务。随着森林学知识基础的改变以及林业信息需求的转变，对模型研究提出了新的更高的要求，模型的研究日渐深入、完善及实用。在森林生长模型研究领域，理论生长方程具有良好的理论解释基础及模拟性能。目前对理论生长方程在林分水平上的应用研究及理论生长方程结构组成形式的剖析均已做过大量的工作，但对方程的数学解析性、方程彼此间的联系和转换关系及其在直径结构方面的应用，尚缺乏系统深入的了解和比较应用研究，对其适用性缺乏足够的分析。就三大模拟模型之一的径阶分布模型而言，已从早期的以概率分布函数为代表的经验模型向以复杂的生理生态为基础的理论生长方程过渡，而且近 20 年来，林分直径结构模型的研究呈现出了许多新的变化。鉴于此，本章对理论生长方程及林分直径结构模型的研究进展做了较为全面的论述。

1.1 理论生长方程研究概述

理论生长方程是指在生物生长模型研究中，根据生物学原理作出某种假设，建立有关生物体大小的微分方程，解出并代入其初始条件或边界条件而导出的模型。它的特点包括逻辑性强、适用性较大、参数可做出生物学解释以及可从理论上对尚未观察的事实进行预测。

当人们考察树木的整个生长过程时，会发现它们的生长遵循一条“S”形曲线，尽管受到环境的影响会出现一些波动，但总的生长趋势是比较稳定的。由于在一个具体的林分内，林分内单株树木的生长在理论上呈“S”形曲线，由单株生长所构成的林分整体生长亦呈“慢—快—慢”的态势，而且由分化所引起的林木径阶株数百分比累积分布也呈现“S”形状态。因此，“S”形或近似“S”形的理论生长方程可以应用于单株、林分及径阶水平的林木生长或分布，即可被用作构建一类、二类及三类模型。不同的理论生长方程适合描述的对象不同，就同一对象而言，“S”形方程的参数个数、结构组成及拐点取值情形对方程模拟精度具有至关重要的影响作用。纵观理论生长方程的发展历程，其经久不衰、应用日渐广泛的内在原因可归结为两点：一是其理论根基的深厚；二是其数学表达式的灵活性及较强的可移植性。目前，对理论生长方程的研究已远远超出了方程原有的含义。鉴于理论生长方程应用领域的广阔，本文对几种主要理论生长方程的起源、应用发展现状及方程间错综复杂的关系予以较为全面的阐述，旨在使人们对理论生长

方程有个清醒的认识并适时、合理地使用之，进而拓宽其应用研究领域以及推动理论生长方程的深入发展。

对于理论生长方程，目前研究、应用较多的主要有：坎派兹式(Gompertz 方程)、逻辑斯蒂式(Logistic 方程)、米切尔里希式(Mitscherlich 方程)、贝塔兰菲式(Bertalanffy 方程)、理查德式(Richards 方程)、舒马赫式(Schumacher 方程)和科尔夫式(Korf 方程)等 7 种。下面重点就这些方程的研究应用情况进行介绍。

1.1.1 理论生长方程的发展现状

1.1.1.1 Gompertz 方程

上述 7 种理论生长方程中，Gompertz 和 Logistic 方程被提出的时间最早，且最初均用于描述种群增长及分布问题。

坎派兹式是由 Benjamin Gompertz 于 1825 年首先提出，用来描述人口衰亡及年龄分布状况。一个世纪以后，该式被用作生长曲线方程，广泛地应用于生物学和经济学领域。Wright 认为“以相对生长率作为测定指标的平均能力多少按一定的百分率下降”，即生长率与生长衰减因子的对数成比例，依此假设原理就可导出 Gompertz 式。1932 年，Winsor 为使 Gompertz 方程更便于应用，将该方程写如下式(1-1)。日本学者末田达彦在研究树干半径生长曲线适合性及理论干曲线方程时应用了式(1-1)，段爱国等(2003)应用该方程模拟林分直径分布时，其精度排在第 4 位。

$$y = k\exp[-\exp(a-bx)] \tag{1-1}$$

其中，$k>0$，$b>0$。

也有一些学者在利用坎派兹式时采用另一种表达方式

$$y = k\exp[-a\exp(-bx)] \tag{1-2}$$

上野洋二郎(1988)应用式(1-2)对单木的生长进行了研究；吴承祯等(1998)将其应用到杉木人工林直径分布结构的研究上，结果表明适合性良好。实质上，式(1-1)与式(1-2)并无多大区别，仅 a 值的取值范围略有不同而已。Gompertz 方程存在一个拐点，仅由渐进线参数决定，致使方程的灵活性受到一定程度的影响而降低。

1.1.1.2 Logistic 方程

逻辑斯蒂式是由比利时数学家 Verhulst (1838)首创，用于描述人口的增长规律，方程的微分、积分形式分别为式(1-3)、式(1-4)。之后，Pear 和 Reed (1920)将其用来描述美国人口增长过程。逻辑斯蒂式大概是生态学上最著名的方程，自创立至今已有 160 多年，引起全世界学者广泛深入的研究。惠刚盈(1995)在国内首次将该方程应用于林分结构的研究。该方程反映生物种群增殖率与环境中的营养物质之间呈一种线性关系，这种线性关系是生物学上极为复杂关系的一种近似表达。

方程的表达式可写如下式(1-5)。应用该方程模拟林分直径分布时，其精度仅次于 Richards 方程。

$$dy/dx = dy(1-y/Y_{max}) \tag{1-3}$$

$$y = Y_{max}/\{1+(Y_{max}-y_0)/y_0 \cdot \exp[-d(x-x_0)]\} \tag{1-4}$$

$$y = C/(1+e^{p-qx}) \tag{1-5}$$

式(1-5)中 C 与式(1-4)中 Y_{max} 均为上渐近线值，两者相等；$p = \ln[(Y_{max}-y_0)/y_0] + dx_0$，$q = d$，$q/Y_{max}$ 为内禀生长率；x_0、y_0 分别是 x、y 的初值，且 C，$q>0$ 。逻辑斯蒂式在生态学和经济学中广泛成功的运用，主要是因为其具有营养动力学上的说理模型的性质，而且它是一条标准的“S”形曲线，而自然界和社会中大量的事物变化又均体现出这一规律(李文灿 1990)。然而，Logistic 方程所建立的理论基础虽然颇合自然界的实际(自然界营养太缺乏，营养物质的增加立即引起增殖率的增加，几乎成正比)，但在营养物质较丰富时(如在微生物的培养和发酵中)，是不能成立的。鉴于此，崔启武和 Lawson(1982)提出了一个新的理论生长模型，该模型为马尔萨斯指数方程和逻辑斯蒂方程的融合与扩充。鉴于 Logistic 方程的拐点在渐进值的 1/2 处，张大勇(1985)在原方程的基础上提出了如下式(1-6)。

$$y = C/[1+\exp(p-qx)]^{\theta} \tag{1-6}$$

方程中参数θ是一个常数，C，$q>0$，式(1-6)的拐点可以在 1/2 左右取得，从而在理论上大大提高了逻辑斯蒂方程的灵活性。

1.1.1.3 Mitscherlich 方程

米切尔里希式由 Mitscherlich 于 1919 年提出，用来描述植物对环境因子的反应，在农业和经济学中，此方程被称为“收益递减律”(law of diminishing returns)。最初，Mitscherlich 提出的方程形式为

$$y = A(1-e^{b_1x_1})(1-e^{b_2x_2})$$

式中，y 为收获量；x_1，x_2 为控制增长的因子。

若把时间看成是一个最重要的影响树木生长的因子，且仅取它为唯一的控制因子，则上式可化为最简。理查德(1969)把它称之为单分子式，其表达式形式可写为

$$y = A[1-l\exp(-mx)] \tag{1-7}$$

式中，A 为上渐近线值，l 为与 y 初值有关的参数，m 为内禀生长率。$A>0$，$m>0$，$0<l\leqslant1$。在以后的许多研究中，人们均习惯采用式(1-7)当 $l=1$ 时的二参数方程形