生态仿真优化实验室
Simulation Optimization Lab

西北农林科技大学
Northwest A&F University

Forest Mensuration

Theory and Methodology

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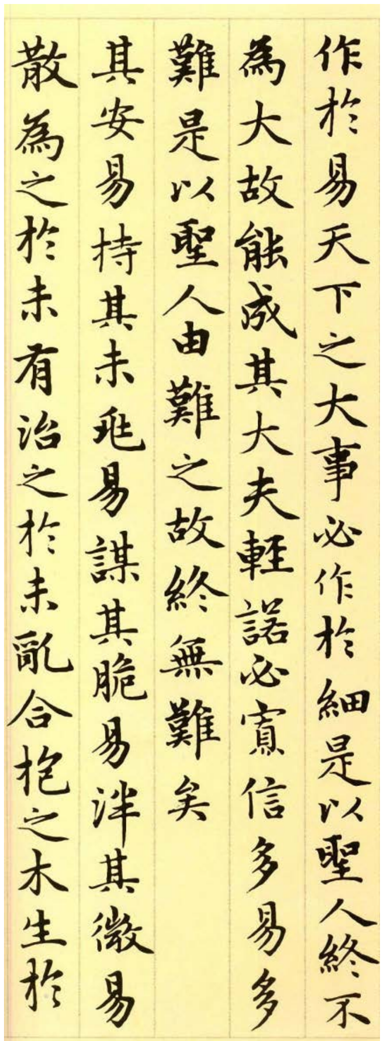
Purposes

- The purpose of this course is to show students how to link their knowledge in forest sciences with an interdisciplinary approach.

- Prerequisites
  - Dendrology
  - Tree phsiology
  - Statistics

Philosophy of forest modeling



作於易天下之大事必作於細是以聖人終不
爲大故能成其大夫輕諾必寡信多易多
難是以聖人由難之故終無難矣
其安易持其未兆易謀其脆易泮其微易
散爲之於未有治之於未亂合抱之木生於

What lies still is easy to grasp; What lies far off is easy to anticipate; What is brittle is easy to shatter; What is small is easy to disperse.

Laozi (Taoteching, chapter 64)

第一讲 绪论

- 第一节 测树学的概念和发展
  数据，公式，模型，系统; 森林调查数据-模型历史
- 第二节 测树学与林业科学其他学科的关系
  森林培育，森林经营，林产工业，森林工业
  林木遗传育种，森林生态学，森林保护学，森林土壤学
- 第三节 测树学理论基础
  异速生长理论，概率密度理论，
  代谢尺度理论，自稀疏理论，林窗理论
- 第四节 误差、准确度、精度与测不准原理
  误差的产生, 准度与精度, 风险，概率与不确定性
- Q1. 在林业生产中，早期森林调查数据与近期数据哪一个重要？为什么？

森林生长理论体系 Theory of forest growth

- 适地适树原则，Species-specific and site-specific

- 林木结构异速生长理论, Allometrics of tree architecture
- 林分结构概率分布理论, Probability distribution of stand structure
- 林木生长代谢尺度理论, Metabolic scaling theory of tree growth
- 林分密度自然稀疏理论, Self-thinning theory of stand density
- 森林更新林窗空间理论, Gap theory of forest regeneration

Equation set of forest growth 森林生长方程组

Equation set of forest dynamics

I	$w_i = \alpha \cdot w^{\beta}$	The allometric relationship of tree structure
II	$f(d_i) = f(A,S,D)$	The probability density function of stand structure
III	$\ln iv = \alpha + 3/4 \cdot \ln v$	The metabolic scaling theory of tree growth
IV	$\ln N = \alpha - 3/2 \cdot \ln V$	The -3/2 self-thinning rule of stand density control
V	$R = \alpha - \beta \cdot G + \gamma \cdot S$	The gap model theory of forest regeneration

森林动态方程组

I	$w_i = \alpha \cdot w^{\beta}$	林木异速生长定律
II	$f(d_i) = f(A,S,D)$	林分结构概率密度分布规律
III	$\ln iv = \alpha + 3/4 \cdot \ln v$	林木生长新陈代谢尺度理论
IV	$\ln N = \alpha - 3/2 \cdot \ln V$	林分密度自疏伐理论
V	$R = \alpha - \beta \cdot G + \gamma \cdot S$	森林更新林窗理论

过程机理理论 Theory of forest productivity

Production ecology 生产生态学理论

- GPP = resource supply
  *fraction of resource acquired%
  *resource use efficiency%

Nutrient => Nutrient cycling 养分循环理论

- Availability, acquisition and NUE (Nutrient Use Efficiency)%

Light => Carbon balance 碳平衡理论

- Availability, absorption, and LUE (Light Use Efficiency)%

Water => Water balance 水平衡理论

- Availability, use, and WUE (Water Use Efficiency)%

Introduction

- This course is designed for students who are preparing to engage in an interdisciplinary study in the fields of
  - silviculture,
  - forest ecology,
  - forest planning,
  - and forest biometrics.

Observation data

- Which type of information is more important in forestry?
- And why?

- Forest stand data from
  - Earlier inventory
  - Later inventory

Forest dynamics

- The aim of this course is to help students acquire skills in predicting and assessing dynamic forest ecosystems in terms of

  - Data
  - Models
  - Decision-support systems
  - Applications

Grading

- Quiz, 30%
- Final, 70%
- Lecture hours：38+10 hrs
- Credits：2.5 crs

- Instructor：Prof. Dr. Tianjian Cao
- E-mail: cao@nwafu.edu.cn

Computer programs to be used in the course

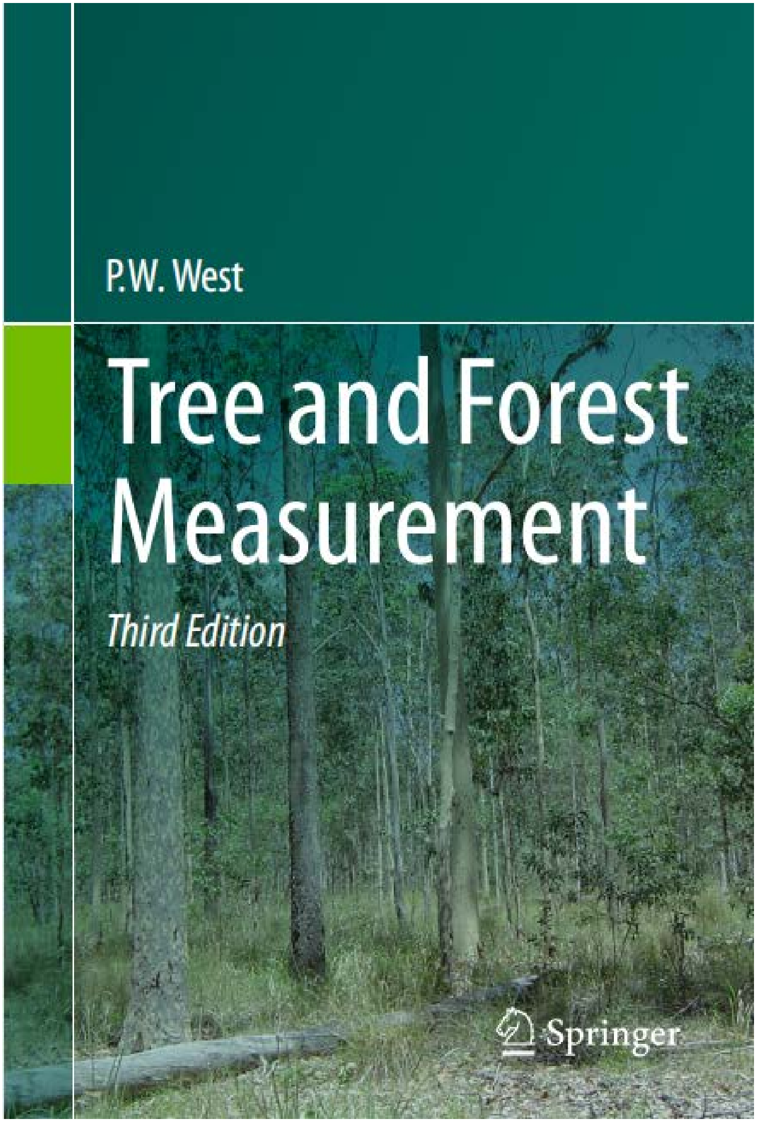
- SPSS
- ForStat
- SigmaPlot
- Simile
- PUME II

- QUASSI
- OPTIFOR

Contents (Forest Mensureation, 4th edition)

Contents (West 2015)

- 1 Introduction
- 2 Measurements
- 3 Stem Diameter
- 4 Tree Height
- 5 Stem Volume
- 6 Stem Volume and Taper Function
- 7 Biomass
- 8 Stand Measurement
- 9 Measuring Populations
- 10 Sampling Theory
- 11 Conducting an Inventory
- 12 The Plane Survey
- 13 Remote Sensing



Contents (Kangas and Maltamo 2006)

- Part I Theory
  - 1 Introduction;
  - 2 Design-based sampling and inference;
  - 3 Model-based inference;
  - 4 Mesurational aspect;
  - 5 Change monitoring with permanent sample plots;
  - 6 Generalizing sample tree information;
  - 7 Use of additional information;
  - 8 Sampling rare populations;
  - 9 Inventories of vegetation, wild berries, and mushrooms;
  - 10 Assessment of uncertainty in spatially systematic sampling
- Part II Applications; Part III Cases; Part IV Future

Contents (Vanclay 1994)

- 1 Introduction
- 2 Whole stand models
- 3 Size class models
- 4 Single-tree and tree list models
- 5 Data requirements
- 6 Constructing growth models
- 7 Forest site evaluation
- 8 Diameter increment
- 9 Mortality and merchantability
- 10 Regeneration and recruitment
- 11 Model evaluation and re-calibration
- 12 Implementation and use
- 13 Future directions

Characteristics of forest data

Different type of measurement error comparing with plots data

1. Temporary plots

    Lacking tree-level information

2. Permanent plots

    Most permanent plots only contain one-time observations

3. Stem analysis

    Accurate but few

Caveats of forest models

- *Impossible to validate any model (Popper 1963).*
- *All models are false, but some models are useful. Our job is to identify the useful ones useful. (G.E.P. Box).*
- *No model can be evaluated in the absence of some clearly stated objective (Goulding 1979).*
- *No criterion is universal, so some subjectivity must always remain.*
- *Empiricism cannot be avoided, and keeps models grounded in reality.*

Source: Monserud (2003), presentation in Symposium of Systems Analysis in Forest Resources, October 7-9, 2003, Stevenson, Washington

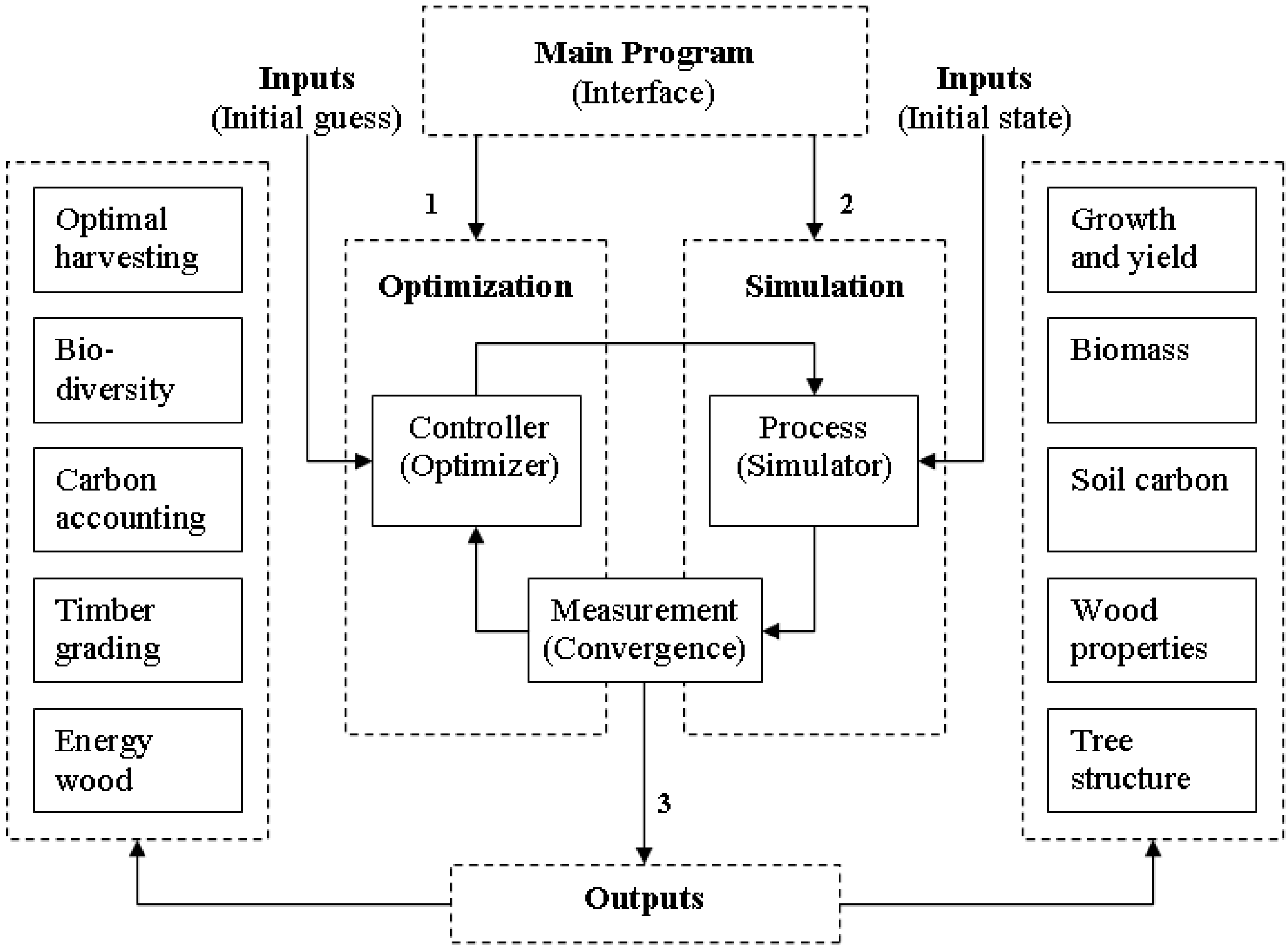
Why forest inventory?

- Forest managers
- Forest owners
- Forest policy makers

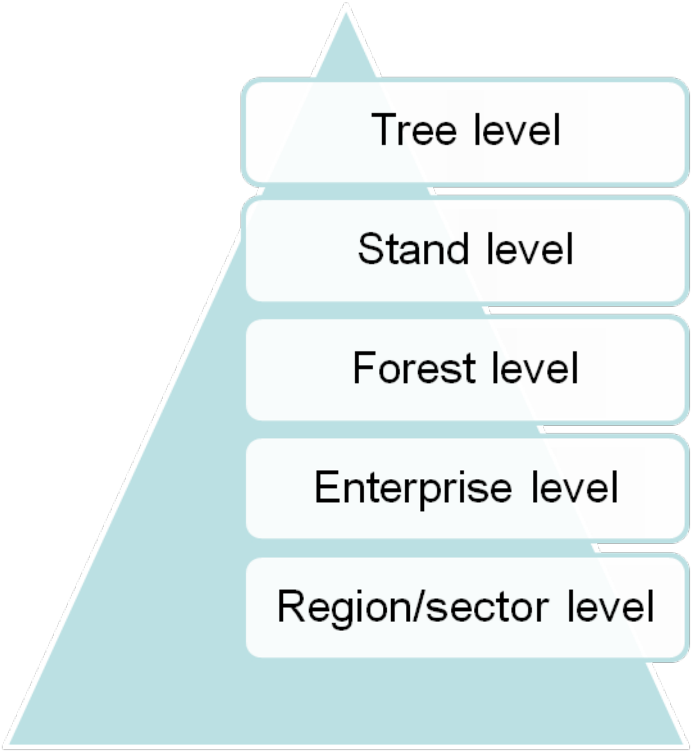
- Investment banks
- Timber industry
- Paper making industry

- Forest ecologists
- Forest parks
- NGOs

OptiFor simulation-optimization system

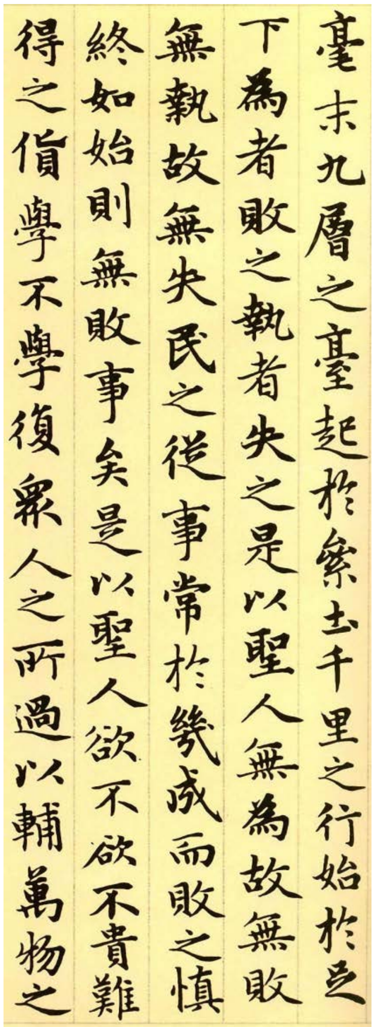


Decision levels



Source: Valsta (1993)

Philosophy of tree growth


毫末九層之臺起於絫土千里之行始於足
下為者敗之執者失之是以聖人無為故無敗
無執故無失民之從事常於幾成而敗之慎
終如始則無敗事矣是以聖人欲不欲不貴難
得之貨學不學復衆人之所過以輔萬物之

Yet a tree broader than a man can embrace is born of a tiny shoot; A dam greater than a river can overflow starts with a clod of earth; A journey of a thousand miles begins at the spot under one's feet.

Forest inventory systems

- National forest inventory,
- inventory for forest management planning,
- inventory for silvicultural operations

- National and local standards for forest inventory

Ecosystem observation systems

- LTER www.lternet.edu
- GTOS www.fao.org/gtos
- ECN www.ecn.ac.uk
- GEMS www.unep.org/gemswater
- CNERN www.cnern.org
- CFERN www.cfern.org

Sufficient data

- Field work can provide necessary and sufficient data efficiently.
- However, it may take several years to obtain the necessary data from permanent plots,
- and few of us can wait that long.
- “Nothing perfect except in our memories…”

Procedure of forest inventory

- Definition

=> Collection

=> Validation

=> Storage

=> Analysis

=> Synthesis

Data collection

- The life cycle of a datum spans its definition, collection, validation, storage, analysis and synthesis.
- All stages are equally important, and an efficient data management system requires a healthy balance between them.
- The first step is to define information needs and devise data collection procedures to satisfy those needs.

Differing data needs

- Stem analyses do not provide reliable growth data for many tree species, e.g., in tropical moist forests.
- Permanent plots can never be completely replaced by temporary plots.

- Resource Inventory
- Continuous Forest Inventory for yield control
- Growth modelling
- Long term monitoring of environmental change

IUFRO Division 4

- http://www.iufro.org/science/divisions/division-4/

- 4.00.00 - Forest Assessment, Modelling and Management
  - 4.01.00 – Forest mensuration and modelling
  - 4.02.00 – Forest resources inventory and monitoring
  - 4.03.00 – Informatics, modelling and statistics
  - 4.04.00 – Forest management planning
  - 4.05.00 – Managerial economics and accounting

4.01.00 – Forest mensuration and modelling

- 4.01.01 – Design, performance and evaluation of experiments
- 4.01.02 – Growth models for tree and stand simulation
- 4.01.03 – Instruments and methods in forest mensuration
- 4.01.04 – Effects of environmental changes on forest growth
- 4.01.05 – Process-based models for predicting forest growth and timber quality
- 4.01.06 – Analysis and modelling of forest structure

Definitions

- forest resources
- forest inventory
- forest resource monitoring
- forest management planning

Definitions, con’t

- Timber value vs. non-timber value
  Timber: sawlogs, pulpwood, energy wood, ...
  Non-timber: mushrooms, hunting, biodiversity, carbon sequestration, amenities, preventing erosion...

- Quantitative method vs Qualitative method
  Quantitative: connected with the amount or number of sth rather than how good it is
  Qualitative: connected with how good sth is, rather than how much of it there is

Data requirements

- LUCC: Land Use and Cover Change
- Forest growth and yield
- Forest operations
- Forest biodiversity
- Forest carbon sequestration
- Forest health
- Forest ecosystem management
- etc.

第二讲 数据采集设计

- 第一节 测树因子与数据采集
  - 数据尺度:

    林木水平Tree level (林木结构, 林冠结构, 林木大小)

    林分水平Stand level (树种组成, 林分结构, 立地条件, 竞争)
  - 数据来源:（临时样地，固定样地，解析木，木芯）
  - 数据种类:

    资源数据resource data (蓄积, 覆盖率)

    动态数据dynamics data (生长, 演替)

    更新数据regeneration data (树种, 种子, 幼苗, 幼树, 进界)

    枯损数据mortality data (径阶, 时间, 林分结构)

    生物多样性数据biodiversity data (乔木层, 草灌层, 土壤层)

    生态数据Ecological data (碳, 氮, 水)

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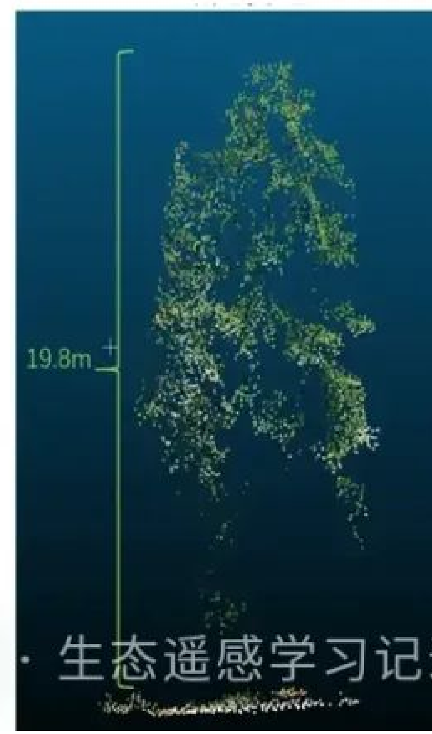
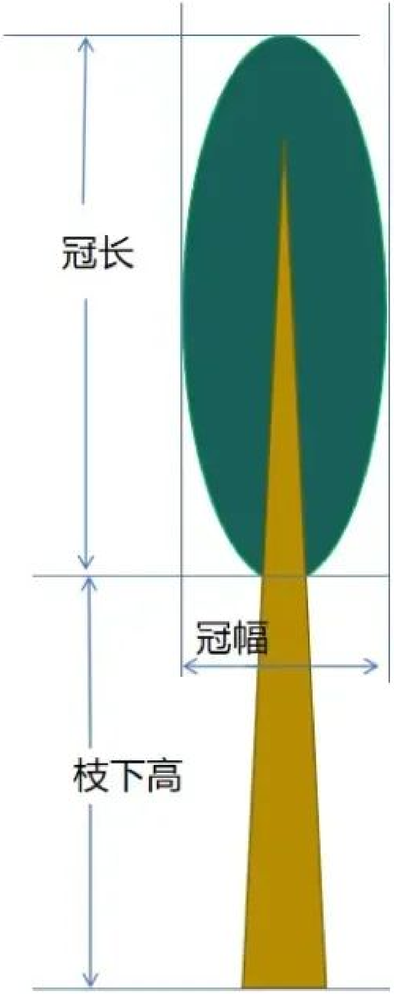
UAV applications

机载激光雷达

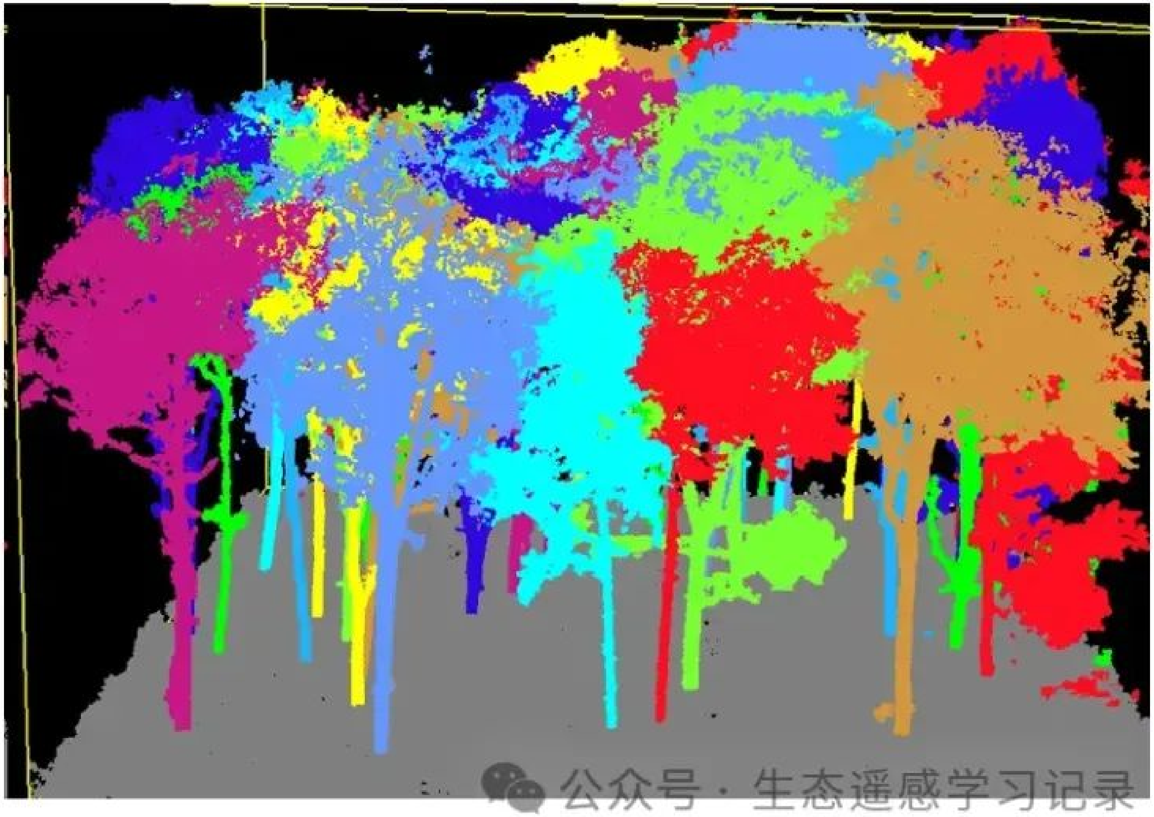
单株树高测定



UAV applications



单木分割



第二讲 数据采集设计

- 第二节 抽样设计理论与方法
  - 典型抽样
  - 点抽样, 随机抽样Point sampling
  - 系统抽样Systematic sampling
  - 带状抽样Stripe sampling
  - 群团抽样
  - 分层抽样
  - …

Sampling theory

- Kiaer 在19世纪末介绍了具有代表性样本的应用。随后Bowley （1912）将随机抽样思想引入了调查抽样。
- Neyman（1934）解释了为什么随机选择优于有目的的选择。基于从给定总体中抽取的一定大小的所有可能样本分布，他提出样本估计置信区间，为抽样理论确立了准确的统计学框架（Bellhouse 1988）。
- 19世纪森林资源调查的主要方法是每木调查，之后人们注意到应用有代表性的样本可以减少调查成本（Loetsch et al. 1973）。
- 早期抽样法在北美、德国和北欧林业方面的应用是目测法
- 从1900至1920年，统计知识逐渐被用于林业文献。由于早期的调查是系统的，因此系统抽样方差估计在这些国家被广泛使用。

Sampling theory, con't

- Israel af Stro:m 19世纪30年代使用了系统带状抽样。
- Hasel（1938）和Osborne（1942）认为系统调查比随机抽样更能给出蓄积量的近视值。
- Finney（1948）提出分层法，考虑最初抽样地点的随机性
- Bitterlich 和 Grosenbaugh 引进不等概率抽样法，提出角规计数抽样法（Bitterlich 1947）。角规抽样法很快被认为是森林抽样的有效方法，因为对木材蓄积量的兴趣。
- Grosenbaugh（1952）应用与大小成比例的概率抽样法（PPS），提出点抽样概念。

Sampling theory, con't

- Scott（1947）提出了森林连续清查（CFI）体系。Bickford（1959）将永久样地与临时样地资料有机结合，进行部分放回抽样（SPR）。
- 基于模型的方法在林业调查中还未被推广（Matern 1960; Mandallaz 1991; Kangas 1993; Gregoire 1998）。
- 现在卫星影像已经逐渐代替了航片(Czaplewski 1999）。

Sampling techniques

- 随机抽样: 简单随机抽样（SRS）是一种最基本的抽样技术，在选择一个具有n个单元的样本时，每一个可能的n个样本的组合，都具有相同等被抽中的机会。
- 系统抽样: 系统抽样是指在总体内按等间距抽取样本单元。例如在一系列的树木中每10株抽取一株或是在一片林分内按等间距抽取样地。
- 分层抽样: 分层意味着把总体划分为互不重叠的副总体，因而使副总体内的变量比在原总体内的变量更为一致。在森林调查中，森林往往是根据森林类型进行分层的。

Example 2.1 系统抽样

- 例如，在一个100 ha林地的一次森林资源调查中，样地被布成方格网，在这个方格里，行距与样地之间的距离均为100 m。总共测102个圆形和点状样地。如果胸径的平均值小于8 cm，就采用半径为2.25 m的圆形样地调查所有林木。否则的话，使用点抽样并取断面积系数为2 的方法，同时如果还有下层林木，也可在20 m2 的圆形样地测量林木。每个样地每公顷林木蓄积量的估计可以被计算出来。
- 系统抽样中的单元不是单独入样的，而且对于系统抽样的标准误没有基于设计的估计值。简单随机估计量可用于估计总体平均值和总量。在此例中，简单随机估计量也用于估计样本方差。

Sampling techniques, con't

- 群团抽样: 当总体可以分成多个独立的群团时采用群团抽样。在森林资源调查中，往往存在多个相邻的样地或相邻的一片树木组成的群团。如果对树的平均值感兴趣的话，每一块样地也可以视为树的群团。
- 重复抽样: 例如刀切法（jackknife）和自助法（bootstrap）。其工作程序如下：

  (1) 从最初放回抽样样本中抽取K个大小为n的重复抽样样本

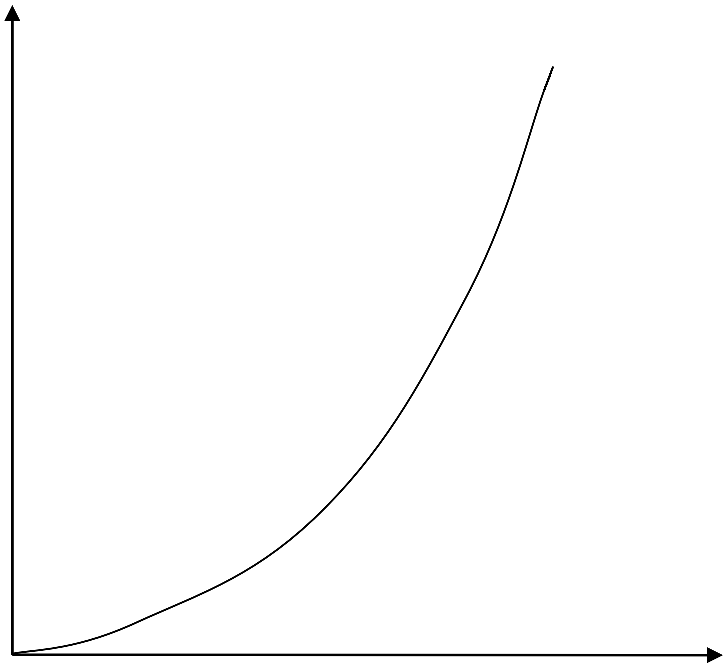
  (2) 计算每个重复抽样样本的相关估计值（例如平均值或比率）。

  (3) 从重复抽样样本的估计值之间的方差中计算该方差的估计量。

Sigma epsilon, or Pi epsilon?

- 抽样方法误差 Sampling
- 抽样设计误差 Design
- 森林调查误差 Inventory
- 森林建模误差 Modeling
- 森林预测误差 Prediction
- 森林规划误差 Planning
- 森林决策误差 Decision

- Tot_e = f(e_i, t)



Interpolation vs. Extrapolation

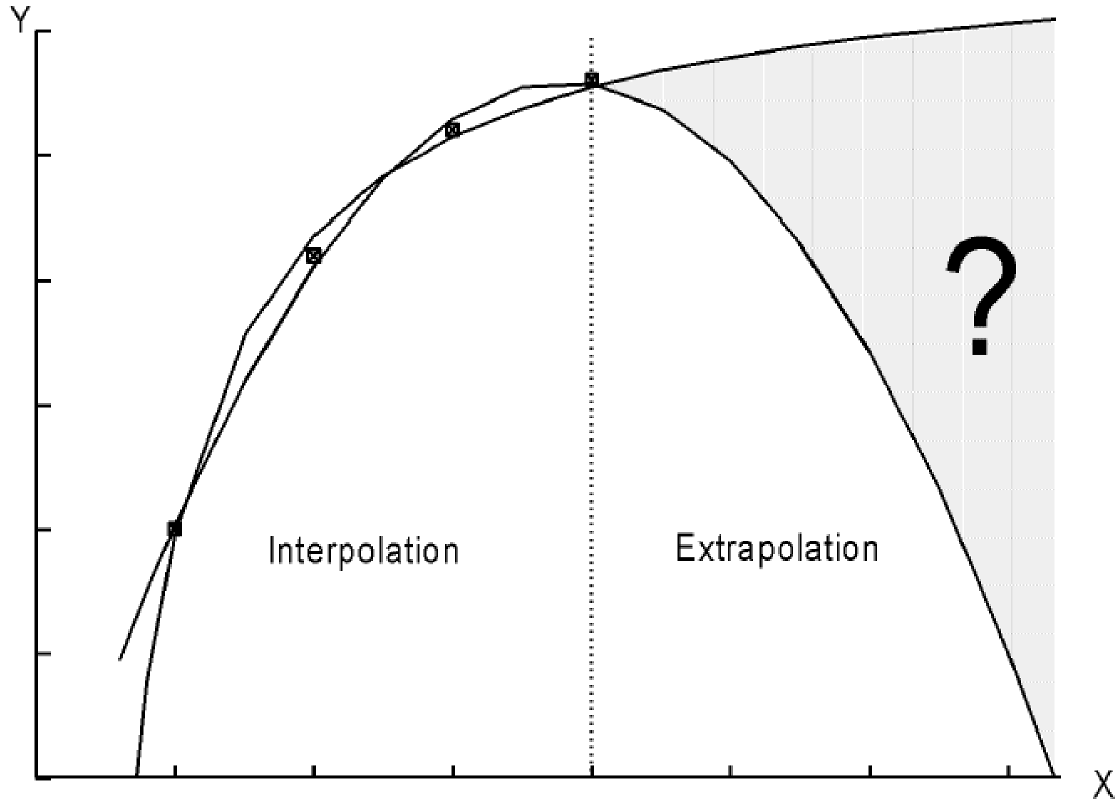


Fig. 5.1. Interpolation is safer than extrapolation. Both these lines have an R^2 better than 0.996, but provide no basis for making a prediction outside the range of the data.

Database weaknesses

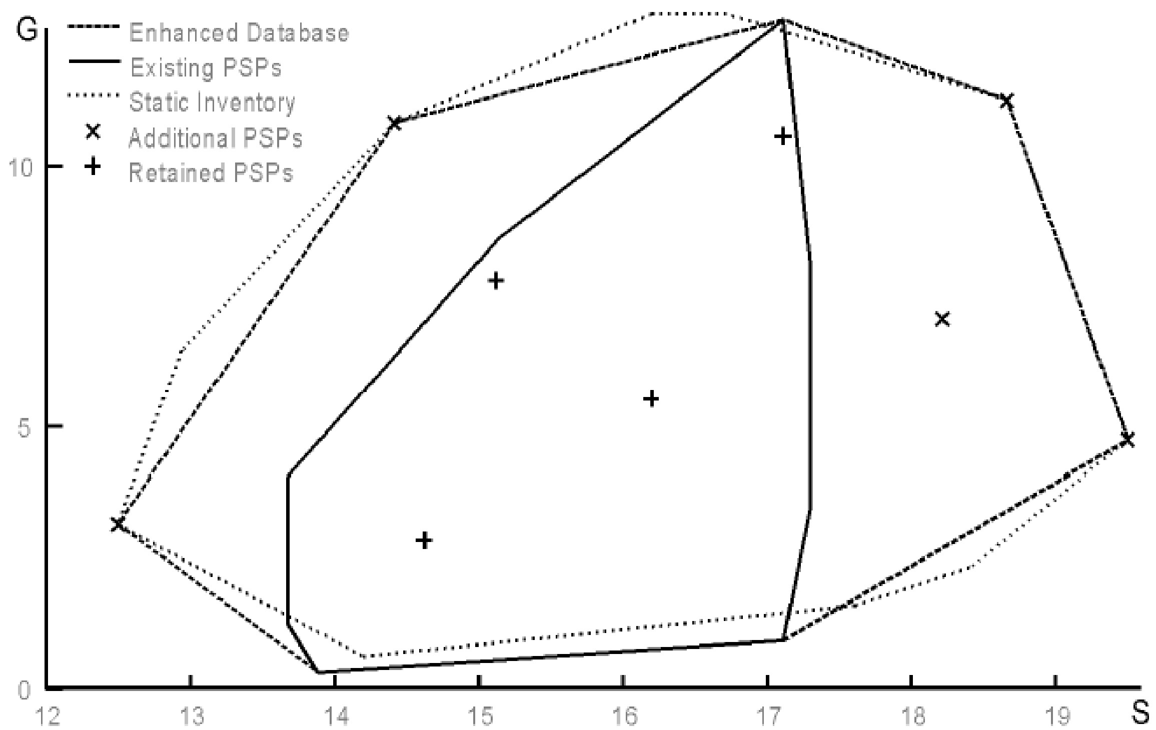


Fig. 5.3. Database weaknesses revealed by comparing dynamic and static inventory data. Five new PSPs (×) would improve the database for modelling (*Callitris* forest in Queensland, redrawn from Beetson *et al*. 1992).

第二讲 数据采集设计

- 第三节 测树工具

  围尺 => 胸径

  布鲁莱斯测高仪 => 树高

  卷尺 => 冠幅

  生长锥 => 木芯

  …
- 第四节 教学软件

  QUASSI, OPTIFOR, Simile, PUME II

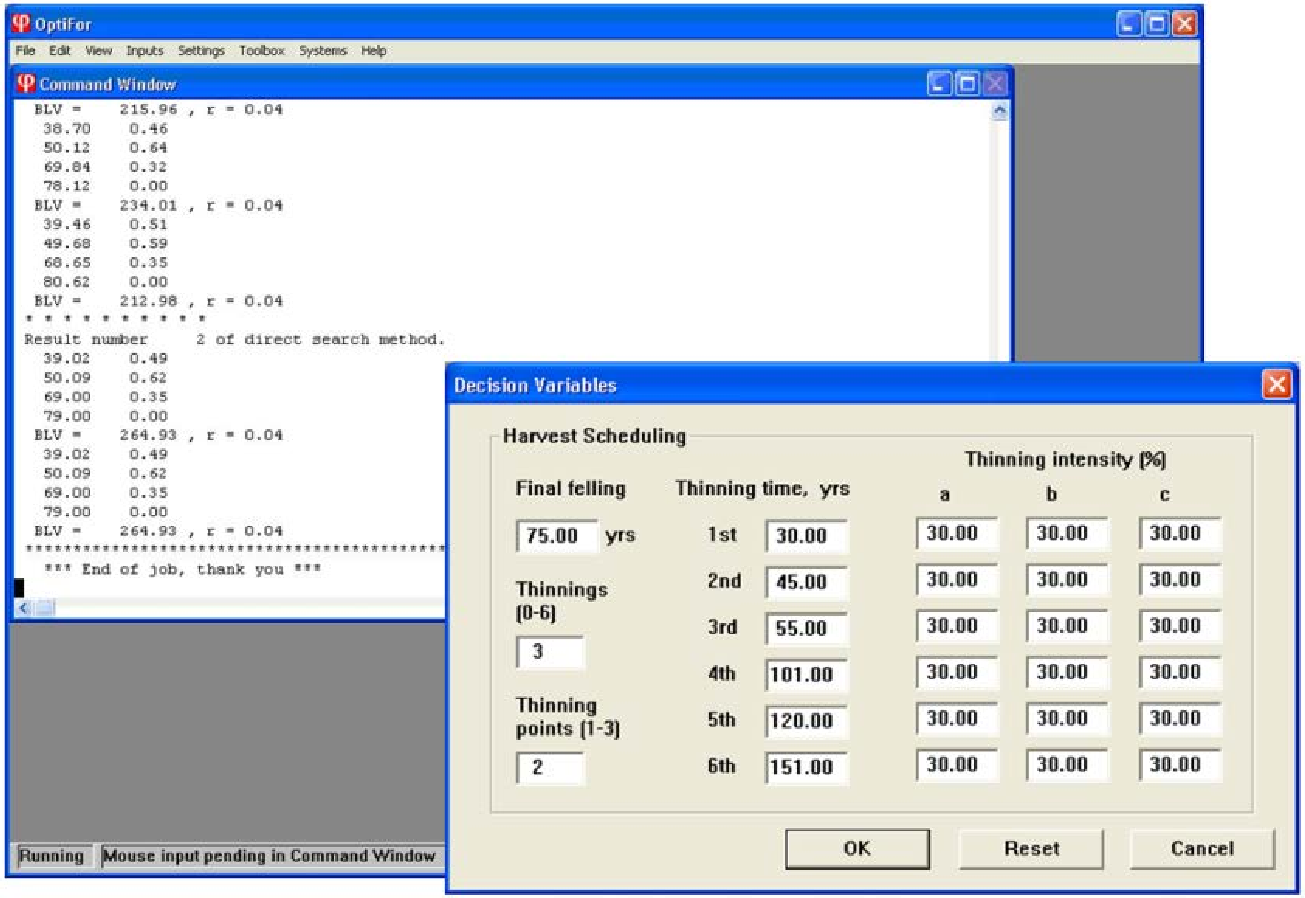
- Q2. 临时样地数据，固定样地数据，解析木数据的采集目的是什么？举例说明不同数据来源的应用。

Differing data needs 数据需求

- 解析木数据。Stem analyses do not provide reliable growth data for many tree species, e.g., in tropical moist forests.
- 固定样地和临时样地。Permanent plots can never be completely replaced by temporary plots.

- Resource Inventory
- Continuous Forest Inventory for yield control
- Growth modelling
- Long term monitoring of environmental change

OptiFor



OptiFor
File Edit View Inputs Settings Toolbox Systems Help
Command Window
BLV = 215.96 , r = 0.04
38.70 0.46
50.12 0.64
69.84 0.32
78.12 0.00
BLV = 234.01 , r = 0.04
39.46 0.51
49.68 0.59
68.65 0.35
80.62 0.00
BLV = 212.98 , r = 0.04
Result number 2 of direct search method.
39.02 0.49
50.09 0.62
69.00 0.35
79.00 0.00
BLV = 264.93 , r = 0.04
39.02 0.49
50.09 0.62
69.00 0.35
79.00 0.00
BLV = 264.93 , r = 0.04
*** End of job, thank you ***
Running
Mouse input pending in Command Window
Decision Variables
Harvest Scheduling
Final felling
75.00 yrs
Thinnings (0-6)
3
Thinning points (1-3)
2
Thinning time, yrs
1st 30.00
2nd 45.00
3rd 55.00
4th 101.00
5th 120.00
6th 151.00
Thinning intensity (%)
a b c
30.00 30.00 30.00
OK
Reset
Cancel

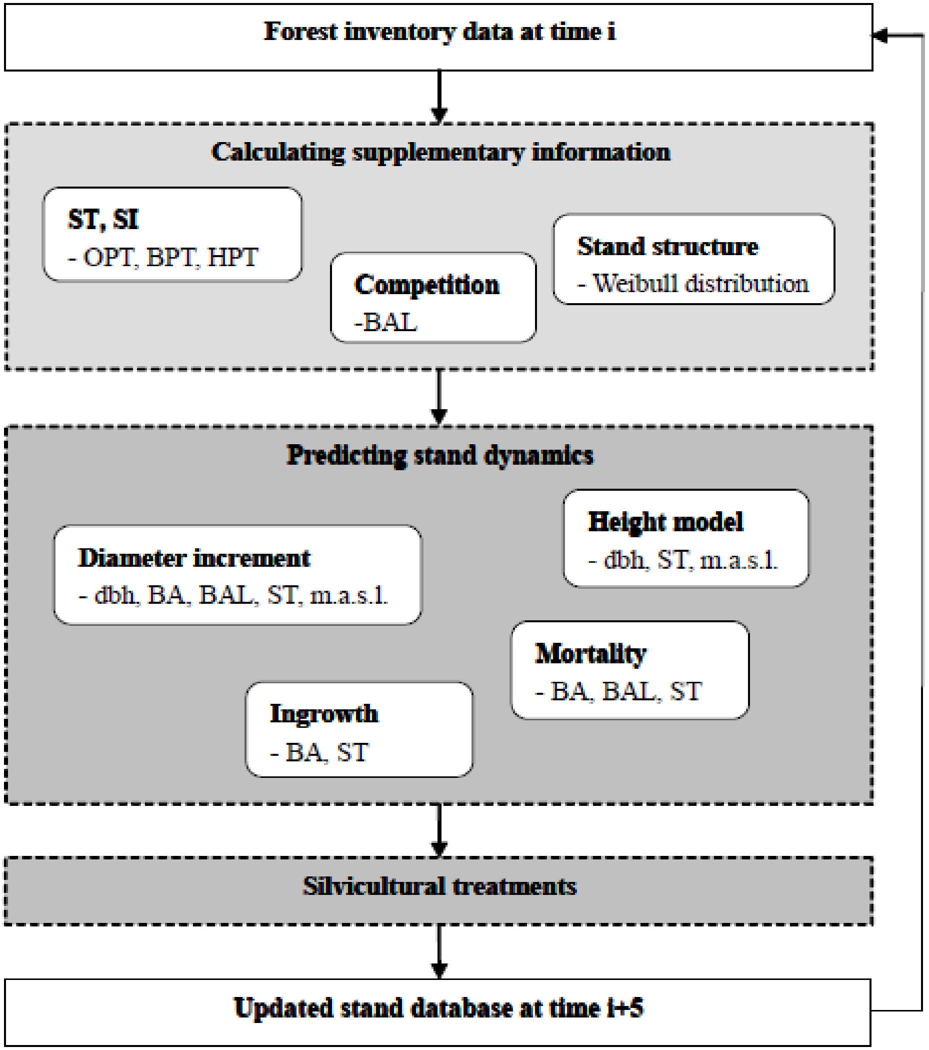
QUASSI (Qinling Uneven-Aged Stand SImulator)

- Collaboration

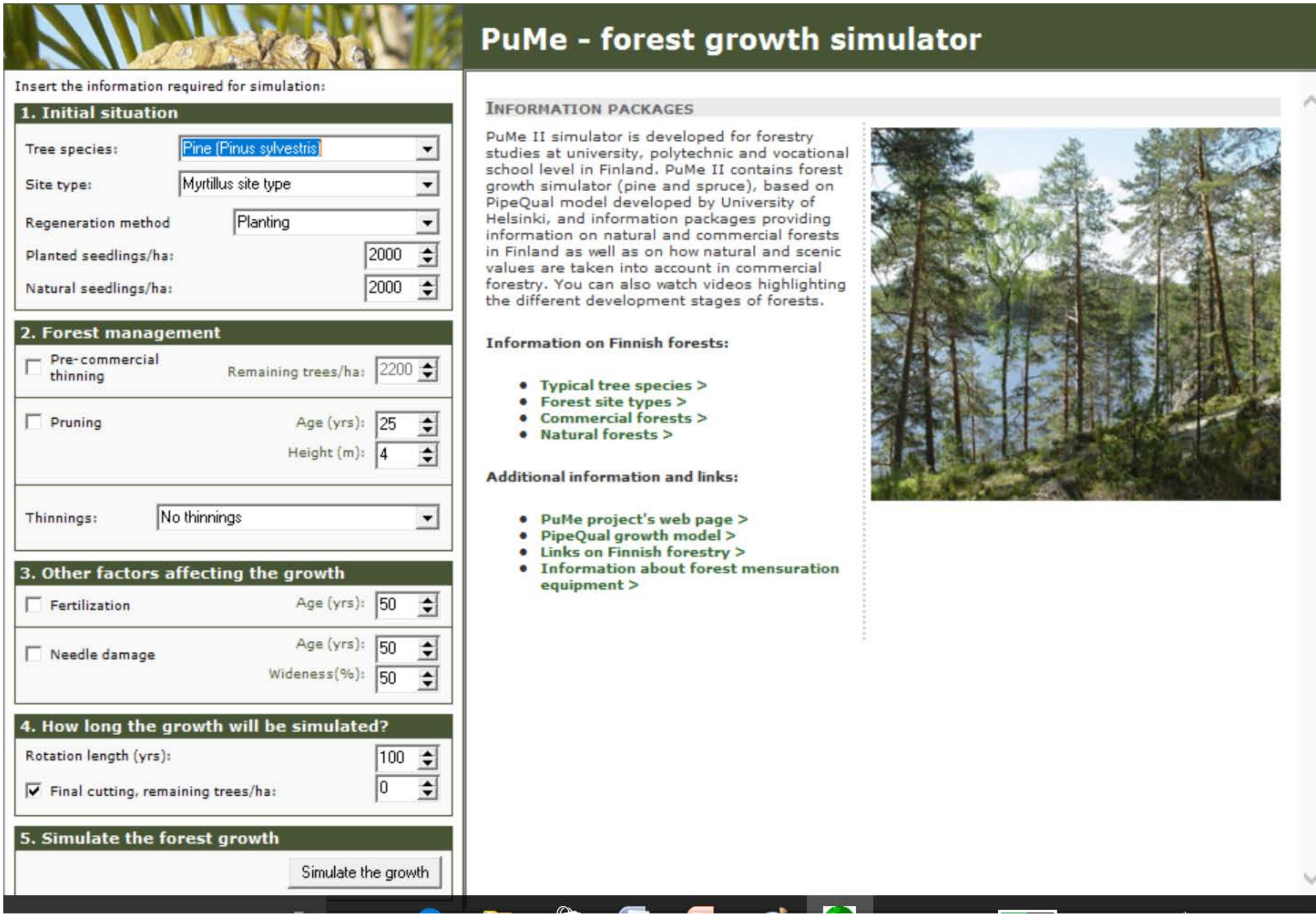
  LSU

  SCU

  UH

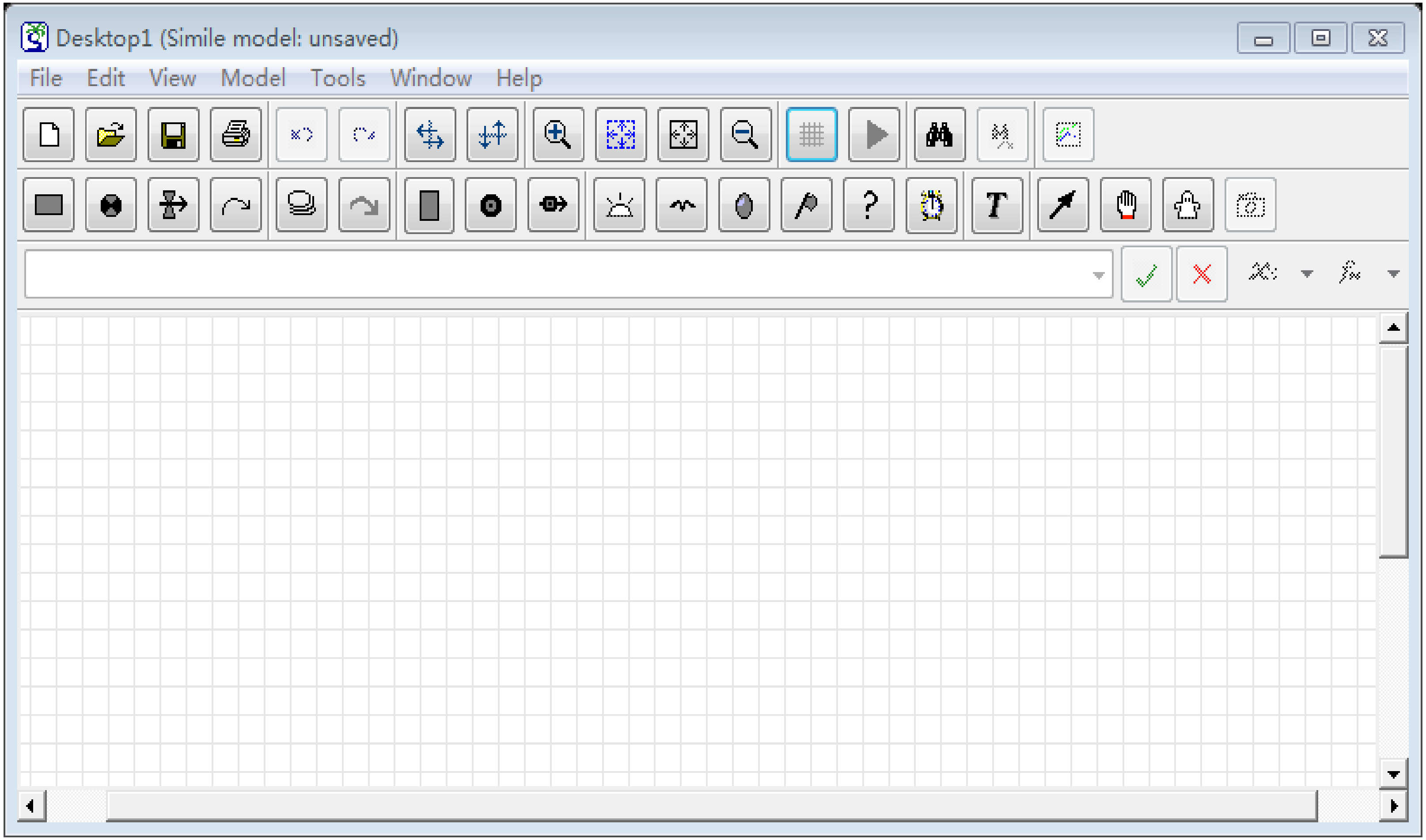


PuMe II



PuMe - forest growth simulator
Insert the information required for simulation:
1. Initial situation
Tree species: Pine (Pinus sylvestris)
Site type: Myrtillus site type
Regeneration method Planting
Planted seedlings/ha: 2000
Natural seedlings/ha: 2000
2. Forest management
Pre-commercial thinning
Remaining trees/ha: 2200
Pruning
Age (yrs): 25
Height (m): 4
Thinnings: No thinnings
3. Other factors affecting the growth
Fertilization
Age (yrs): 50
Needle damage
Age (yrs): 50
Wideness(%): 50
4. How long the growth will be simulated?
Rotation length (yrs): 100
Final cutting, remaining trees/ha: 0
5. Simulate the forest growth
Simulate the growth
INFORMATION PACKAGES
PuMe II simulator is developed for forestry studies at university, polytechnic and vocational school level in Finland. PuMe II contains forest growth simulator (pine and spruce), based on PipeQual model developed by University of Helsinki, and information packages providing information on natural and commercial forests in Finland as well as on how natural and scenic values are taken into account in commercial forestry. You can also watch videos highlighting the different development stages of forests.
Information on Finnish forests:
Typical tree species >
Forest site types >
Commercial forests >
Natural forests >
Additional information and links:
PuMe project's web page >
PipeQual growth model >
Links on Finnish forestry >
Information about forest mensuration equipment >

Interface of Simile



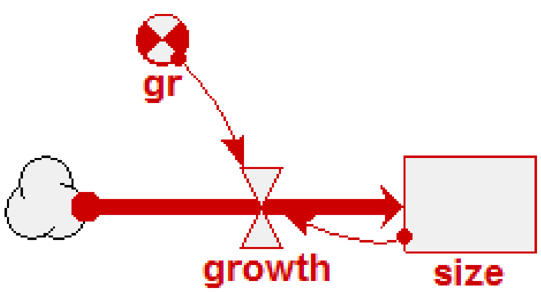
Model linkages with Simile

- http://www.simulistics.com/

- Stage 1: Modelling the growth of a single tree
- Stage 2: Extending the model to represent a population of trees
- Stage 3: Calculating aggregate information
- Stage 4: Visualising the trees in space

Simile step-by-step

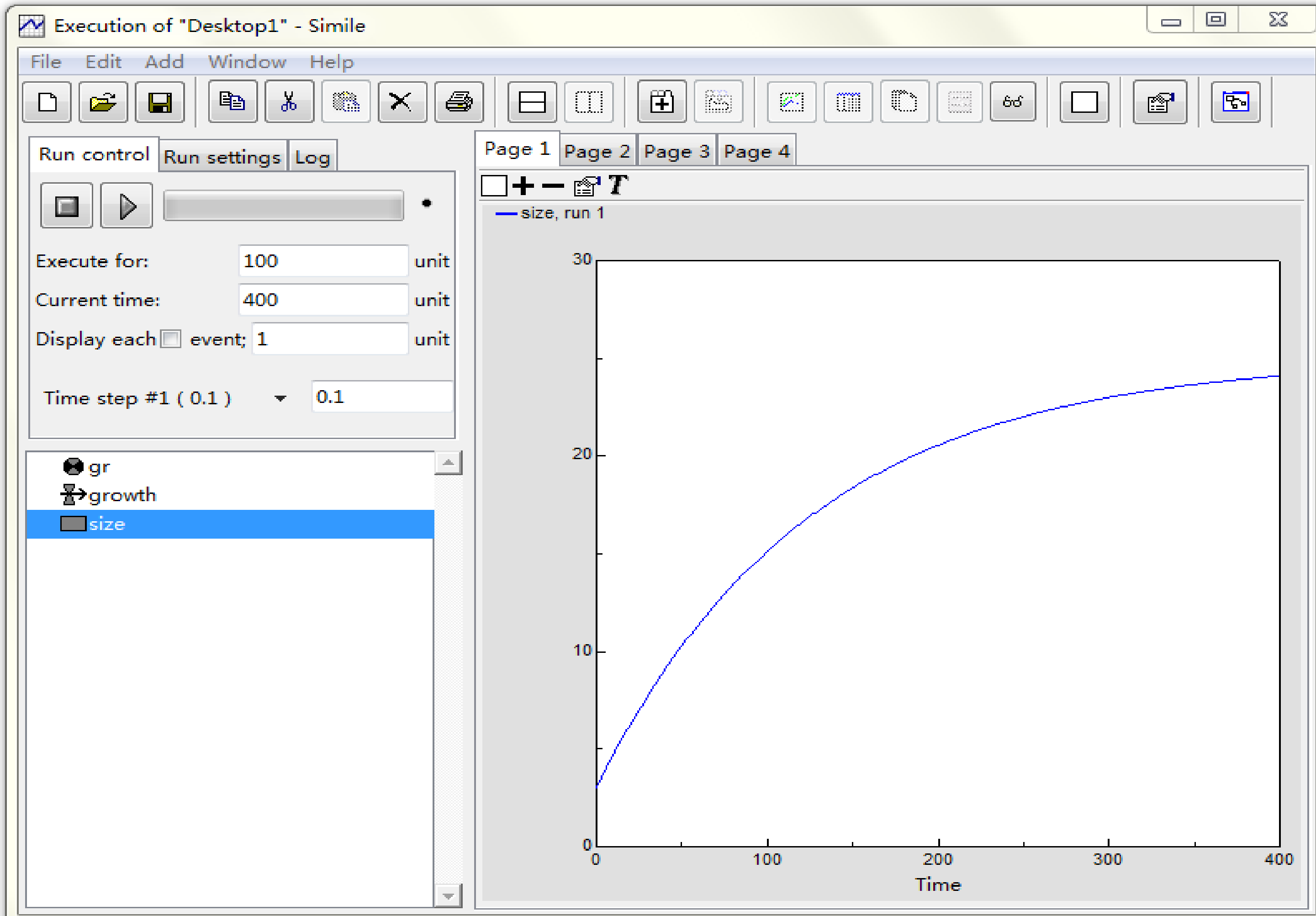
- Step 1 Add a compartment to the desktop, and rename it size.
- Step 2 Draw a flow into the size compartment, and rename it growth.
- Step 3 Add a variable to the desktop, above the growth flow, and rename it gr.
- The variable gr represents the maximum rate of growth of the tree.
- Step 4 Draw an influence arrow from both the size compartment and the gr to the growth flow.



Simile step-by-step, con’t

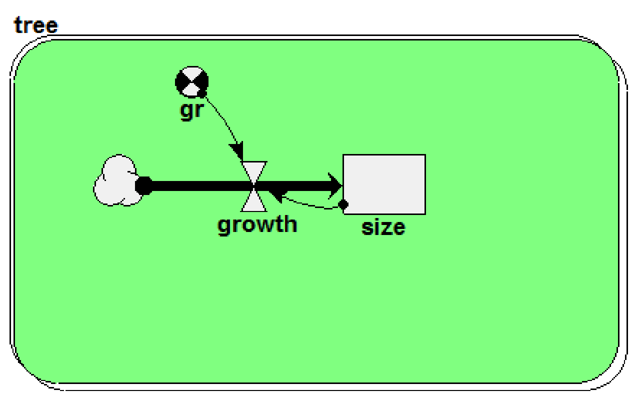
- Step 5 Enter the following expression for the growth flow: gr*(1-size/25)
- Step 6 Set the initial value for the size compartment to 3.
- Step 7 Set the value for the variable gr to 0.2.
- Step 8 Prepare the model for running.
- Step 9 Set up a plotter display helper for the size compartment
- Step 10 Run the model

Size growth of single tree



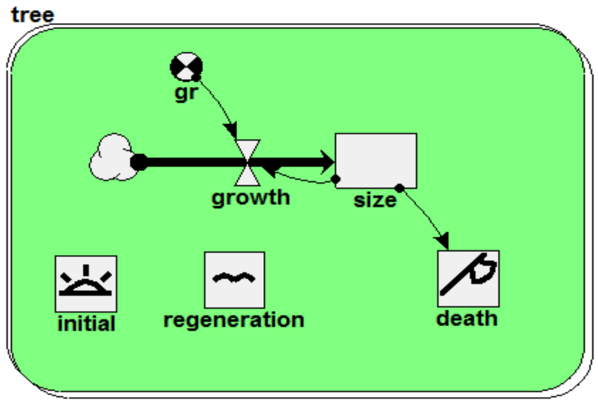
Extending the model to a stand

- Step 1 Draw a submodel box to completely enclose your model diagram.
- Step 2 Rename the submodel tree.
- Step 3 Open up the submodel Properties dialogue window.
- Step 4 Click the radio button labelled "Using population symbols".
- Step 5 Choose a nice background colour for the submodel.
- Step 6 Close the submodel properties dialogue window.
- Step 7 Change the expression for gr from its current value (0.2) to rand_const(0.1,0.3).



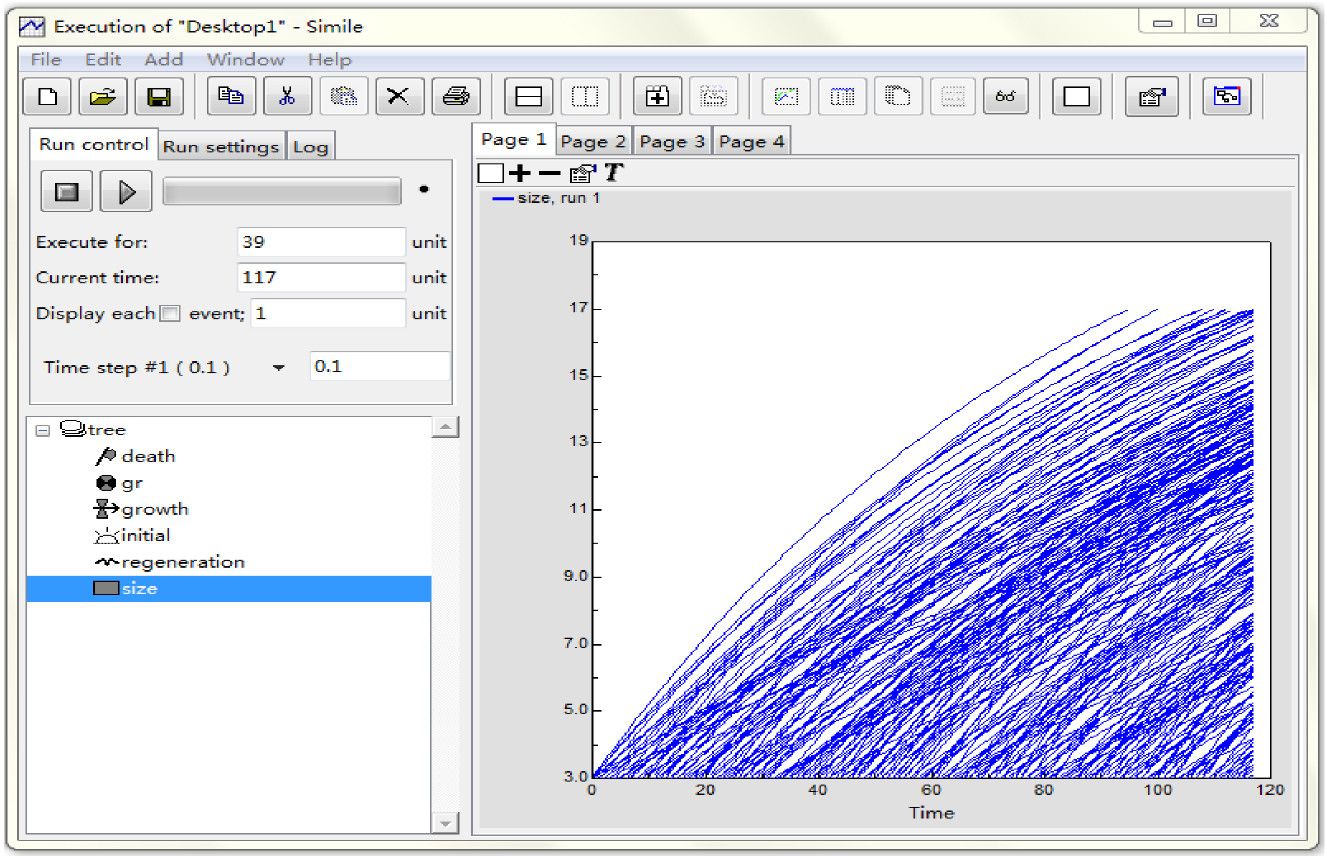
Extending the model, con't

- Step 8 Add a creation symbol to the model diagram, and give it a value of 5. 
- Step 9 Add an immigration symbol to the model diagram, and give it a value of 2.
- Step 10 Add a loss symbol to the model diagram.
- Step 11 Rename the loss symbol death.
- Step 12 Draw an influence arrow from the compartment size to this symbol.



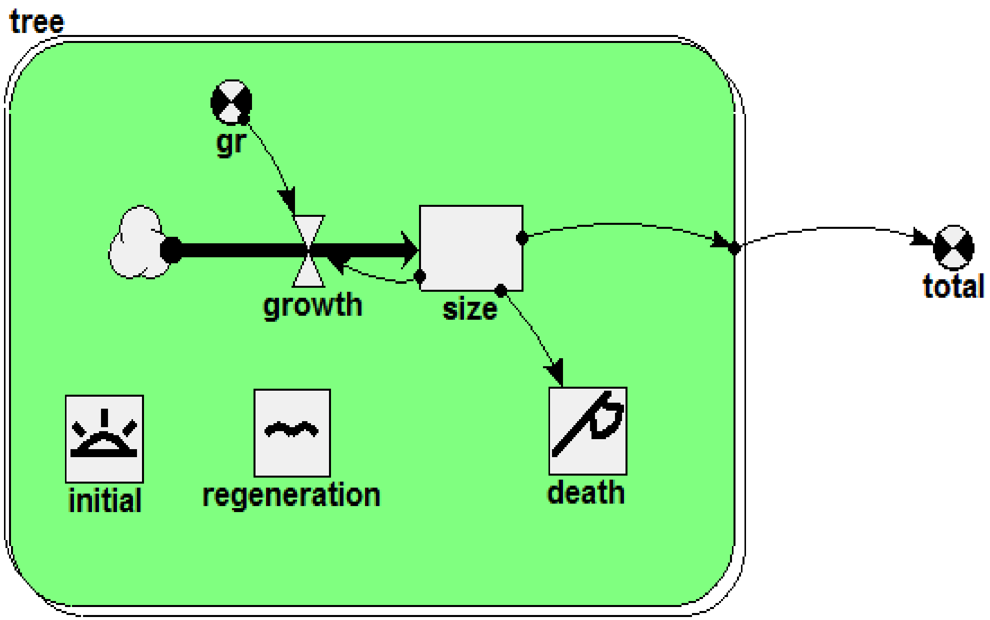
Rebuild the model

- Step 13 Enter the expression size>17 for the symbol labelled death.
- Step 14 Rebuild the model, and run it again.



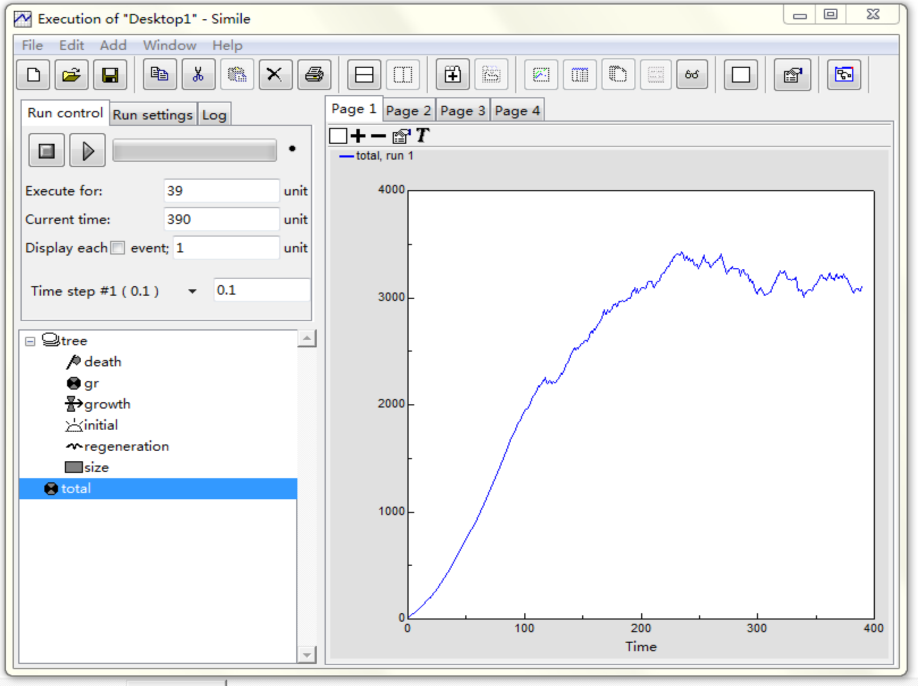
Calculating aggregate information

- Step 1 Add a variable outside the tree submodel, and rename it total.
- Step 2 Draw an influence arrow from the compartment size inside the tree submodel to the variable total.



Rerun the model, con’t

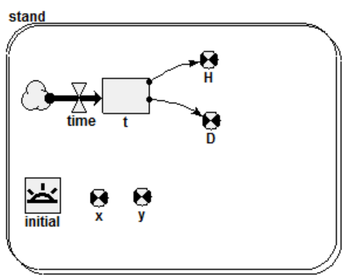
- Step 3 Enter the expression sum({size}) for the variable total.
- Step 4 Re-build the model.
- Step 5 Call up a plotter display for the variable total.
- Step 6 Run the model again.

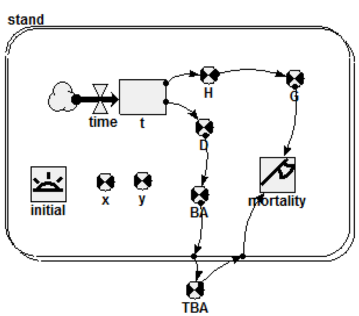


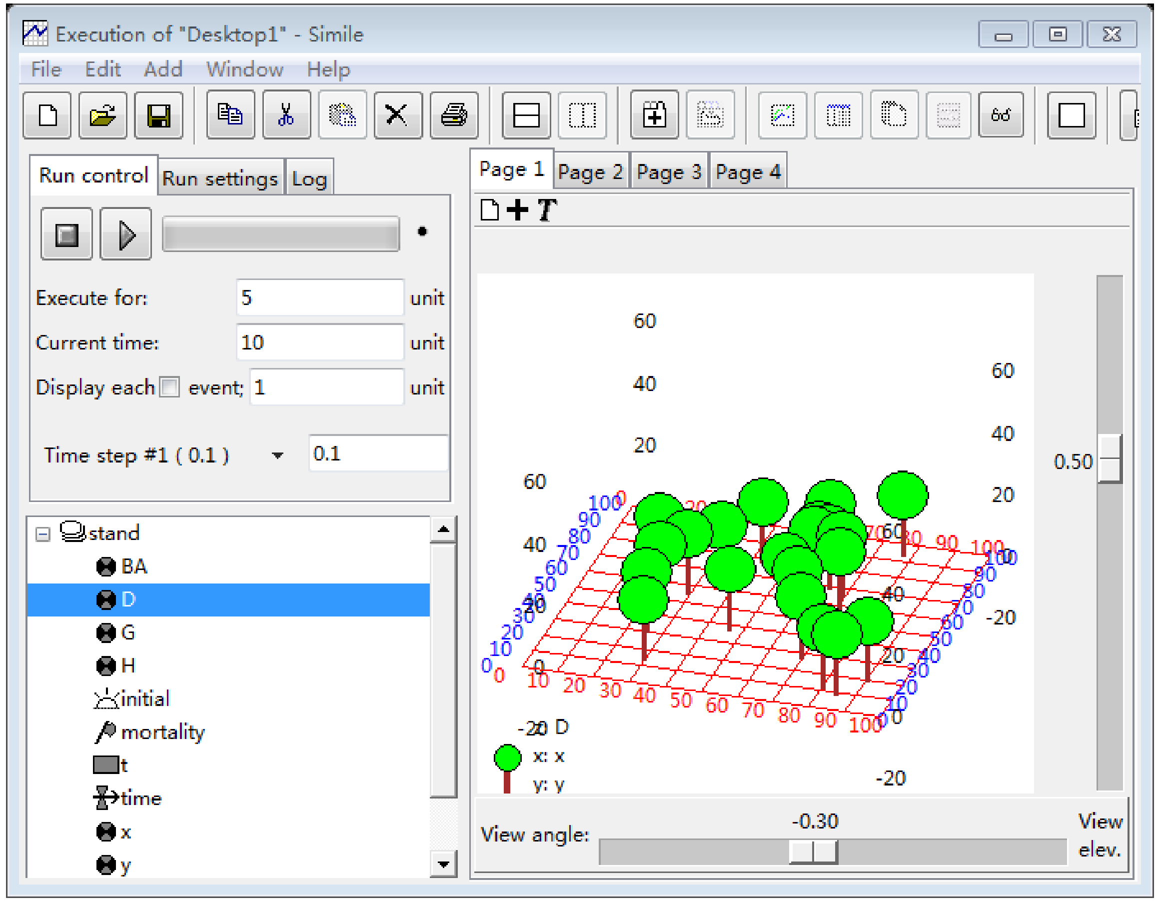
Visualising the trees

- Step 1 Add two variables inside the tree submodel, and rename them x and y.
- Step 2 Enter the following expression for the variable x: rand_const(0,50)
- Step 3 Enter the following expression for the variable y: rand_const(0,100).
- Step 4 Re-build the model.
- Step 5 Call up the lollipop display. When it prompts you for the three variables required to set up the display, click on the variable x, the variable y, and the variable size respectively, in that order.
- Step 6 Run the model again.

Visualization, con't







第三讲 林木结构

- 第一节 树干形状与树木结构
  - form factor, tree structure
- 第二节 伐倒木树干材积
  - with or without bark?
- 第三节 单株立木材积
  - height measurment?
- 第四节 异速生长原理
  - tree allometry, crown allometry
- Q3. 一元材积表，二元材积表，干形，削度方程的计算原理是什么？其精度提高与误差产生的原因是什么？

异速生长原理

- v = f(dbh), v = f(dbh,height)
- w_i = f(dbh), w_i = f(dbh,height)

- Allometric relationships
- w_i = alpha*w^beta
  - DBH ~ Height
  - DBH ~ Crown width
  - Height ~ Crown length
  - Crown ~ Roots
  - Basal area ~ Crown
  - Sapwood area ~ Crown

林木结构动态变化

- 立地

  对树高-胸径结构, 林冠结构的影响
- 年龄

  对树高-胸径结构, 林冠结构的影响
- 林层

  对树高-胸径, 林冠结构的影响
- 混交
  - 对树高-胸径, 林冠结构的影响，
  - tree-by-tree mixture vs group-by-group mixture

树高胸径动态变化

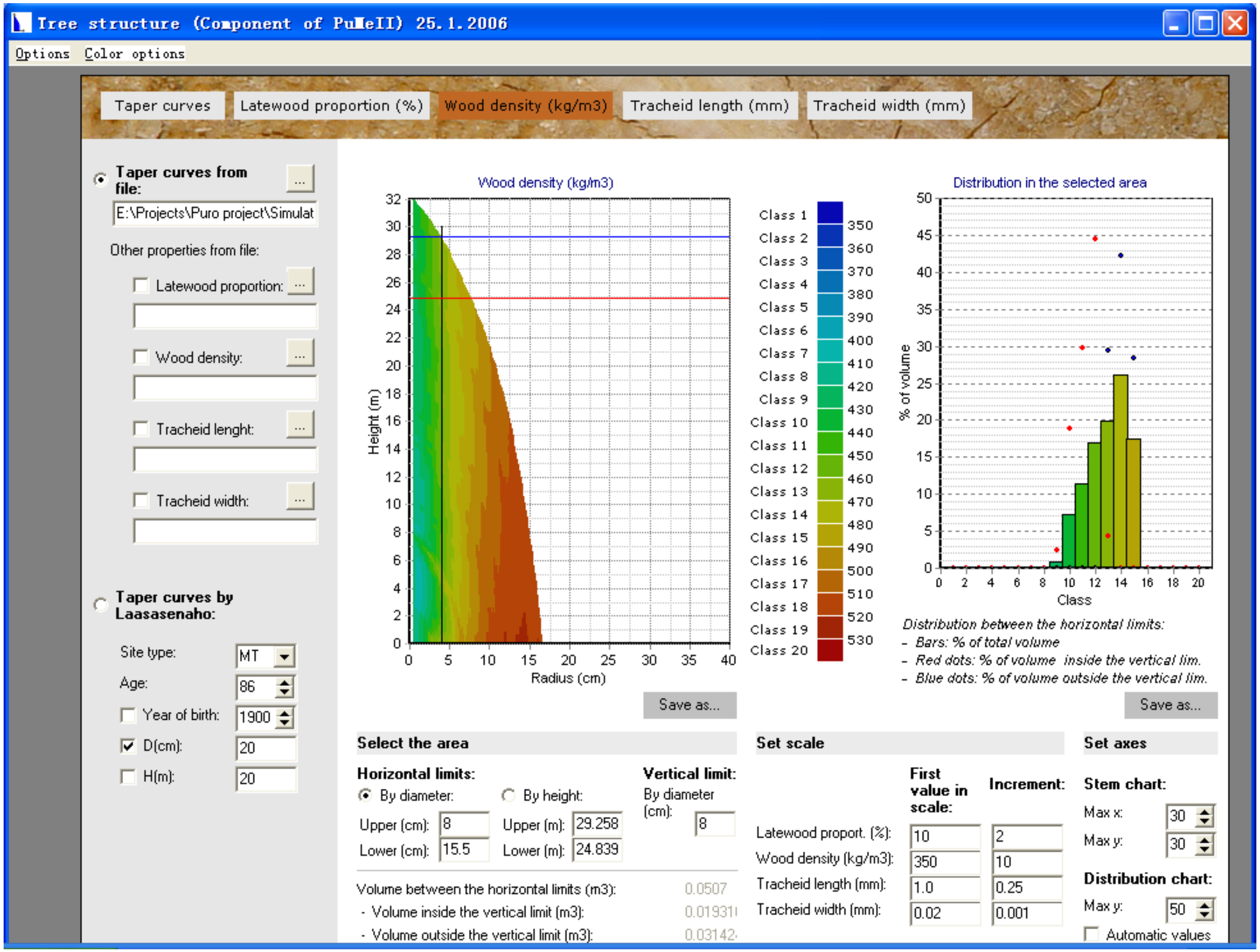
- 胸径动态变化，阔叶树 vs 针叶树
    - 针叶树，increased
    - 阔叶树，decreased

- 树高动态变化，林层

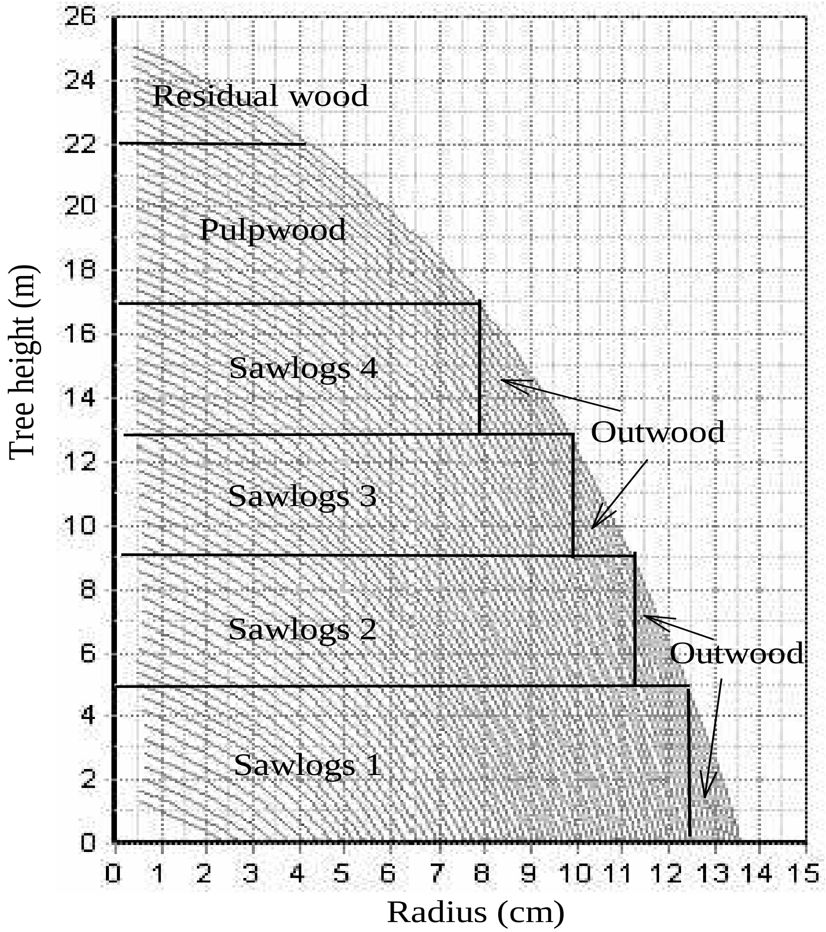
	纯林	混交林
针叶树	delta_H_sp1*100%	delta_H_sp1*(1-10%)
阔叶树	delta_H_sp2*100%	delta_H_sp2*(1+2%)

- 树高胸径结构，
    - Site effects
    - Competition

Tree structure analyzer (Cao et al. 2007)



Timber assortment (Cao et al. 2008)



第四讲 林分临时样地

- 第一节 林分调查因子
  - age, species composition, stand structure
  - regeneration method, site quality, DBH, Hdom
  - stand density, basal area, volume
- 第二节 适地适树原理
  - site specific, species specific
- 第三节 林木大小、立地条件与竞争
  - size, site, competition
- 第四节 矩形样地、圆形样地与带状样地
  - plot shape, inventory cost, sampling design
- Q4. 树高胸径结构，林冠结构，根冠比的生物学原理是什么？为什么要计算林木的结构？

Sampling techniques by data requirements

Table 5.1. Different applications require different sampling techniques.

Plot characteristics	Principal objective of permanent plot system			
	Resource inventory	Continuous forest inventory	Growth modelling	Site monitoring
Permanence	Temporary	Permanent	Permanent	Permanent
Area	Variable, $\propto$ tree size	Fixed	Fixed	Fixed
Within-plot variance	Hetero-geneous	Homo-geneous	Homo-geneous	Homo-geneous
Placement	Stratified random	Systematic	Stratified random	Purposive or systematic
Sample unit	Plot	Plot	Tree	Plant parts

Sampling principles

- Temporal distribution
  - Short time periods may give rise to biased growth estimates, and longer periods of observation offer a better basis.
- Spatial distribution
  - Permanent plots should sample an adequate geographical range, including latitude, longitude, elevation and other topographical features such as ridge and valley locations.
- Site factors
  - the sampling system should ensure that the full range of site factors (e.g. soil type and depth) is included in the permanent plot system.
- Stand conditions
  - stand structure and composition, should be manipulated experimentally to provide the best database.

Experiments design

- Passive monitoring data: survey data from forest areas under routine management.
- Treatment response data: from paired treatment and control plots (controlled experiments).

- Number of plots
- Size and shape of plots
- What to measure
- When to remeasure
- Data administration

Sampling design

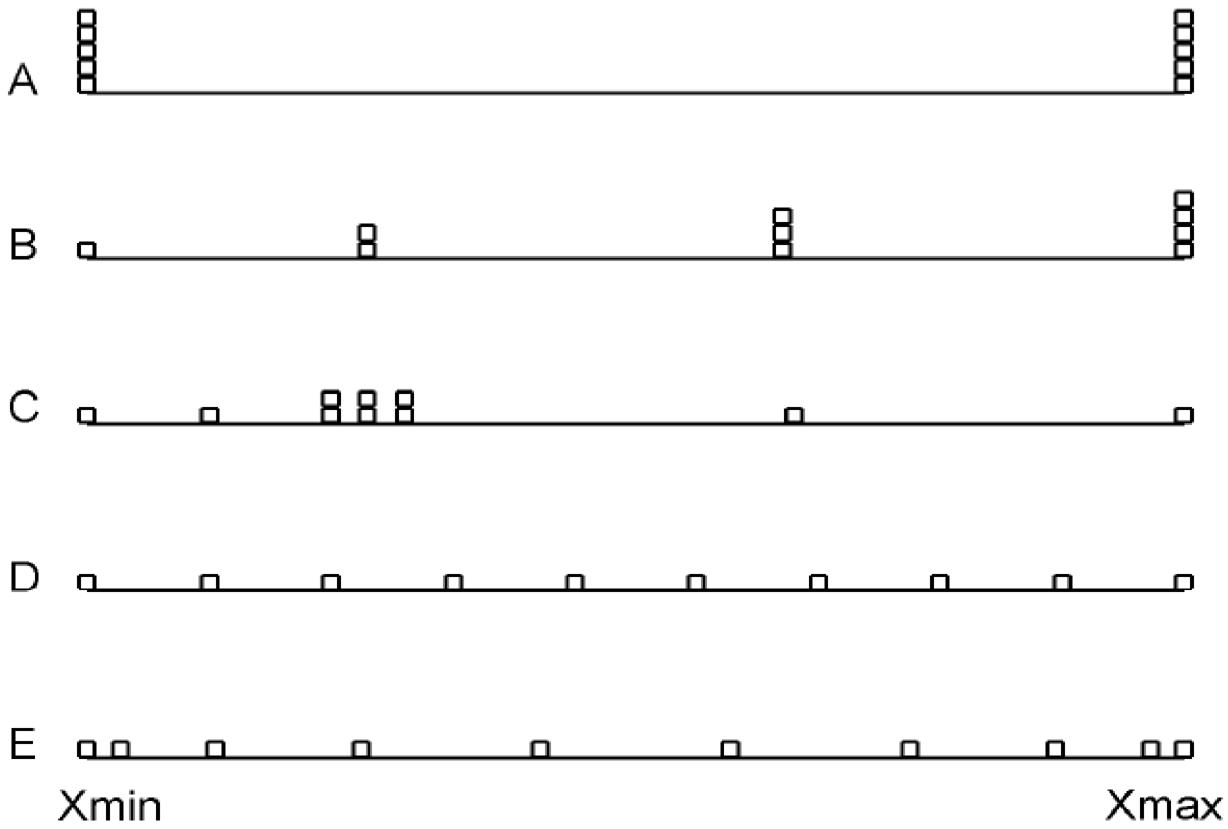


Fig. 5.2. Efficient placement of ten samples to (A) estimate slope of a straight line, (B) detect curvilinearity where variance ∝ X, (C) calibrate an optimum, (D) detect a threshold, and (E) fit a curved relationship.

Variables should be measured

- At the initial enumeration
  - Plot location, dimensions, orientation and area,
  - Species and coordinates of all trees on the plot,
  - Topographic details, including altitude, aspect, slope, position on slope,
  - Forest type and floristic attributes,
  - Physical soil characteristics (depth, texture, colour, parent material), and
  - Uniformity of the site

Variables, con't

- At the first measure, immediately after any harvest, and periodically (e.g. every second or third measure):
  - Sufficient tree heights for the determination of site productivity (or data necessary for alternative estimates of site productivity),
  - Merchantable heights and defect assessments of all stems (including non-commercial species, as utilization standards may change with time),
  - Crown characteristics (position, length, width, form, etc.);

Variables, con’t

- At every measure, assess all stems (including non-commercial; every stem from the previous measure must be reconciled) for:
  - Diameter (over bark, breast high or above buttress), height to measure point, and validity (to indicate defects at measure point and anomalous but correct increments),
  - Status (alive, dead, harvested, treated) and stance (erect, leaning, fallen, broken), and
  - Tree coordinates (recruits only);

Variables, con’t

- As necessary, record the occurrence of:
  - Logging, treatment and other activities, and the prescription used,
  - Scars and other damage with may affect measurements or growth,
  - Meteorological phenomena (drought, flood, etc.),
  - Mast years (heavy seed crops),
  - Pests, diseases, fire, or any othe aspect which may affect growth.

Forest inventory

Field form

Plot No ..... Subplot ..... Page ... of ...
Subplot Dimensions ...... x ...... Date ../../....
Orientation ..... Coordinates ....
Location ....
....
Assessing Officer ....

Tree number Coordinates					
Family Genus Species Common name					
DBH Point of measure Valid/approx					
Alive/dead/cut/missing Erect/leaning/fallen Broken/injury					
Tree height Bole height Crown position Crown form Crown diameter					
Merchantable length Stem straightness Stem defects					
Notes: Flower/fruiting Pests/disease					

Project 1. Predicting height growth

- (1) Data for modeling stand height growth

  Data set 1: point sampling data (Tab. 2.1, p.49, Tab. 4.1, p.57)

  Data set 2: stem analysis data (Appendix)

- (2) Candidate equations for height growth

H = a*exp(-b/Age), H = a*(1-exp(-b*Age)), H = a/(1+c*exp(-b*Age)),

H = a*exp(-b*exp(-c*Age)), H = a*exp(-b*Age^(-c)), H = a*(1-exp(-b*Age))^c

- (3) Statistic tests

  R^2, RMSE

- (4) Questions to be answered

4a. Predict height growth using different data sets.

4b. Compare and discuss prediction errors caused by different data and models, and explain why.

第五讲 林分固定样地

- 第一节 固定样地种类
  - NFI plots, research plots
- 第二节 固定样地作用
  - long-term, remeasured, dynamics
- 第三节 矩形样地与圆形样地
  - 20*30, 20*20, R fixed, d, h, x, y,
- 第四节 大样地
  - 100*100, biodiversity,

- Q5. 为什么要设立固定样地？其目的与理论依据是什么？

Plot layout

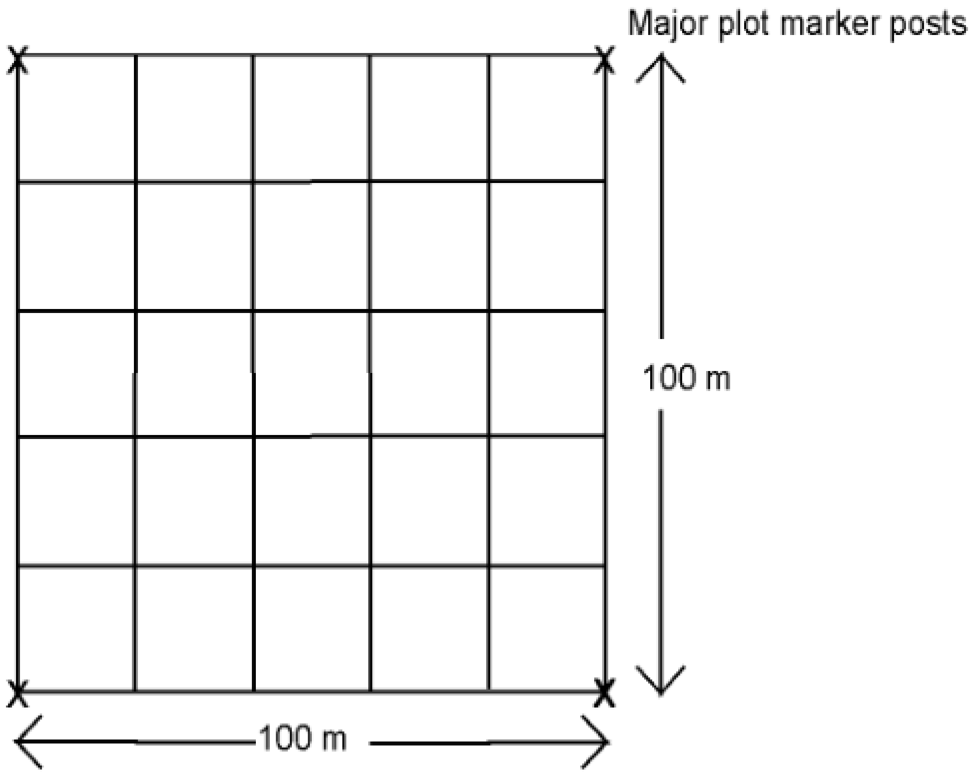


Fig. 5.4. Recommended plot layout for permanent sample plots.

Data problems

- The greatest problem facing many agencies is that the data necessary for growth model development are not available.

- Unreliable measurements
- Changes to procedures
- Mistaken or undetermined species identities

- No data set can be perfect, but many will be found to contain deficiencies that will frustrate future analyses.

Density experiment design

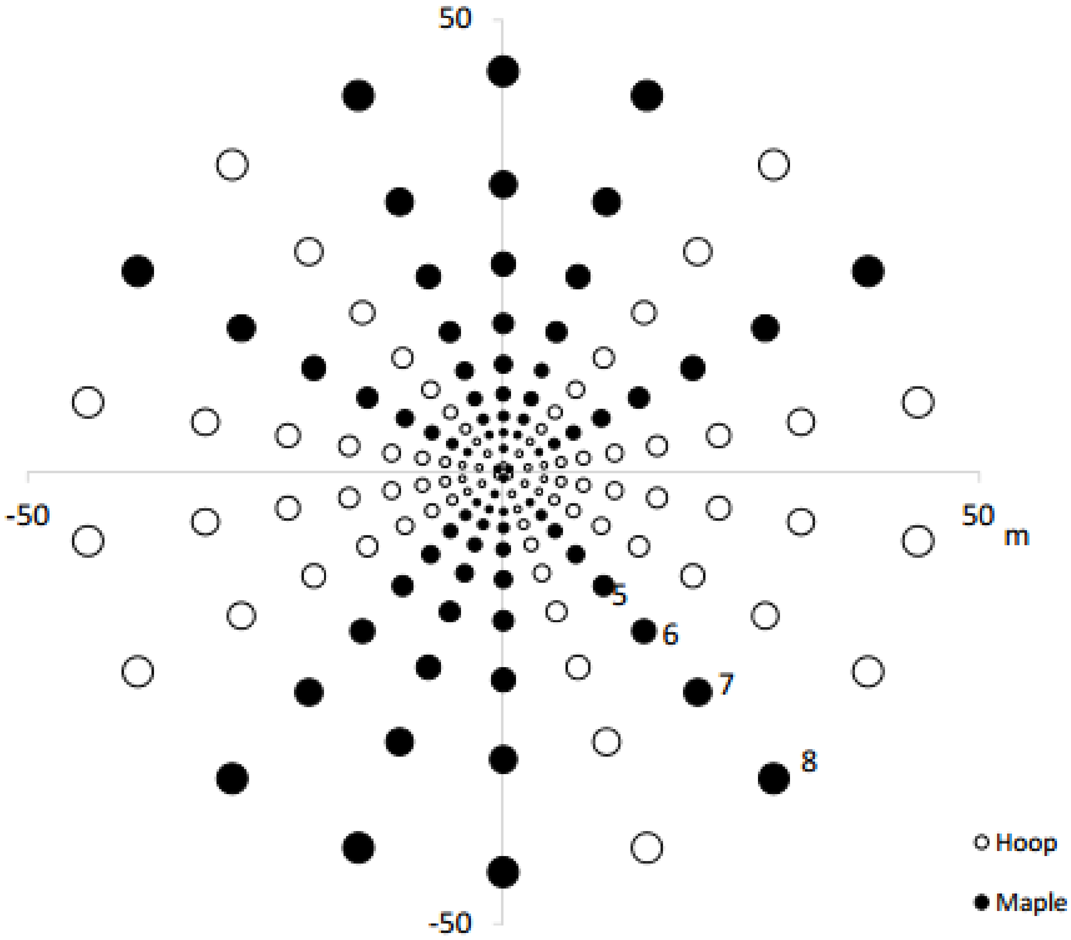


Figure 2. Google Earth image of Mt Mee Nelder trial, 20 July 2009 (© 2012 Google, © 2012 GeoEye, 27.096°S, 152.734°E), showing the two species, survival, and proximity of other plantings.

Planting experiment design

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	o	o	o	o	o	o	o	o	o	+	o	+	+	+	+	+	+	+	+	+
2	o	o	o	o	o	o	o	o	+	o	+	o	+	+	+	+	+	+	+	+
3	o	o	o	o	o	o	+	o	o	+	o	+	+	o	+	+	+	+	+	+
4	o	o	o	o	o	o	o	o	+	o	+	o	+	+	+	+	+	+	+	+
5	o	o	o	o	o	o	o	o	o	+	o	+	+	+	+	+	+	+	+	+
6	o	o	o	o	o	o	o	o	+	o	+	o	+	+	+	+	+	+	+	+
7	o	o	x	o	o	o	□	o	o	□	x	+	+	x	+	+	+	□	+	+
8	o	o	o	o	o	o	o	□	+	o	+	o	x	+	+	+	+	+	+	+
9	o	x	o	x	o	x	o	x	o	+	o	+	□	+	□	+	□	+	□	+
10	x	o	x	o	x	o	□	o	x	□	x	□	+	x	+	□	+	□	+	□
11	o	x	o	x	o	x	+	x	o	+	o	+	□	o	□	+	□	+	□	+
12	x	o	x	o	x	o	x	o	x	□	x	□	+	□	+	□	+	□	+	□
13	x	x	x	x	x	x	x	+	□	x	□	x	o	□	□	□	□	□	□	□
14	x	x	o	x	x	x	+	x	x	+	o	□	□	o	□	□	□	+	□	□
15	x	x	x	x	x	x	x	x	□	x	□	x	□	□	□	□	□	□	□	□
16	x	x	x	x	x	x	x	x	x	□	x	□	□	□	□	□	□	□	□	□
17	x	x	x	x	x	x	x	x	□	x	□	x	□	□	□	□	□	□	□	□
18	x	x	x	x	x	x	□	x	x	□	x	□	□	x	□	□	□	□	□	□
19	x	x	x	x	x	x	x	x	□	x	□	x	□	□	□	□	□	□	□	□
20	x	x	x	x	x	x	x	x	x	□	x	□	□	□	□	□	□	□	□	□

Figure 4. Design for a mixed species trial, showing planting positions for four species (o, +, x and □) in a 20 x 20 grid, showing three different viewpoints: the 3x3 viewpoint with 36 plots (top left), the 4x4 viewpoint with 25 plots (top right), and the 5x5 viewpoint with 16 plots (bottom left).

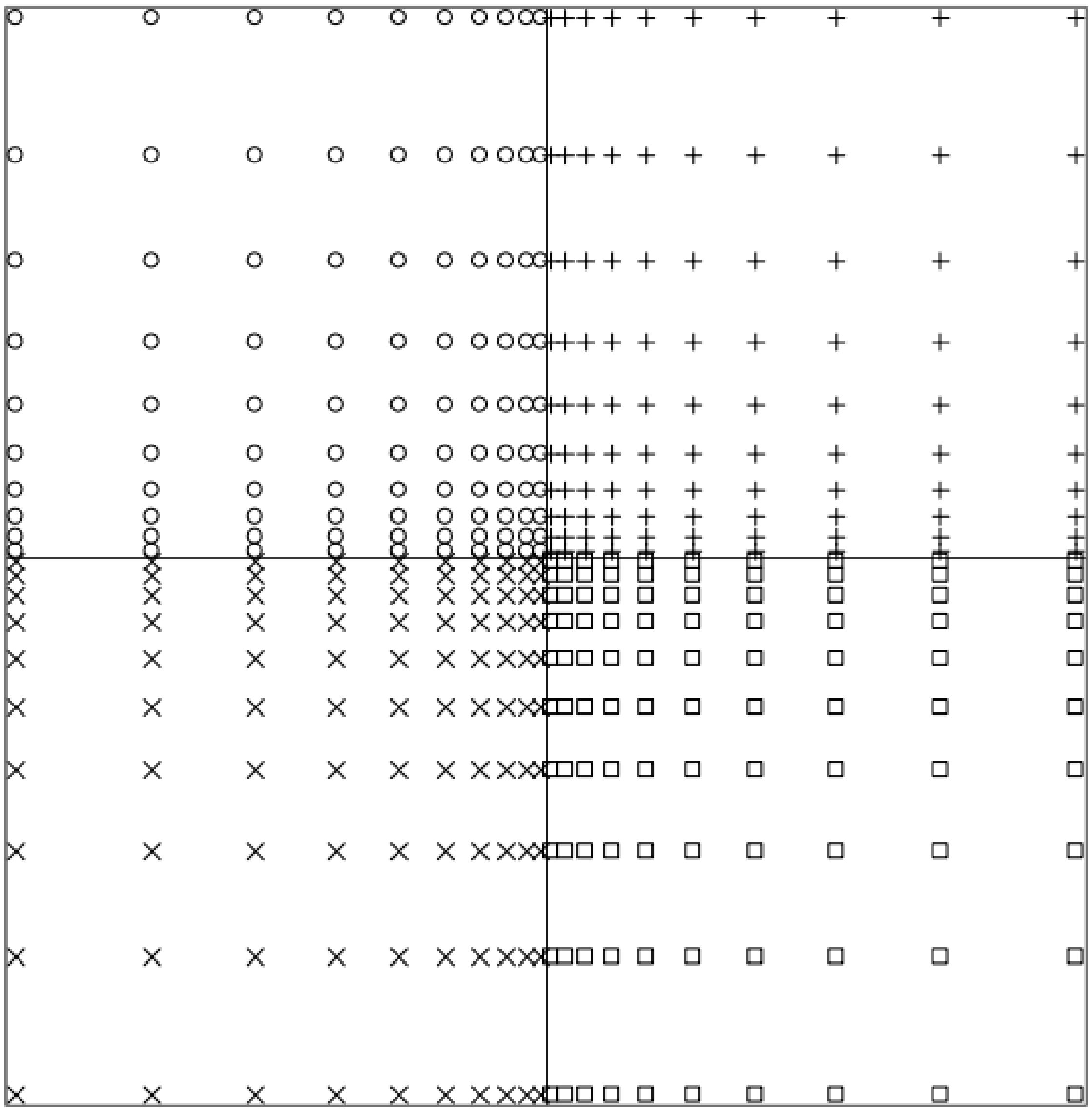
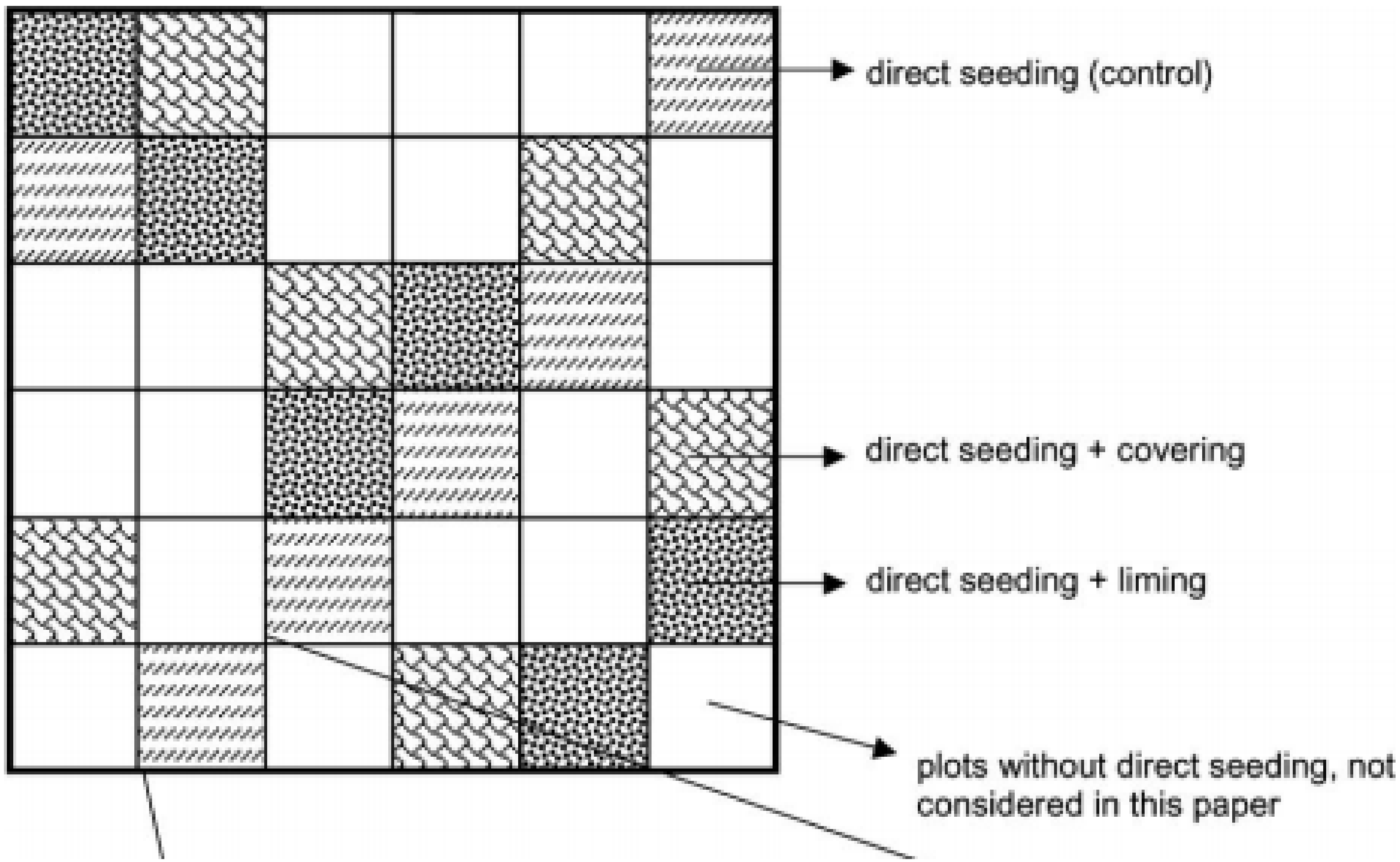
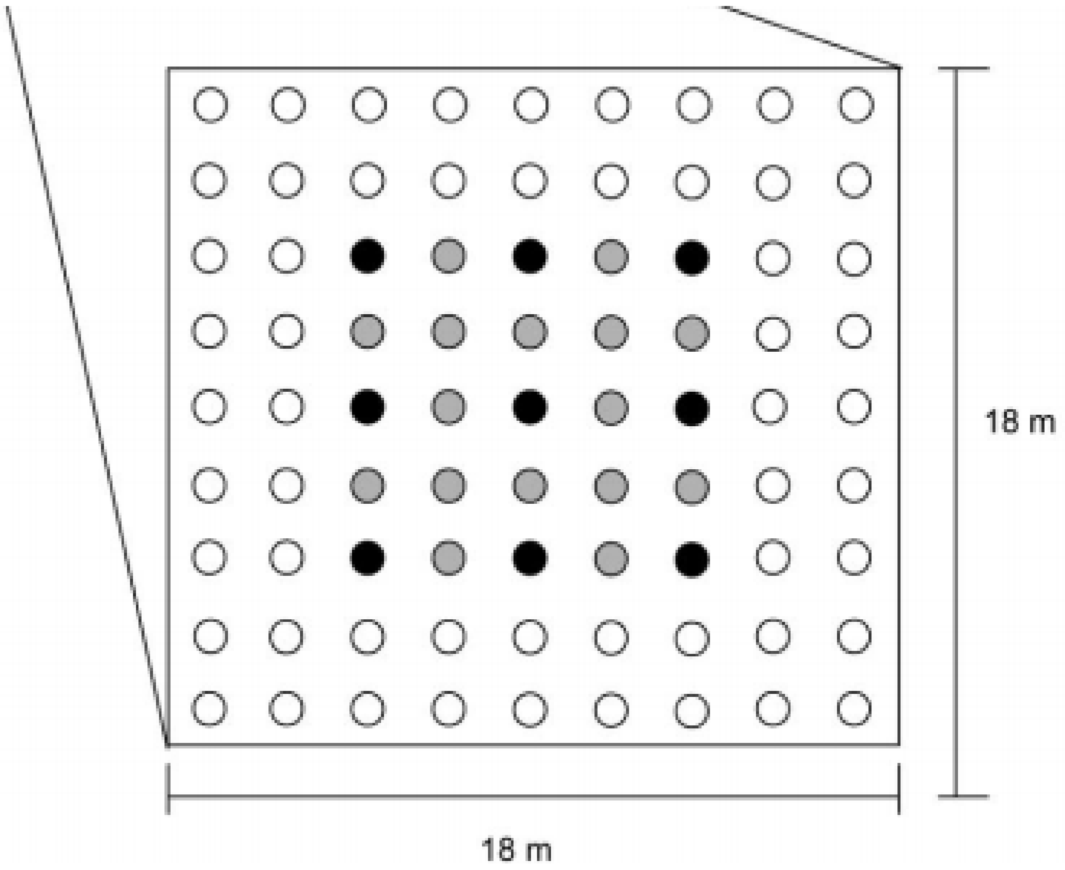


Figure 5. A possible design for a clinal planting to supplement the design in Figure 1, showing planting positions for 100 trees of each of four species (shown as o, x, + and □).

Regeneration experiment design



Experimental design



Lab Exercise

- Design a form to record field measurements during the initial enumeration of a permanent plot in a forest near you. Take it to the field and try it ! Enter the data from the form into a text or spreadsheet file on a computer.
- What problems did you detect in the field and during data entry, and how would you improve your form next time?
- Would you use the same form when the plot was re-measured; if not, what changes would you make?
- How could you include some of the data from the initial measure on the remeasure form, so that field crews could cross-check these details?

Types of forest inventory

- NFI (National Forest Inventory)
  一类调查，国家森林资源连续清查，p.83
  计划每5年调查1次
  样地大小 20m * 30m，2km * 4km 坐标单元
  全国约 230,000个样地

- Forest management planning
  二类调查，森林资源规划设计调查，p.83-84
  林业局 => 林场 => 林班 => 小班

- Silvicultural operations
  三类调查，作业设计调查，p. 84

森林调查 Forest inventory

- 小班定位
- 块状样地调查
- 块状样地境界测量
- 块状样地调查内容
- 标准地的基本要求
- 标准地的形状和面积
- 临时样地调查
- 固定样地调查

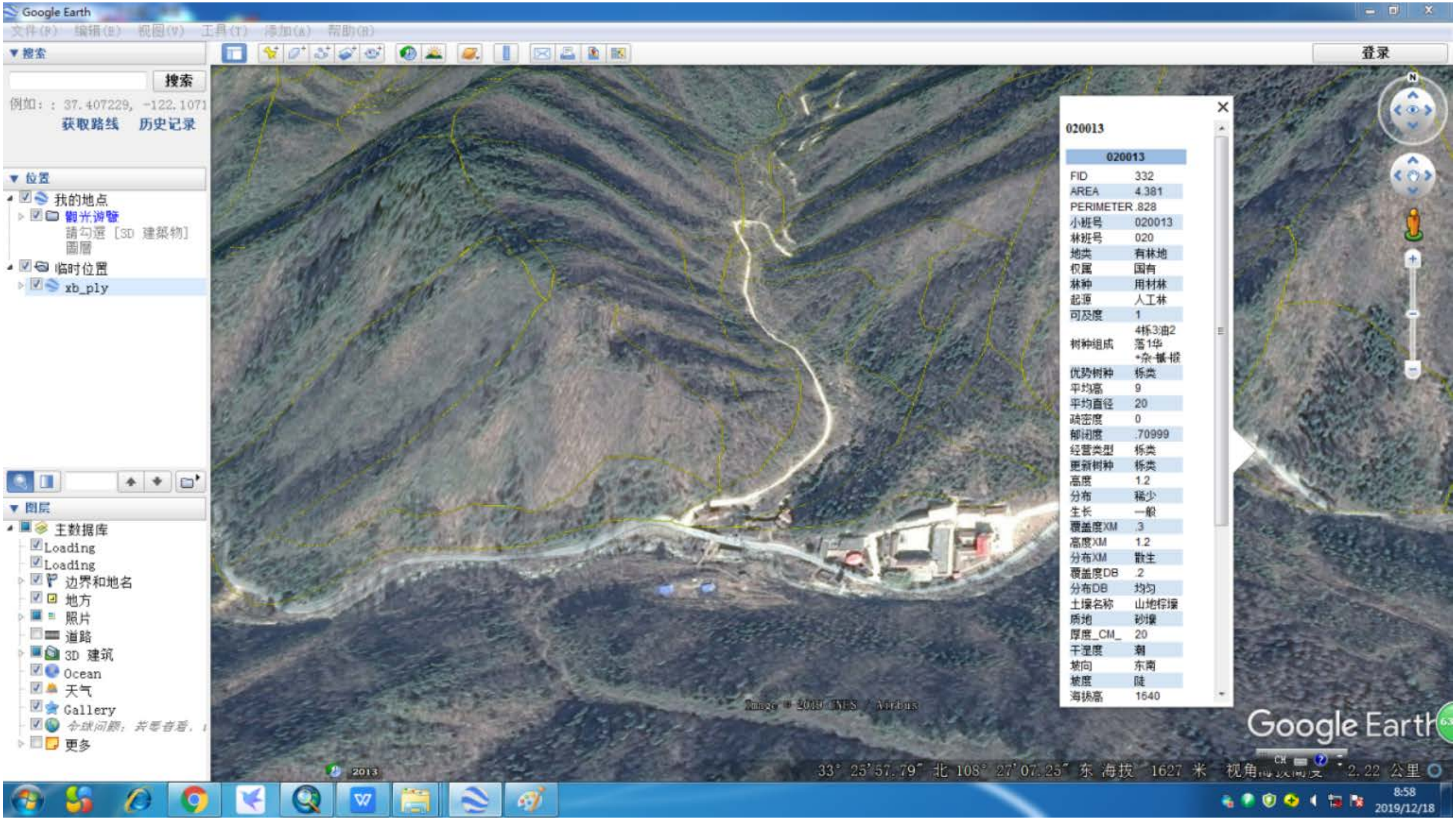
欧洲森林调查

- 瑞典
  - 瑞典NFI 从1923 年开始，以系统抽样为基础，包括永久样地（1983年确立）和临时样地。
  - 调查样地形状为方形或矩形，其大小在瑞典的不同地方而有所变化，南方比北方样地之间距离更近。
- 德国
  - 第二次全国森林调查，约44000个面积为150m * 150m，采用4km * 4km 或 2km * 2km 方格，
  - 方形群团样地的每个角落形成角规抽样次级样地中心
  - 断面积系数4.

北美森林调查

- 加拿大
  - 世界10%的森林，北半球森林的30%
  - 省政府77%，联邦政府16%，7%私有
  - 省级森林调查，10-15年
  - 全国森林调查，依靠省级数据输入
  - 工业林经营调查（经营管理调查，作业调查）
- 美国
  - 森林调查与分析（FIA），始于1930年。
  - P1，卫星图片，把土地分为森林和非森林用地
  - P2，每2439 ha 设置一个样地（森林生态系统资料）
  - P3，第二阶段样地，每39024 ha 设置一个（扩大的生态学数据）

火地塘教学林场二类调查 2005

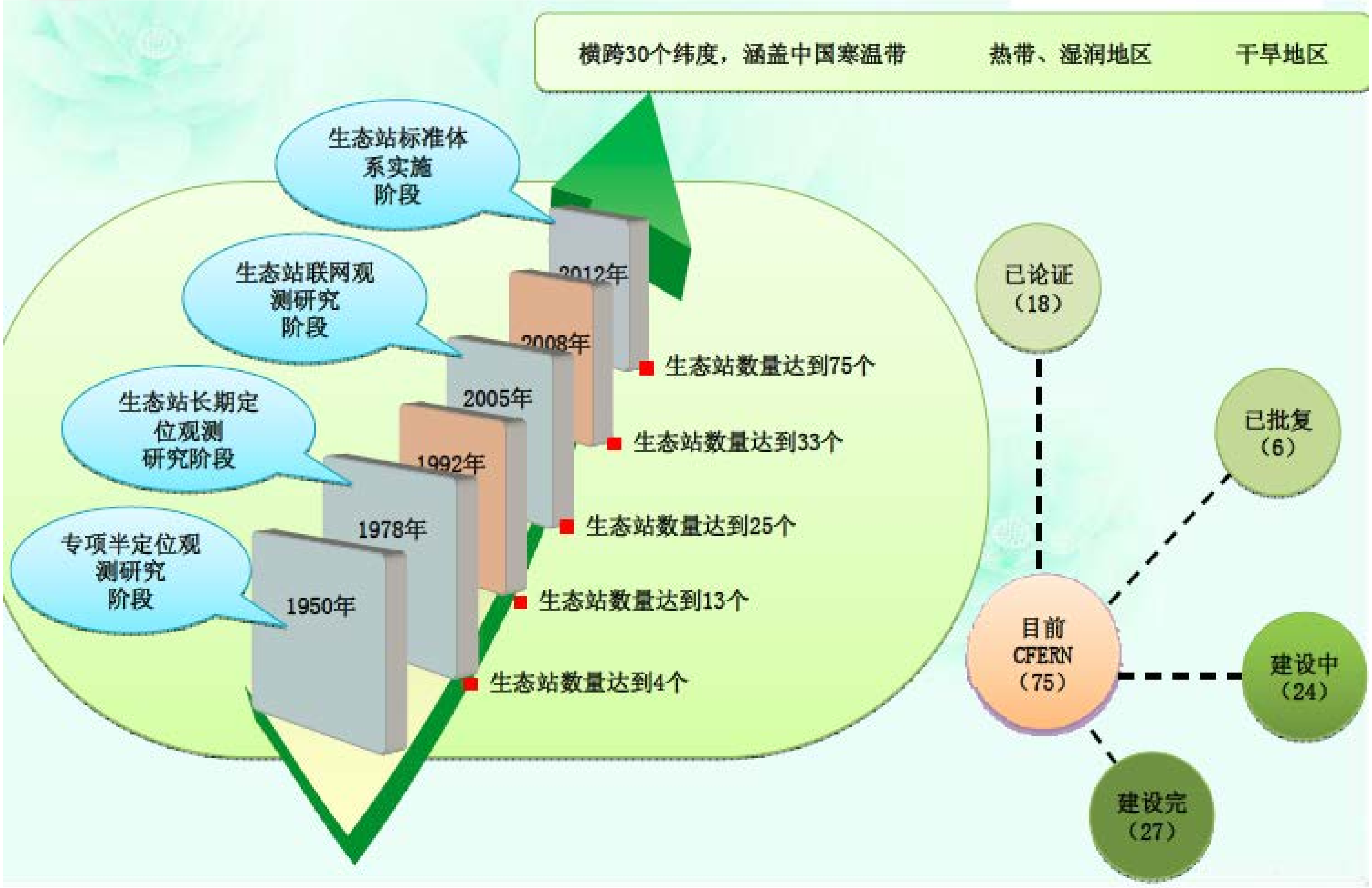


生态系统定位观测指标体系

- LTER 美国长期生态学计划 www.lternet.edu
- GTOS 全球陆地观测系统 www.fao.org/gtos
- ECN 英国环境变化网络 www.ecn.ac.uk
- GEMS 全球环境监测系统 www.unep.org/gemswater
- CNERN 国家生态系统观测研究网络 www.cnern.org
- CFERN 中国森林生态系统定位研究网络 www.cfern.org

CFERN 森林生态系统定位观测指标体系

CFERN history, www.cfern.org



CFERN 森林生态系统定位观测体系

- 森林水文
- 森林气象
- 森林土壤
- 森林病虫害
- 土壤微生物
- 森林群落
- 森林生产力
- 生物多样性
- 森林植物

水量分配空间格局

观测方法：LY/T1952-2011　森林生态系统长期定位观测方法　P13-18

通过定量研究林冠截留率、凋落物蓄水能力、土壤的渗透和蓄水能力，对森林生态系统不同层次水量空间分配格局及水量平衡分析，揭示森林生态系统水文要素的时空规律，为研究森林植被变化对水分的分配和径流的调节提供基础数据。

观测内容及仪器

观测内容	仪器
大气降水量	自记雨量计和激光雨滴谱仪
穿透降水量	集水槽和自记雨量计
树干径流量	自记雨量计和树干径流收集槽
枯枝落叶层持水量	精密电子天平
地表径流量	自记翻斗流量计 地表径流量测量系统
土壤含水量	铝盒、电子天平（精度0.01g），取土铲、烘箱、干燥器、时域反射仪（TDR）
壤中流量	壤中流收集槽和自记雨量计

常规气象

观测方法： LY/T1952-2011 森林生态系统长期定位观测方法 P54-57

目的：在森林典型区域内通过对风、温、光、湿、气压、降水、土温等常规气象因子进行系统、连续观测，获得具有代表性、准确性和比较性的林区气象资料，了解典型区域气象因子的变化规律，为确定影响森林植被生长发育的关键气象因子及研究森林对气候的影响提供基础数据。

观测内容

天气现象、风、空气温度、地表面和地下10cm、20cm、30cm、40cm的土壤温度、空气湿度、辐射、冻土、大气降水、水面蒸发。

仪器

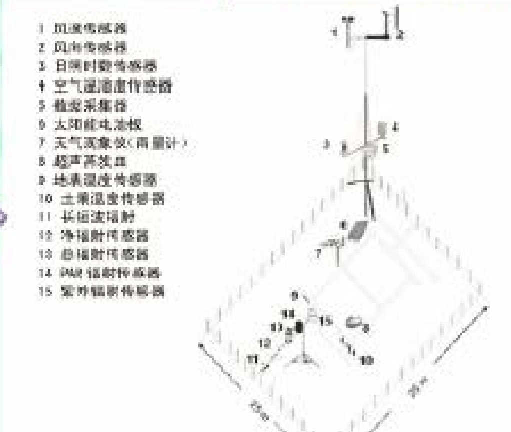
- 天气现象观测仪
- 自动气象站

在同一地区的不同部位，由于受不同地形的影响，气象要素均可能会有显著的差异，都不能真实反映这个地区自由大气的实际变化情况。

观测场设置 → 25m×25m；丘陵、浅山地区 20m（南北向）×16m（东西向）

观测场内仪器布设和安装

自动气象站和天气气象观测仪



森林常规气象观测场布设

森林小气候

观测方法： LY/T1952-2011 森林生态系统长期定位观测方法 P57-61

目的：通过对森林生态系统典型区域不同层次风、温、光、湿、气压、降水、土温等气象因子进行长期、连续观测，了解林内气候因子梯度分布特征及不同森林植被类型的小气候差异，揭示各种类型小气候的形成过程中的特征及其变化规律，为研究下垫面的小气候效应及其对森林生态系统的影响提供数据支持。

观测内容

项目或指标	位置和高度
风向	冠层上3m和地被层（2个高度）
温度	冠层上3m、冠层下1.5m、冠层中部、地被层（4个高度）
湿度	
风速	
总辐射	冠层上3m、冠层下1.5m、冠层中部、地被层（4个高度，总辐射或光合有效辐射任选一种，在冠层上可加净辐射）
净辐射	
光合有效辐射	
土壤热通量	地面下5cm、10cm（2个深度）
土壤温度	地面以下（5cm、10cm、20cm、40cm）（4个深度） 地面下（5、10、15、20、40、60、100cm）处
土壤水分	地面下（5cm、10cm、20cm、40cm）
降水量 雨强	地被层（1个高度）

仪器

森林小气候观测系统

碳通量

观测方法： LY/T1952-2011 森林生态系统长期定位观测方法 P61-63

目的：通过微气象法为主体的通量观测方法对典型森林生态系统植被-大气界面的CO_2及水热量通量进行长期、连续地观测，掌握其动态变化规律，并分析森林生态系统碳源/汇的时空分布特征，探讨森林生态系统碳收支和水热平衡过程及其对环境变化的响应，为深入研究森林生态系统中的碳循环过程及其调控机理提供科学依据。

仪器 → 涡度相关系统

观测内容：
- 湍流数据
  - x轴水平风速
  - y轴水平风速
  - z轴垂直风速
- 二氧化碳绝对密度
- 水汽绝对密度
- 脉动温度

优点：
1）对环境无干扰；
2）研究尺度适宜；
3）样地可纵向空间扩展；
4）可连续观测。

局限：
1）地形坡度易使CO2发生侧漏；
2）小范围推至大范围时误差较大；
3）夜间湍流混合不均匀会引起呼吸通量低估；
4）在复杂地形等非理想条件下，同量观测结果不确定因素较多。

观测场设置 → 要求 ：下垫面相对平，坡度不超过5° ；风向相对稳定；植被在上风向有足够的水平纵身；研究区域面积≥1ha。

土壤理化性质

观测方法： LY/T1952-2011 森林生态系统长期定位观测方法 P31-37

目的： 通过对森林生态系统土壤理化性质指标长期连续观测，了解森林生态系统土壤发育状况及其理化性质的空间异质性，分析森林生态系统土壤与植被和环境因子之间的相互影响过程，为深入研究森林生态系统各生态学过程与森林土壤之间的相互作用，充分认识土壤在森林生态系统中的功能提供科学依据。

观测内容

土壤物理性质观测指标：土壤层次、土壤厚度、土壤颜色、土壤湿度、土壤结构、土壤机械组成、土壤质地、土壤容重、土壤含水量、土壤总孔隙度、毛管孔隙度、非毛管孔隙度等。

土壤化学性质观测指标：土壤pH值、土壤阳离子交换量、土壤交换性钙和镁（盐碱土）、土壤交换性钾和钠、土壤交换性酸量（酸性土）、土壤交换性盐基总量、土壤碳酸盐量（盐碱土）、土壤有机质含量、土壤水溶性盐分总量、土壤全氮量、碱解氮量、亚硝态氮量、土壤全磷含量、有效磷含量、土壤全钾含量、速效钾含量、缓效钾含量、土壤全镁含量、有效态镁含量、土壤全钙含量、有效钙含量、土壤全硫含量、有效硫含量等。

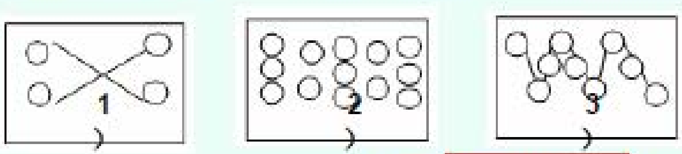
土壤有机碳

观测方法： LY/T1952-2011 森林生态系统长期定位观测方法 P37-39

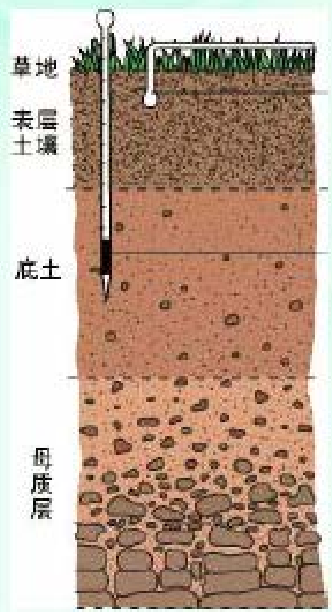
目的： 通过对森林生态系统土壤有机碳储量系统连续观测，建立土壤碳库清单，评估其历史亏缺或盈余，测算土壤碳固定潜力，为进一步深入研究森林生态系统碳循环，为合理评价土壤质量和土壤健康、正确认识森林土壤固碳能力提供基础依据。

样地布设

对角线采样法	样地平整，肥力均匀，采样点不少于5个。
棋盘式采样法	样地平整，肥力不均匀，采样点不少于40个。
蛇形采样法	地势不平坦，肥力不均匀，采样点根据样地面积而定。



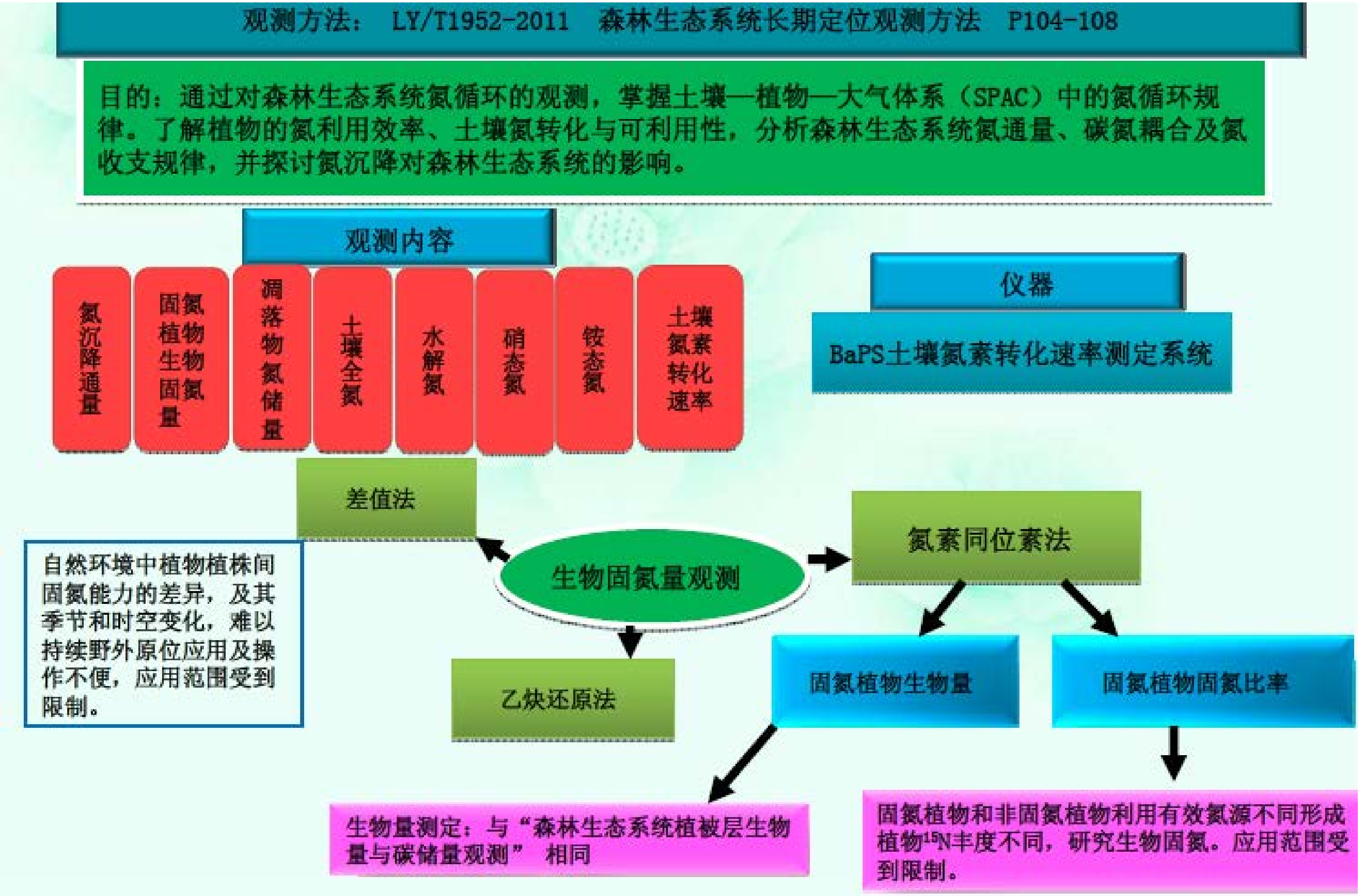
观测与采样方法
- 剖面法
- 土钻法



观测内容
- 土壤有机碳储量
- 土壤有机碳密度
- 土壤有机碳含量
- 土壤容重
- 土层厚度

全球土壤有机碳密度分布

氮循环


观测方法： LY/T1952-2011 森林生态系统长期定位观测方法 P104-108
目的：通过对森林生态系统氮循环的观测，掌握土壤—植物—大气体系（SPAC）中的氮循环规律。了解植物的氮利用效率、土壤氮转化与可利用性，分析森林生态系统氮通量、碳氮耦合及氮收支规律，并探讨氮沉降对森林生态系统的影响。
观测内容
氮沉降通量
固氮植物生物固氮量
凋落物氮储量
土壤全氮
水解氮
硝态氮
铵态氮
土壤氮素转化速率
仪器
BaPS土壤氮素转化速率测定系统
差值法
自然环境中植物植株间固氮能力的差异，及其季节和时空变化，难以持续野外原位应用及操作不便，应用范围受到限制。
生物固氮量观测
乙炔还原法
氮素同位素法
固氮植物生物量
固氮植物固氮比率
生物量测定：与“森林生态系统植被层生物量与碳储量观测” 相同
固氮植物和非固氮植物利用有效氮源不同形成植物15N丰度不同，研究生物固氮。应用范围受到限制。

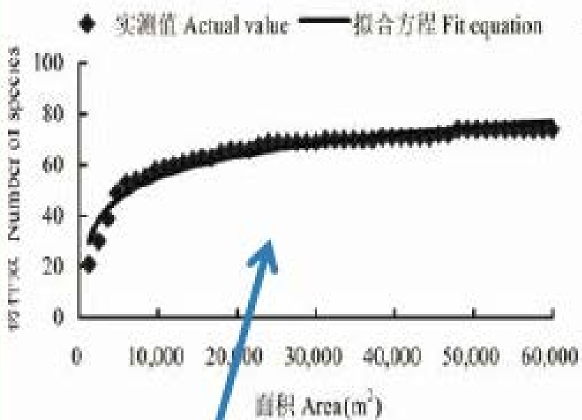
固定样地

观测方法： LY/T1952-2011 森林生态系统长期定位观测方法 P73-79

通过选定具有代表群落基本特征（如种类组成、群落结构、层片、外貌以及数量特征等）的地段作为森林生态系统长期定位观测样地，获取森林生态系统结构参数的样地观测数据，为森林生态系统水文、土壤、气候等观测提供背景资料。同时，揭示森林生态系统生物群落的变化规律，为深入研究森林生态系统的结构与功能、森林可持续利用的途径和方法提供数据服务。

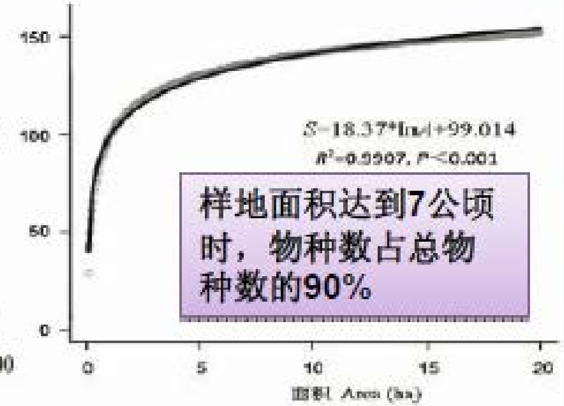
样地选择

在具有代表性的植被类型且受人为干扰少、交通便利的地方设置；面积足够大、林相相同、地形变化尽量一致。根据以往研究成果和大于种群最小面积原则，样地面积设为6ha。



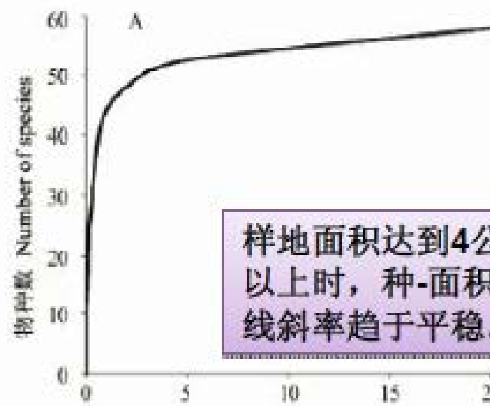
巩合德等（2011）（京半山）

样地面积达到6公顷时，物种数占总物种数的80%。



样地面积达到7公顷时，物种数占总物种数的90%。

杨庆松等（2011）（天童山）



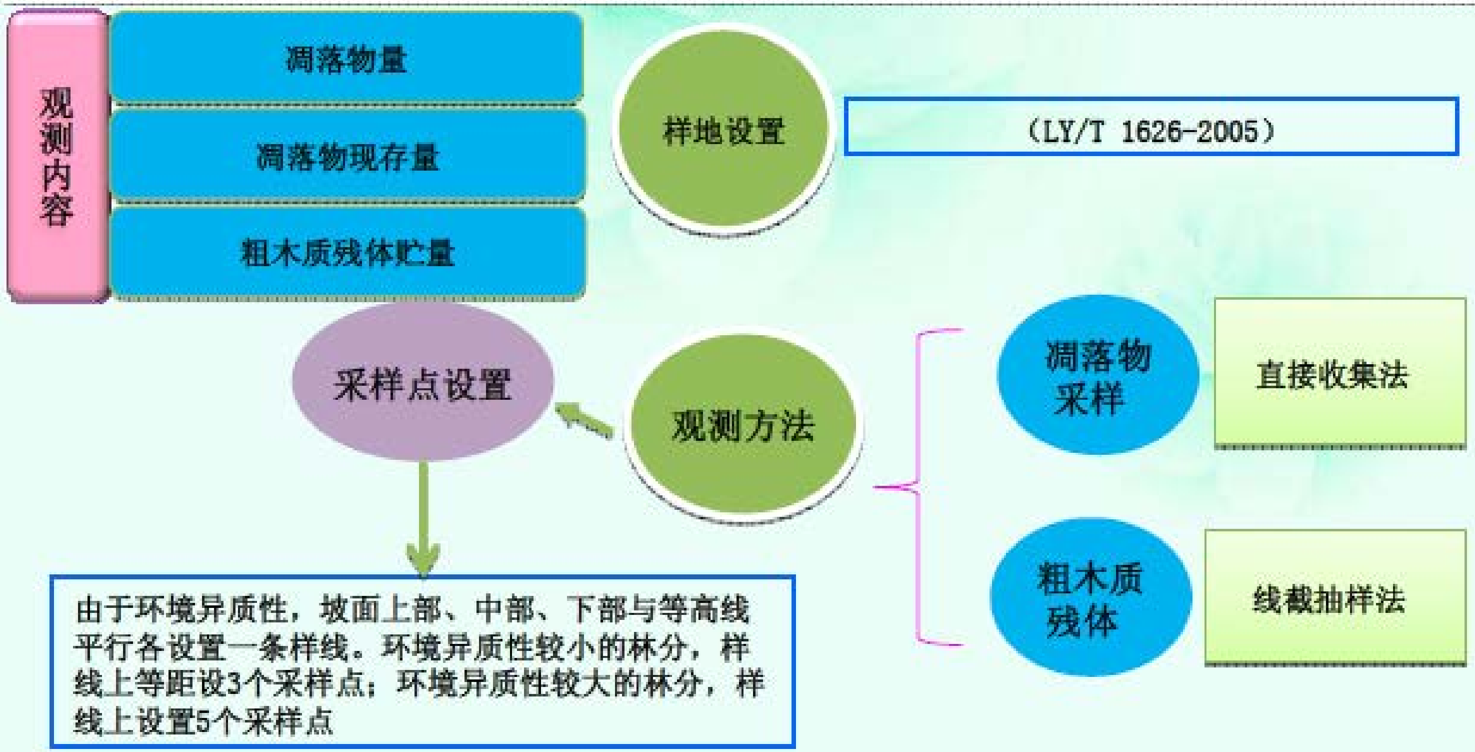
样地面积达到4公顷以上时，种-面积曲线斜率趋于平稳。

刘海丰等（2011）（东灵山）

凋落物与粗木质残体

观测方法：LY/T1952-2011　森林生态系统长期定位观测方法　P90-94

目的：通过对森林生态系统凋落物、粗木质残体的长期观测，获取年凋落物量、粗木质残体贮量和凋落物分解速率的准确数据，掌握凋落物和粗木质残体分解规律，探讨凋落物和粗木质残体种类、数量和贮量上的消长与森林生态系统物质循环及养分平衡的相互关系，为研究森林土壤有机质的形成和养分释放速率、测算森林生态系统的生物量和生产力奠定基础。



植被层碳储量

观测方法：　LY/T1952-2011　森林生态系统长期定位观测方法　P86-90

野外实测森林生态系统总生物量与净初级生产力，探索基于森林生态系统碳密度空间分布特征；研究森林生态系统碳储量及年净固碳量的动态变化规律，为森林生态系统碳汇功能以及森林生态系统碳储量和碳循环研究提供基础数据。

观测内容

- 乔木层生物量
- 灌木层生物量
- 草本层生物量
- 藤本生物量

样地清查法

平均生物量法

直接、准确，技术简单，适合于长期连续观测　。

生物量转换因子法

对于某一特定的森林类型而言，生物量转换因子是立木的生物量和蓄积量的集中体现，与树木的年龄、种类组成、立地条件和林分密度等有关，不能准确估算森林生物量。

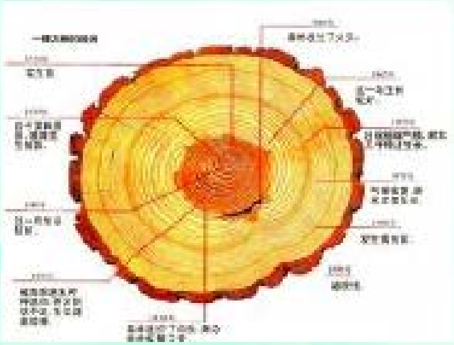
生物量转换因子连续函数法

存在着一定的数学推理问题，即难以实现由样地调查推算到区域尺度的转换　。

年轮分析

观测方法：　LY/T1952-2011　森林生态系统长期定位观测方法　P94-99

通过树木年轮宽度、密度测定及年轮元素分析，建立树木年轮表，探求不同树种生长与气候因子的关系，推测过去环境变化尤其是环境污染状况。根据区域内的气象资料和同时期的树木年轮信息，建立树木年轮数据与气象数据的相关关系，并据此重建典型气候带的气候变化谱，进一步揭示气候变化对森林生态系统的影响。



观测内容

- 年轮宽度
- 早材宽度
- 晚材宽度
- 早材密度
- 晚材密度
- 年轮密度
- 最大年轮密度
- 最小年轮密度
- 早材晚材界线密度

仪器

- 负离子检测仪
- 量子级联激光探测器系统

观测方法

采样方法：每个样地同个树种样本为20~30株，树木基部、根茎无动物洞穴、无干梢、树干通直，树龄较长的古老树木；有休眠的树木应在树木的休眠期进行，无休眠的树木四季皆可采样，采集完成后应对树体进行面病虫害预防措施。

样地设置：根据研究目的，按照海拔、坡向、坡位等因素进行样地设置，选取土层较薄、坡度较大、受人类干扰小的地点。

森林健康评估

观测方法： LY/T1952-2011 森林生态系统长期定位观测方法 P116-120

通过对人类活动或自然因素所引起森林生态系统破坏和退化所造成的森林生态系统结构紊乱和功能失调的诊断，获得一个实用、有效、可操作性的评估指标体系。同时对森林生态系统生产力水平、结构状态、抵抗外界干扰能力以及服务功能综合能力进行评估，揭示森林生态系统的健康状况，推动森林生态系统管理目标的实现。

观测内容

- **生产力指标**：胸径年平均生长量、树高年平均生长量、林分蓄积生长量 、年增长生物量、林地当年凋落量。
- **结构指标**：森林覆盖率、起源、林冠结构、生物多样性指数、郁闭度、灌木盖度、草本盖度、群落现存生物量、保护动植物的种类数、土壤pH值 。
- **干扰指标**：人为干扰程度、病虫害发生程度 、水灾危害程度、旱灾危害程度、火灾发生程度 、酸雨危害程度、林地土壤的侵蚀强度、林木受污染物危害的程度。
- **服务功能指标**：水质等级、林外林内温度差值、林外林内湿度差值、固定CO_2 量、 O_2 释放量、空气负离子浓度、吸收污染物能力。

森林健康评价指标

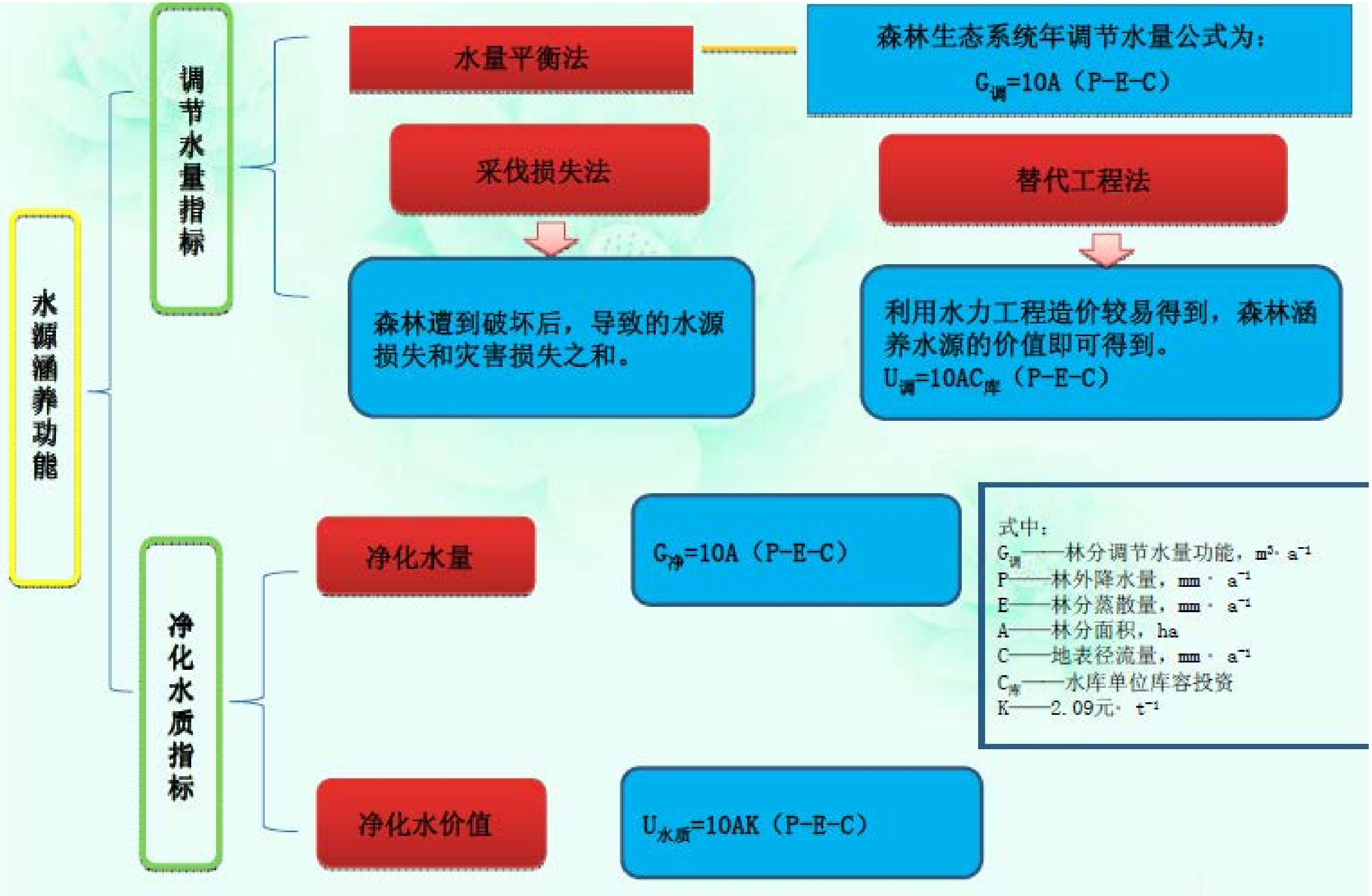
根据LY/T 1721-2008的评估公式，计算生态观测单元的物质量和价值量，通过由点到面的数据转换，把各测算单元数据逐级汇总得出结果。

$$FEHI = \ln\left(\sum_{i=1}^{5} P \bullet \sum_{j=1}^{10} S \bullet \sum_{m=1}^{8} D \bullet \sum_{n=1}^{7} F\right)$$

FEHI——森林生态系统健康评估指数
P——生产力指标
S——结构指标
D——干扰指标
F——生态功能指标
当干扰指标中任何一项指标赋值为1 时，所评估的森林生态系统健康等级即为不健康状态。

健康分类	评判指标
不健康	FEHI＜9.0
亚健康	9.0≤FEHI＜10.0
基本健康	10.0≤FEHI＜11.0
健康	FEHI≥11.0

水源涵养功能评价指标


水源涵养功能
调节水量指标
水量平衡法
森林生态系统年调节水量公式为：
G调=10A（P-E-C）
采伐损失法
森林遭到破坏后，导致的水源损失和灾害损失之和。
替代工程法
利用水力工程造价较易得到，森林涵养水源的价值即可得到。
U调=10AC库（P-E-C）
净化水质指标
净化水量
G净=10A（P-E-C）
净化水价值
U水质=10AK（P-E-C）
式中：
G调——林分调节水量功能，m³·a⁻¹
P——林外降水量，mm·a⁻¹
E——林分蒸散量，mm·a⁻¹
A——林分面积，ha
C——地表径流量，mm·a⁻¹
C库——水库单位库容投资
K——2.09元·t⁻¹

土壤保育，固碳释氧功能评价指标

保育土壤功能

固土指标 →

年固土量：$G_{固土}=A(X_2-X_1)$

固土价值：$U_{固土}=AC_{土}(X_2-X_1)$

保肥指标 →

年保肥量：$G(N、P、K)=A(N、P、K)(X_2-X_1)$

年保肥价值：

$U_{肥}=A(X_2-X_1)(NC_1/R_1+PC_1/R_2+KC_2/R_3+MC_3)$

$G_{固}$——林分年固土量，$t\cdot a^{-1}$

X_1——林地侵蚀模数，$t\cdot ha\cdot a^{-1}$

X_2——无林地土壤侵蚀模数，$t\cdot ha\cdot a^{-1}$

A——林分面积，ha

M——土壤林分有机质含量，%

N——土壤平均含氮量，%

P——土壤平均含磷量，%

K——土壤平均含钾量，%

$C_{1,2,3}$——化肥价格，元

$R_{1,2,3}$——化肥中元素含量，%

固碳释氧功能

森林固定CO_2量的计算方法

实验测定固定CO_2的量

光合作用和呼吸作用方程式

年固碳量：$G_{碳}=A(1.63R_{碳}B_{年}+F_{土壤碳})$

年制氧量：$G_{氧}=1.19AB_{年}$

年固碳价值：$U_{碳}=AC_{碳}(1.63R_{碳}B_{年}+F_{土壤碳})$

年制氧量：$G_{氧}=1.19C_{氧}AB_{年}$

营养积累，大气净化功能评价指标

森林生物多样性评价指标

基于Shannon-Wiener指数森林物种多样性保育价值的计算方法

其公式为：$U_{生物} = S_{生} A$

第一次修正

增加濒危指数修正的物种多样性保育价值评估计算方法

- 公式为：$U_{总} = (1+\sum_{i=1}^{n} E_i \times 0.1) S_{生} A$

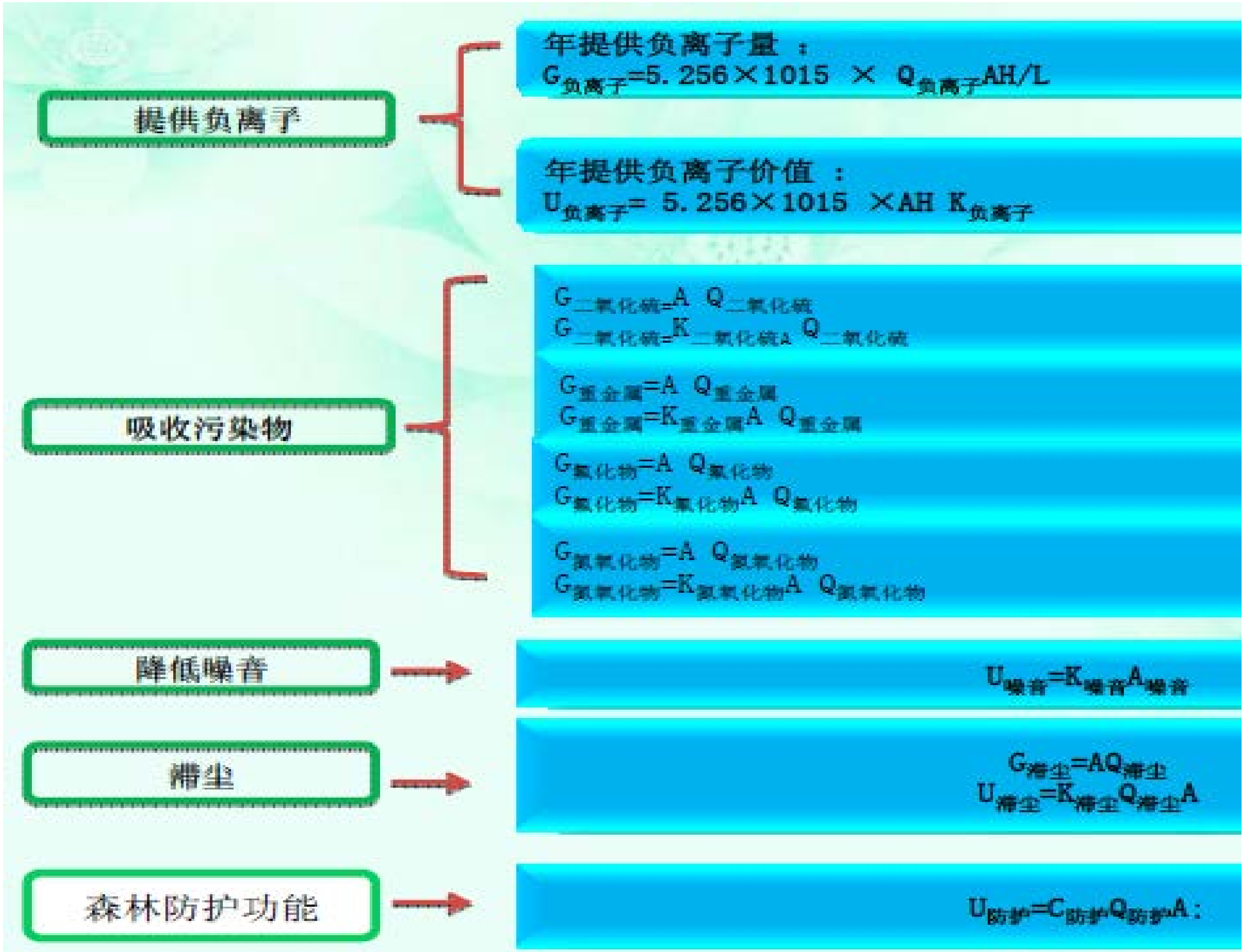
再次修正

增加特有种指数再次修正的物种多样性保育价值评估计算方法

- 公式为：$U_{总} = (1+\sum_{m=1}^{x} E_m \times 0.1+\sum_{n=1}^{y} B_n \times 0.1) S_{生} A$

式中：$U_{总}$为林分年物种保育价值；E_m为评估林分（或区域）内物种m的濒危分值；B_n为评估林分（或区域）内物种n的特有种指数；x为计算濒危指数物种数量；y为计算特有种指数物种数量；$S_{生}$为单位面积物种多样性保育价值量，单位：元·hm^{-2}·a^{-1}；A为林分面积，单位：hm^2。

森林防护功能评价指标


提供负离子
年提供负离子量：
G负离子=5.256×1015 × Q负离子AH/L
年提供负离子价值：
U负离子= 5.256×1015 ×AH K负离子
吸收污染物
G二氧化硫=A Q二氧化硫
G二氧化硫=K二氧化硫A Q二氧化硫
G重金属=A Q重金属
G重金属=K重金属A Q重金属
G氟化物=A Q氟化物
G氟化物=K氟化物A Q氟化物
G氮氧化物=A Q氮氧化物
G氮氧化物=K氮氧化物A Q氮氧化物
降低噪音
U噪音=K噪音A噪音
滞尘
G滞尘=AQ滞尘
U滞尘=K滞尘Q滞尘A
森林防护功能
U防护=C防护Q防护A：

森林生态系统服务功能评估规范

ICS 65.020
B65

LY

中华人民共和国林业行业标准

LY/T 1721 —2008

森林生态系统服务功能评估规范

Specifications for assessment of forest ecosystem services in China

第六讲 林分结构

- 第一节 林分直径结构
- 第二节 林分树高结构
- 第三节 林分空间结构
- 第四节 林分年龄结构
- 第五节 三参数Weibull分布

第六讲 林分结构十问

- Q6.1 人工林与天然林的林分结构有何区别?
- Q6.2 幼龄林与成熟林的林分结构有何区别?
- Q6.3 如果有生物 (e.g. 病虫害) 或人为 (e.g. 间伐) 干扰?
- Q6.4 混交林的树种组成与林分结构特点是什么？
- Q6.5 自疏伐与天然更新如何改变树种组成与林分结构？

- Q6.6 大径材培育的林分结构应如何调控?
- Q6.7 生物多样性的林分结构应如何调控?
- Q6.8 森林病虫害的林分结构应如何调控?
- Q6.9 森林防火的林分结构应如何调控?
- Q6.10 森林碳汇的林分结构应如何调控?

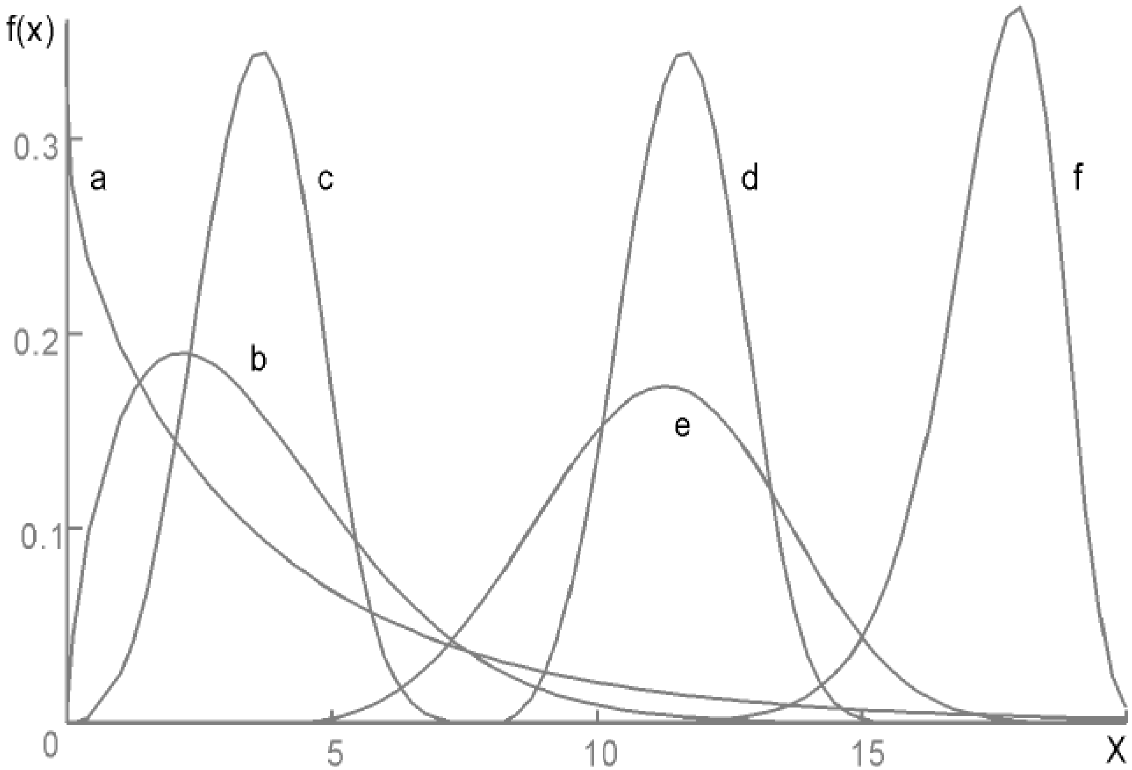
Diameter distribution models

表 1-1 林分直径分布主要模型

Table1-1 Main stand diameter distribution model

概率密度函数(Probability density function)	说明(Explanation)
正态分布函数(Normal distribution function) $F(x) = 1/(\sqrt{2\pi}.\delta)exp\,(-\frac{(x-\overline{x})^2}{2\delta^2})$	x 和$\overline{x}$为直径实测值和平均值；δ 为直径 x 的标准差
β 分布函数(β distribution function) $F(x) = x^{a-1}(1-x)^{b-1}/\beta(a,b)$	a，b 为形状参数，$0 \le x \le 1$
Weibull 分布函数(Weibull distribution function) $F_x(x, a, b, c)\begin{cases}\left(\frac{c}{b}\right) * \left(\frac{x-a}{b}\right)^{c-1} \times exp\left[-\left(\frac{x-a}{b}\right)^{c}\right] \\ 0\end{cases}$	$a \ge 0$，b，$c > 0$；a 为位置参数（直径分布最小径阶下限值）；b 为尺度参数；c 为形状参数
对数正态分布函数(Lognormaldistribution function) $F(x) = 1/(\sqrt{2\pi}c)exp\,(-(log(x)-b)^2\,/(2c^2))$	b 为变量 log（x）的数学期望值；c 随机变量 log（x）的标准差
负指数分布函数(Negative exponential distribution function) $Y = ae^{-bx}$	Y 为每个径阶的林木株数；x 为径阶；e 为自然对数的底；a 和 b 为表示直径分布特征的常数
倒J型对数分布函数(LogarithmicJ-shaped function) $N = exp\,(a * e^{(-bD)})$	N 为株数；D 为胸径；a,b 为模型参数
限定性函数（Limitingfunction） $N_{max} = a_0 {D_g}^{a_1}$	N_{max} 为活立木最大株数；D_g 为平均直径的平方；a_0，a_1 是模型参数
Logistic 分布函数(Logistic Distribution function)	

Whole-stand distribution models



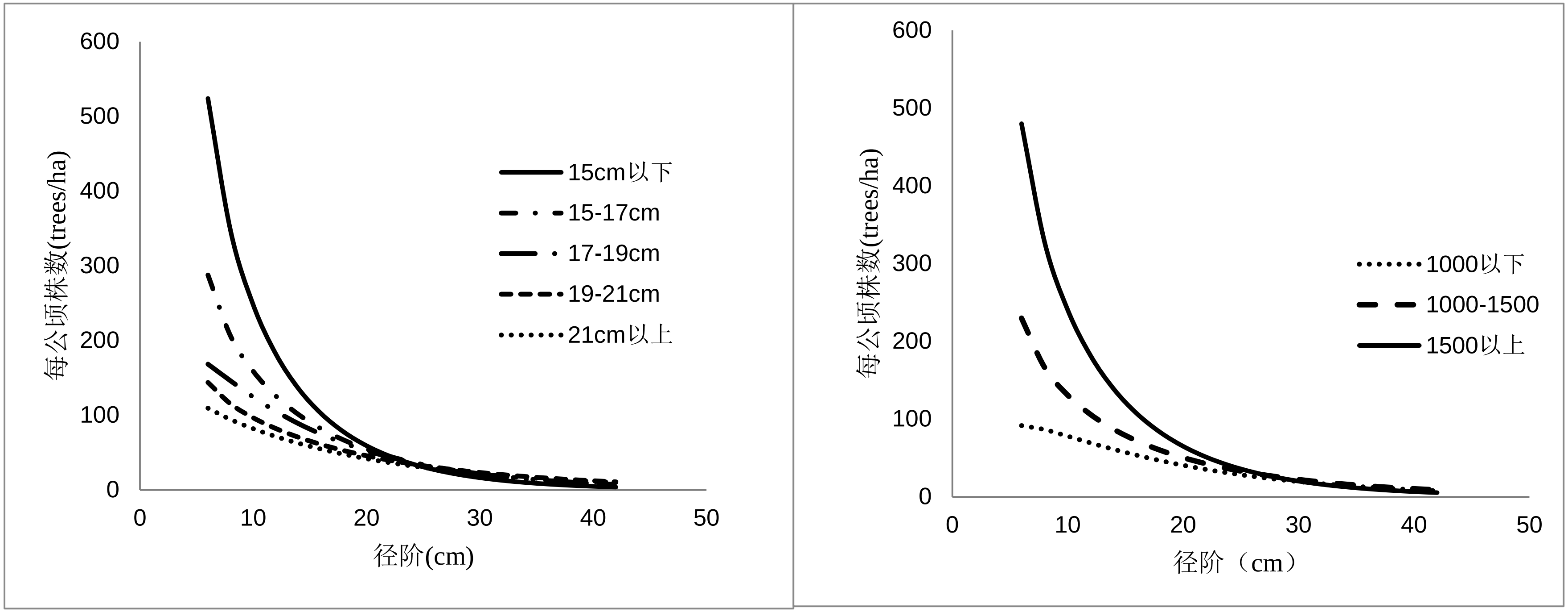
$$f(x) = \frac{\beta}{\alpha}\left[\frac{x-\gamma}{\alpha}\right]^{\beta-1} \exp\left[-\left(\frac{x-\gamma}{\alpha}\right)^{\beta}\right]$$

Fig. 2.3. Possible diameter distributions generated by the Weibull p.d.f. (Eqn 2.9), showing the influence of each parameter (Table 2.1) on the shape of the distribution.

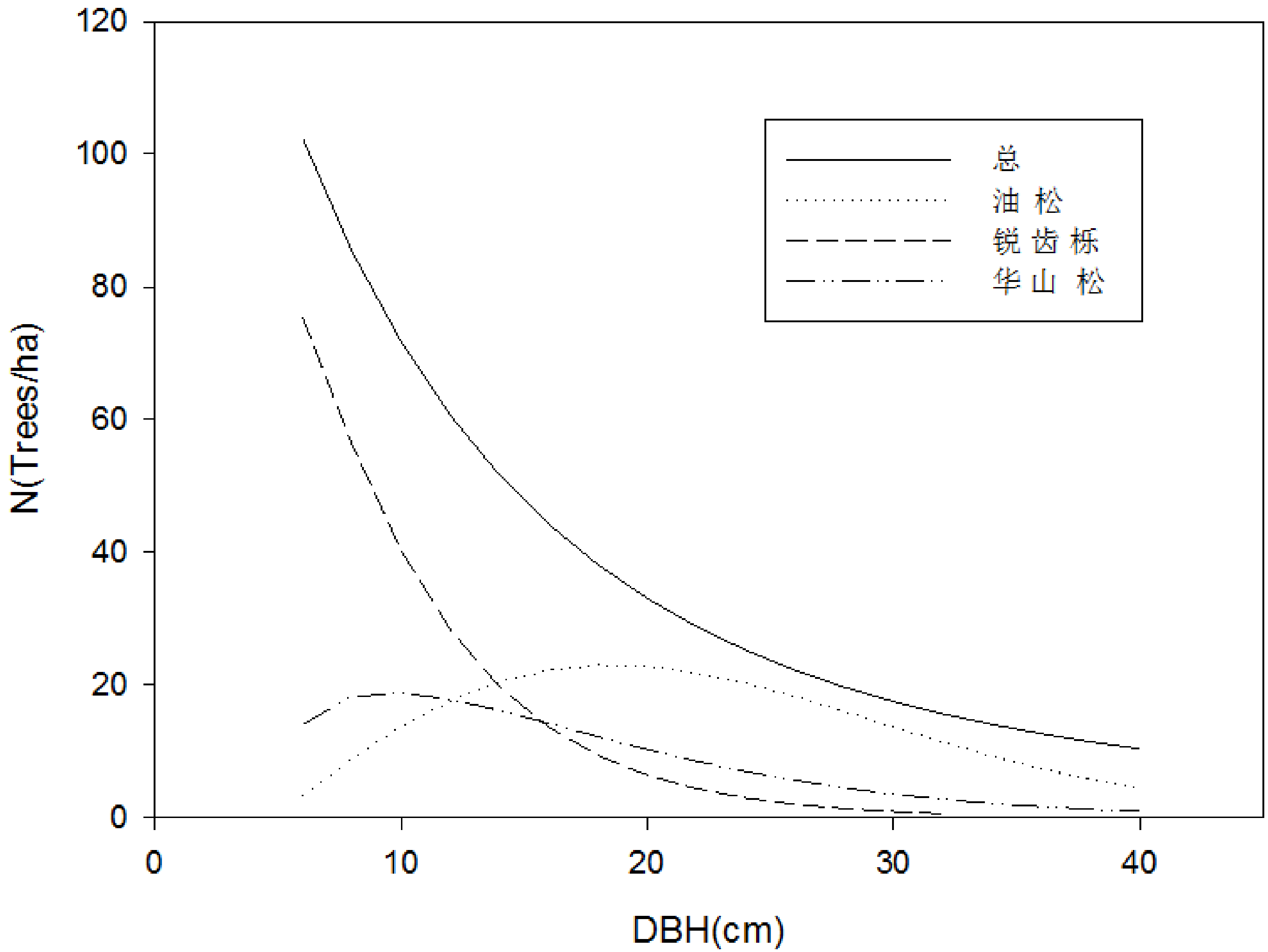
Weibull distributions

Example	alpha	beta	gamma
a	4	0.95	0
b	4	1.6	0
c	4	3.6	0
d	4	3.6	8
e	8	3.6	4
f	18	18.0	0

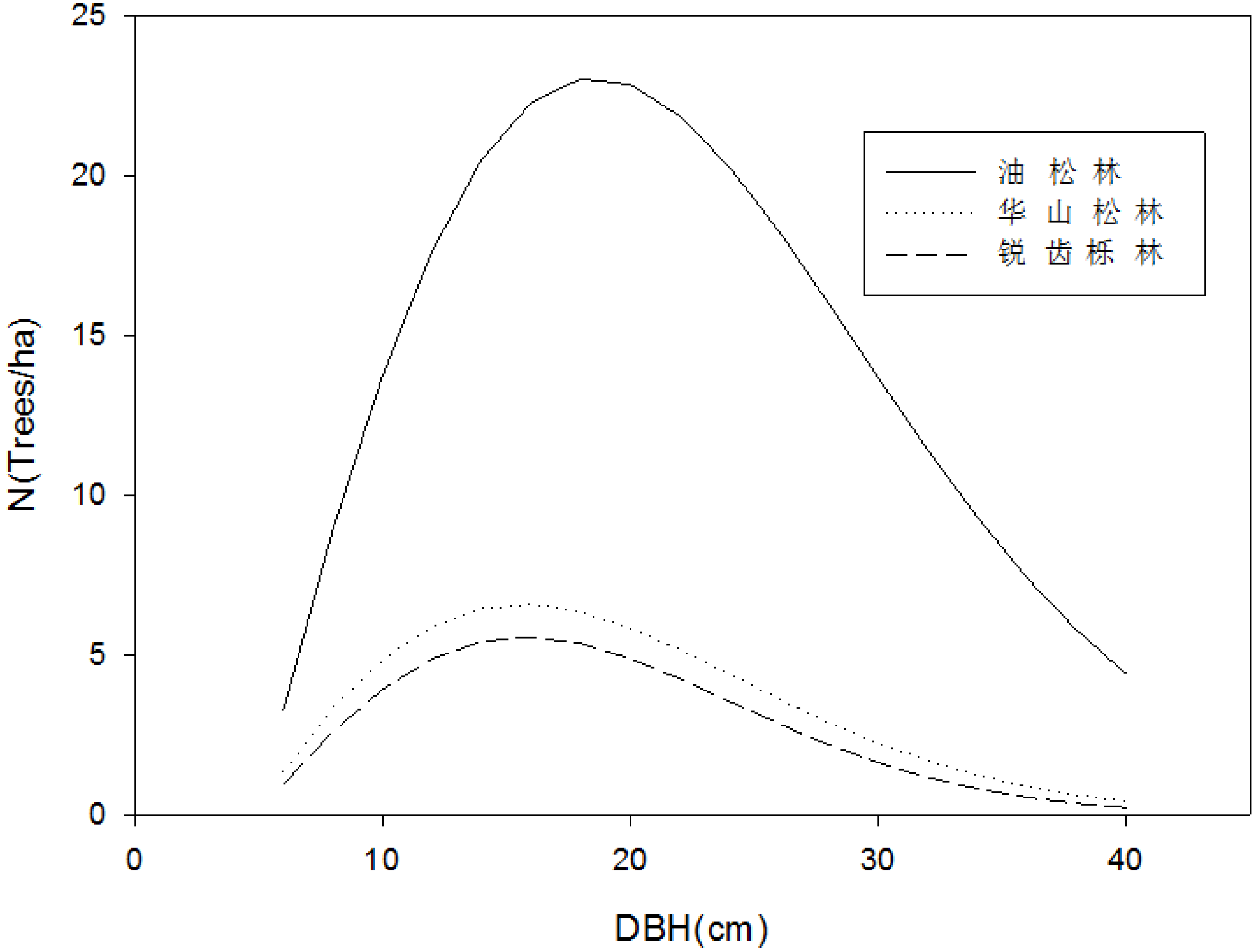
Diameter distribution by D_ave and #tree at stand level



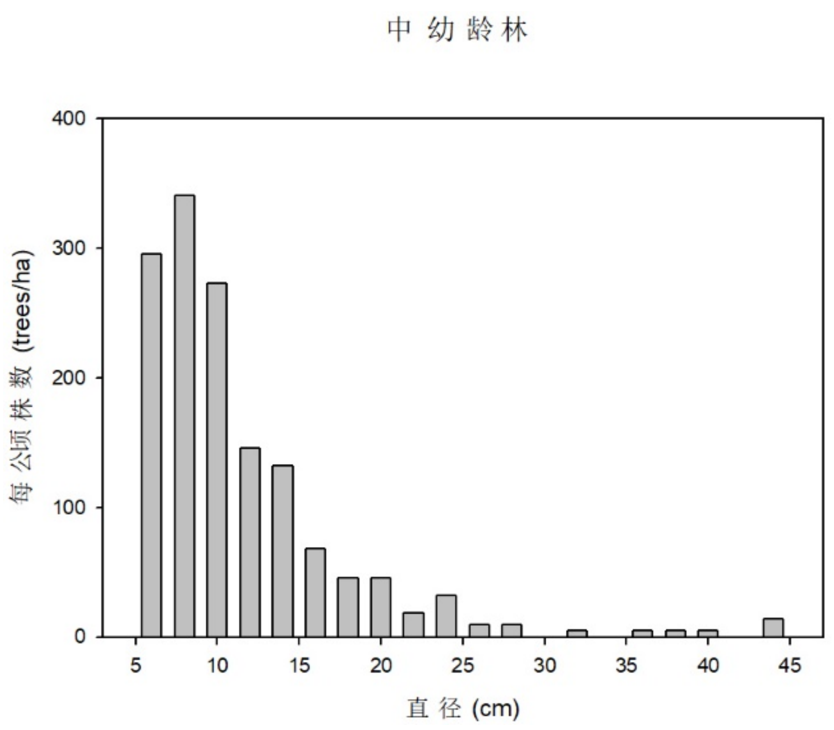
Diameter distribution by tree species

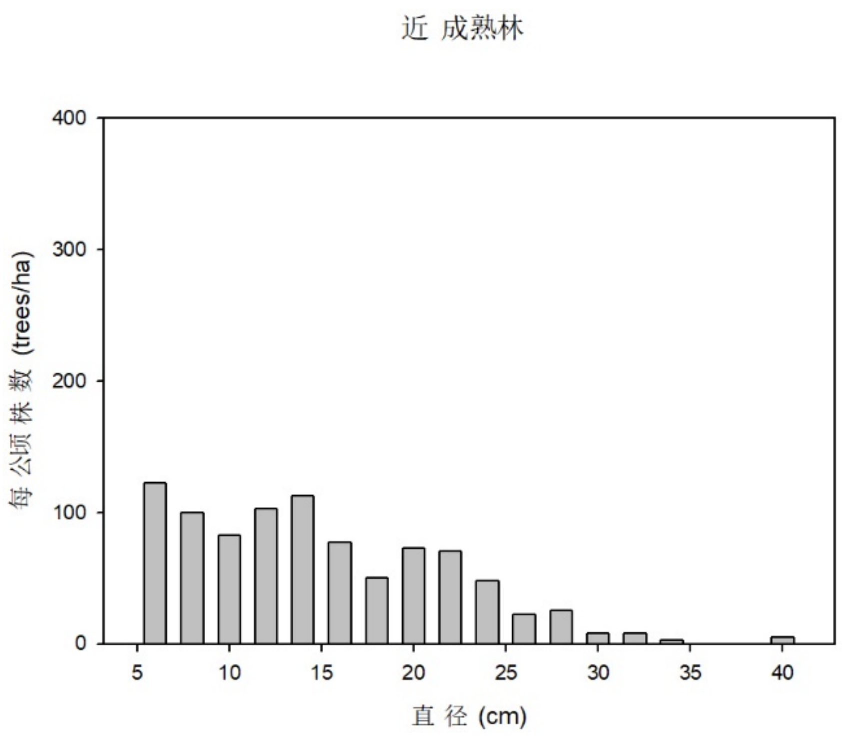


各优势林中油松的直径分布

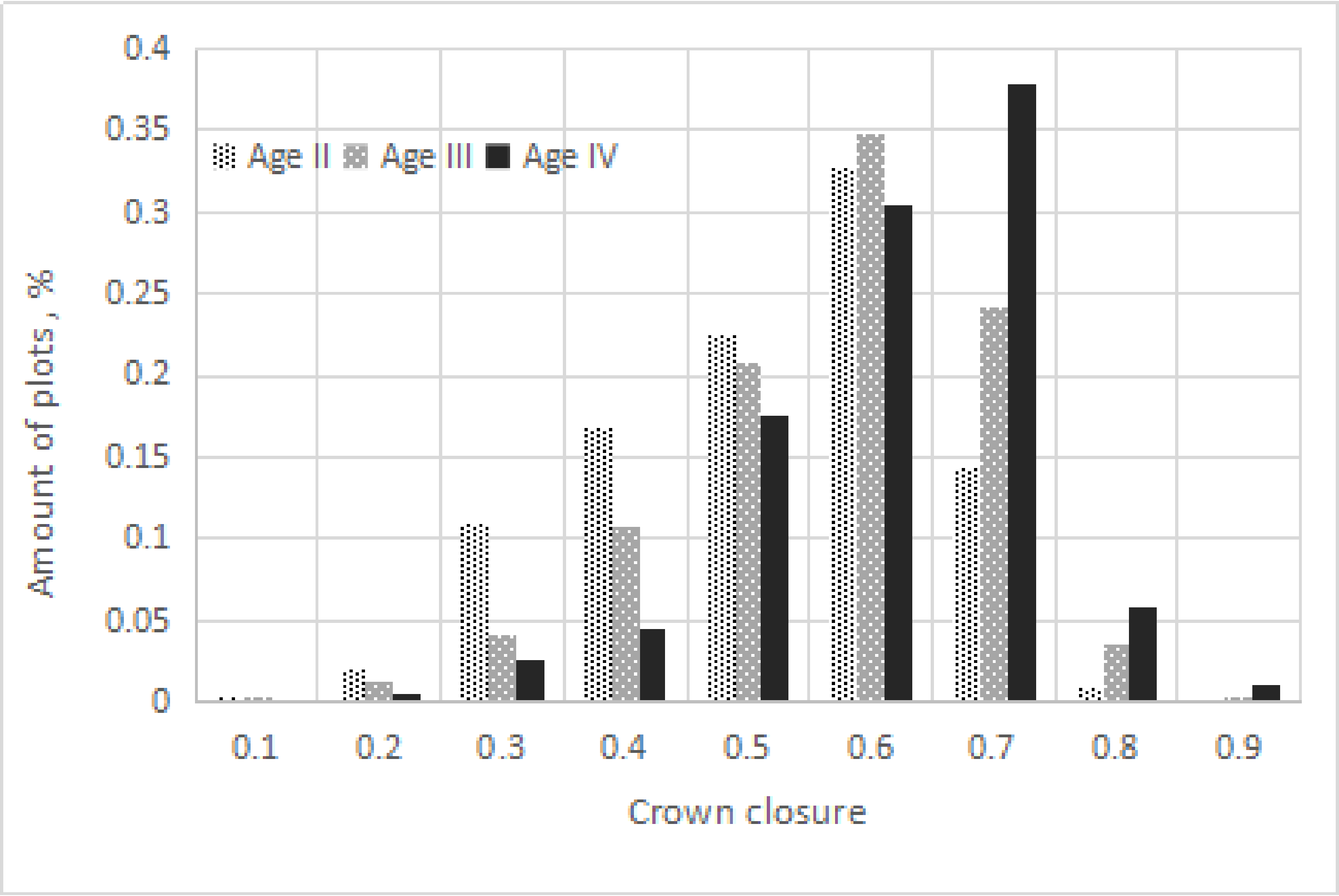


林分径阶结构动态变化


中 幼 龄 林
400
300
200
100
0
每 公顷 株 数 (trees/ha)
5
10
15
20
25
30
35
40
45
直 径 (cm)

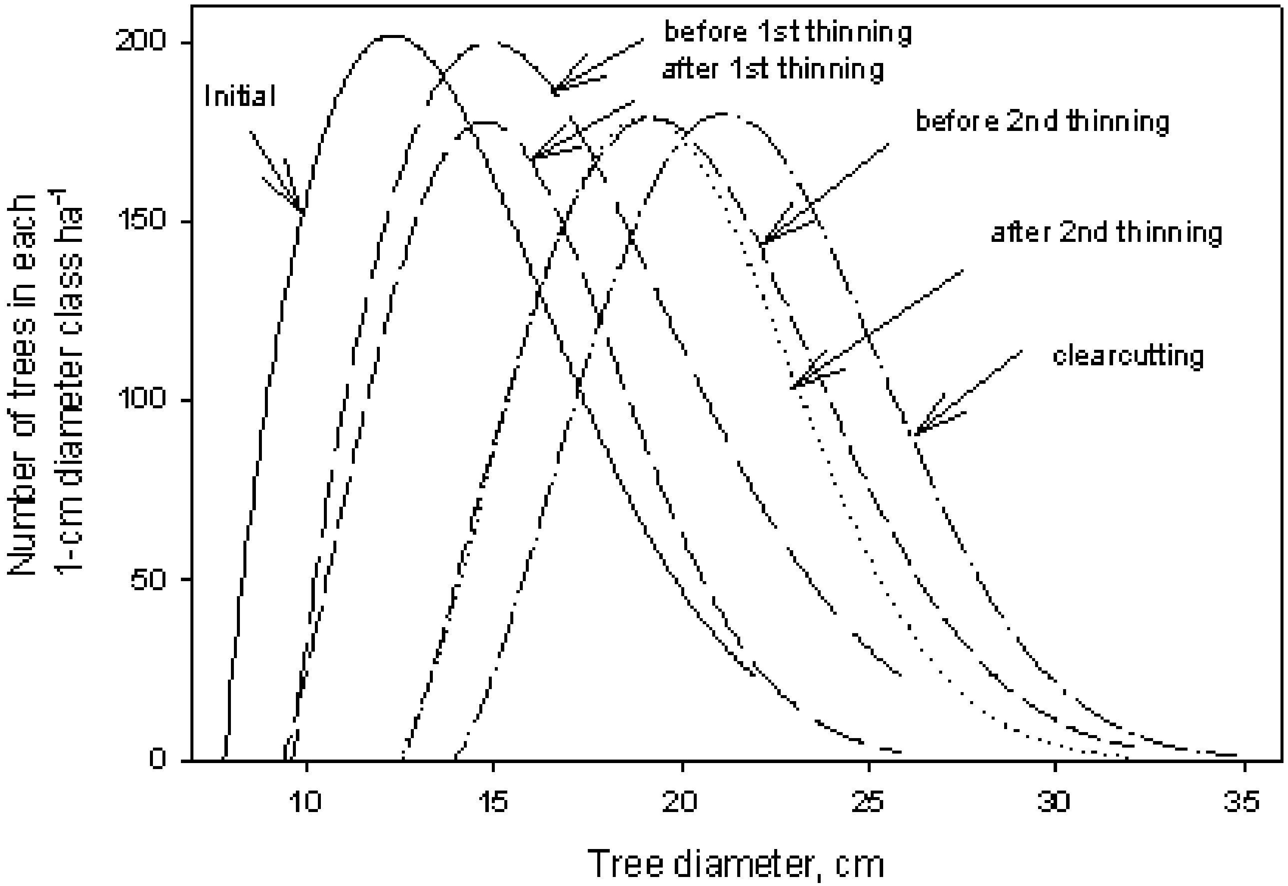

近 成熟林
400
300
200
100
0
每 公顷 株 数 (trees/ha)
5
10
15
20
25
30
35
40
直 径 (cm)

栎类林年龄结构 vs. 郁闭度



Stand structure development (Cao, 2003)

- Optimal solutions of plot 61 at 3% rate of interest, fit to 4-parameter Weibull distributions.



第七讲 同龄林立地质量

- 第一节 直接法和间接法
- 第二节 地位级和立地指数
- 第三节 林型与地被指示物
- 第四节 密度控制与自疏伐理论

- Q7. 直接法和间接法立地质量评价的区别和联系是什么？如果间伐？如果气候变化？

Forest site evaluation

- Plantations vs. natural forests
- Forest types and forest productivity
- Site index, site form, or site class
- Dynamics of forest site quality
- Multi-data and site evaluation
- Biomass production and forest productivity

Project 2. Forest Type and Stand Structure

- Tools: SigmaPlot, SPSS, or SAS
- Forest inventory data: 76 pine-oak stands (stand level, size class level)
- Hints: Species composition, diameter size class, Weibull distribution

Questions to be answered:

- 1. Draw a figure to analyze the stand structure of pine-oak forests in general.
- 2. Draw figures for the diameter structure of pine-dominated, oak-dominated, and mixed stands.

Project 2, con’t

- 3. Compare the diameter structure of pine in pine-dominated, oak-dominated, and mixed stands, and try to explain why.
- 4. Compare the diameter structure of oak in oak-dominated, pine-dominated, and mixed stands, and try to explain why.
- 5. Write down Weibull distribution equations (2-parameter, 3-parameter, 4-parameter).
- 6. Fit the curves of diameter structure of previous questions using Weibull distribution, and analyze the advantages of using 3-parameter Weibull distribution in diameter distribution.

Forest site evaluation

- Plantations vs. natural forests
- Forest types and forest productivity
- Site index, site form, or site class
- Dynamics of forest site quality
- Multi-data and site evaluation
- Biomass production and forest productivity

Methods for site evaluation

	Direct	Indirect
Phytocentric	Wood volume	Tree height
Geocentric	Soil moisture & nutrient status Photosynthetically active radiation	Climate Land form Physiography Plant indicators

Source：Vanclay (1994)

Classification of forest site

- Based on geo-factors
- Based on soil-factors
- Based on plant indicators
  - Cajander (1926)，forest floor vegetation
  - Daubenmire (1968)，community
- Based on climate, terrain, soil, and vegetation

Forest types in Qinling

2800-3200 m *Larix chinensis*

2400-2800 m *Abies fargesii*

2000m-2400 m *Betula albo- sinensis*, *Betula albo-sinensis* var*. septerionalis*

1700-2000 m *Pinus armandii - Betula albo- sinensis*

1400-1700 m *Pinus tabulaeformis - Quercus aliena* var. *acuteserrata*

800-1400 m *Quercus aliena, Quercus glandulifera* var. *brevipetiolata*

栎类林型 Forest types for oak stands

林型	海拔	坡向	坡位	水分	主要树种
辽东栎-土庄绣线菊-披针叶苔草群丛	1390-1450	南坡、东南坡	上坡	较差	辽东栎、油松、土庄绣线菊、榛子、火绒草
辽东栎-虎榛子-披针叶苔草群丛	1380-1460	西北坡		较好	辽东栎、油松、白桦、榛子、龙芽草、北柴胡
辽东栎-胡枝子-大油芒群丛	1300-1360	北坡、东北坡	中下坡	较好	辽东栎、白桦、胡枝子、连翘、榛子等
辽东栎-水栒子-披针叶苔草群丛	1400	北坡	下坡	较好	辽东栎、油松、白桦、水栒子、榛子
辽东栎-白刺花-草地早熟禾群丛	1400	西南坡	中上坡	较差	辽东栎、侧柏、白刺花、北京丁香、山桃、虎榛子
辽东栎-黄蔷薇-华北风毛菊群丛	1290-1320	东南坡、西南坡	上坡	较差	辽东栎、油松、黄蔷薇、卫矛、虎榛子

Source：康永祥 (2007)

栎类立地类型 Site types for oak stands

辽东栎-黄蔷薇

辽东栎-胡枝子

栎类立地类型 Site types for oak stands

栎类混交-黄蔷薇

栎类混交-胡枝子

栎类立地类型 Site types for oak stands

林型	海拔（m）			坡度			坡位	蓄积（m^3）		
	最低	最高	平均	最小	最大	平均		最小	最大	平均
辽东栎-黄蔷薇	1048	1606	1404	0º	55º	29º	中上坡及山脊	22.2	260.5	90.3
辽东栎-胡枝子	1079	1519	1376	10º	45º	34º	中下坡	38.2	105.3	78
槲栎-黄蔷薇	1334	1509	1463	20º	40º	34º	中上坡及山脊	32.6	145.4	86.1
槲栎-胡枝子	1116	1495	1366	20º	48º	33º	中上坡	47.0	115.2	81.8
麻栎-黄蔷薇	1071	1388	1254	2º	31º	16.7º	中上坡	61.3	119.0	80.2
麻栎-胡枝子	1133	1377	1224	5º	35º	15.3º	中下坡	34.0	162.6	77.8

Site index，or Site form？

- Site index, even-aged plantations, Hdom
- Site form, uneven-aged forests, D? （Weiskittel et al.，2011）
- Nigh（1995）, Wang（1998）, mixed forests

Site index vs. site form（Wu et al. 2015）

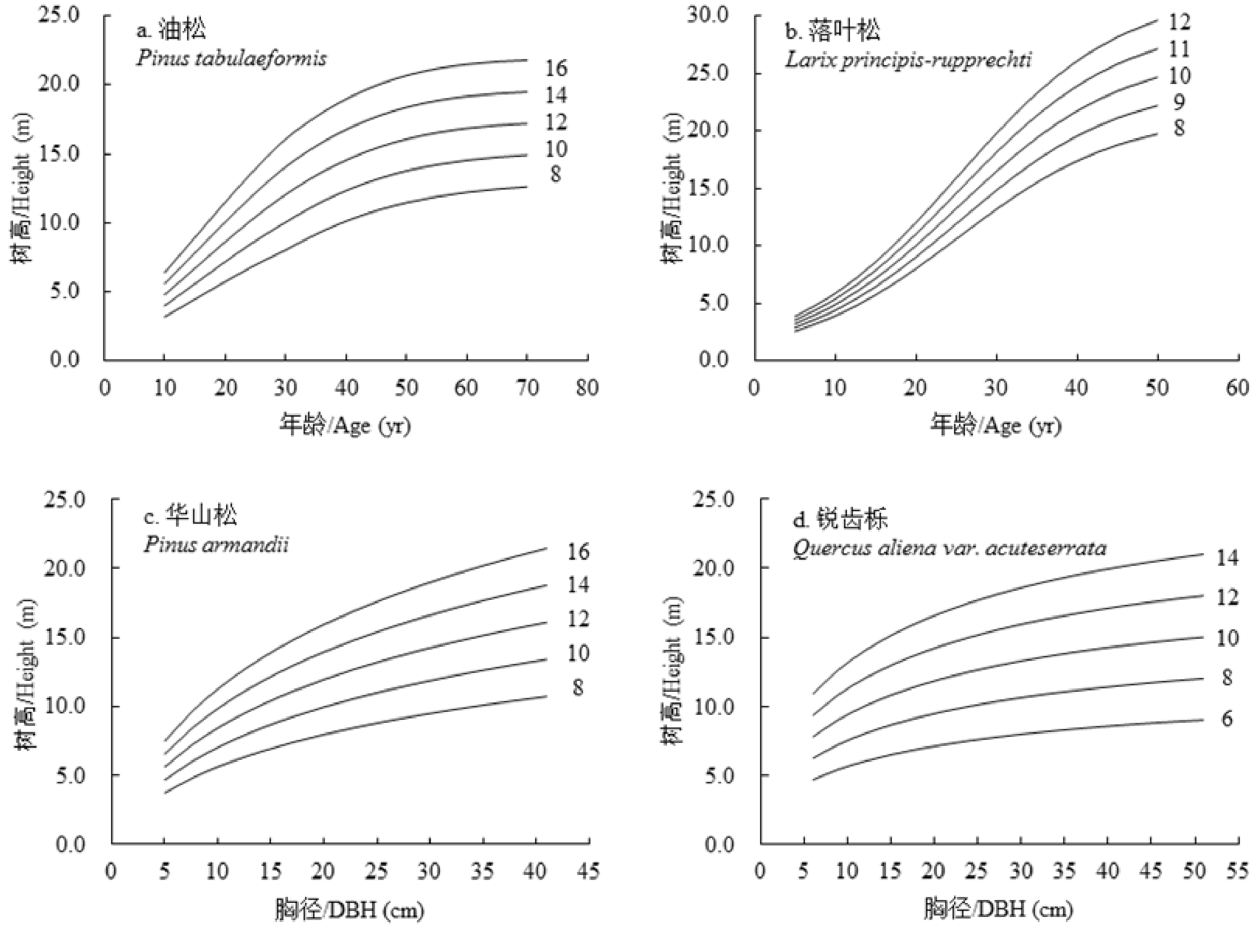


图 3-1 油松（a）落叶松（b）立地指数、华山松（c）锐齿栎（d）立地形曲线簇

Fig.3-1 Examples of site index and site form curves by species

Site form

GC，Guide Curve
ADA，Algebraic Difference Approach

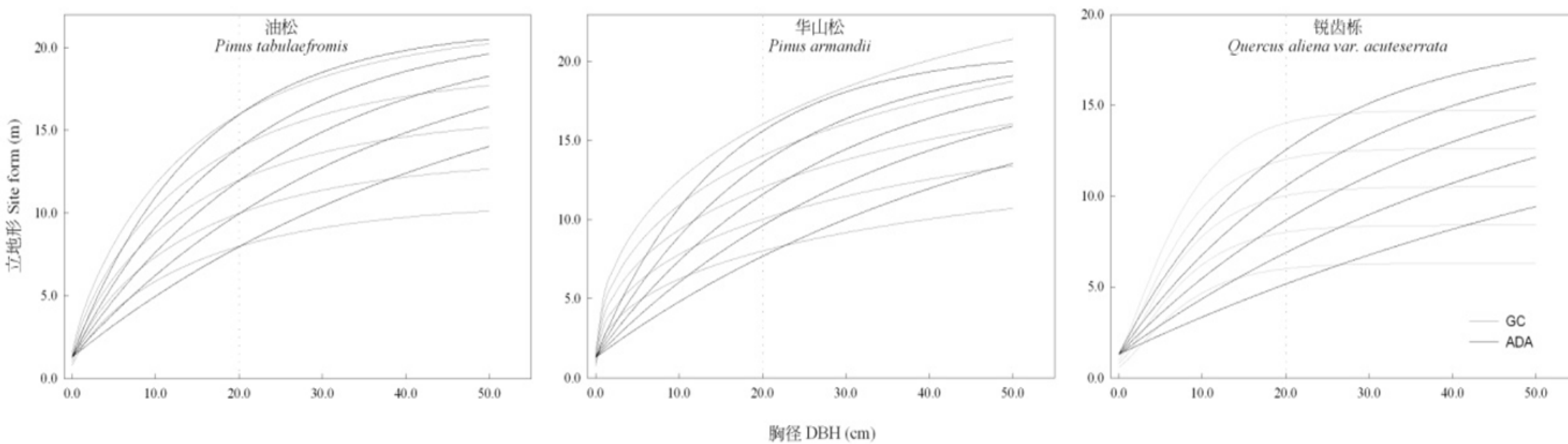


图 4-1 油松、华山松和锐齿栎立地形曲线簇

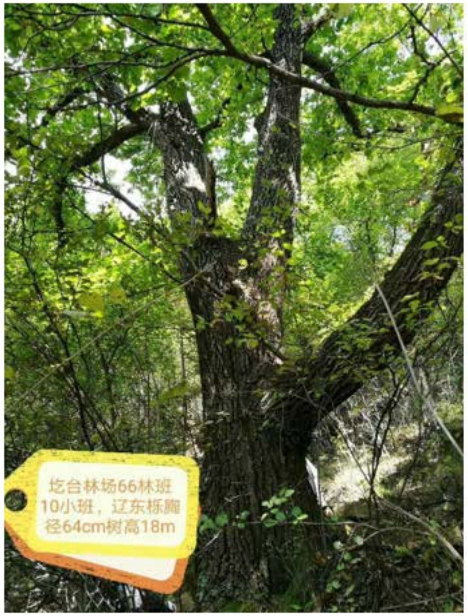
Fig.4-1 Curves of site form by species

第八讲 异龄林立地质量

- 第一节 蓄积与生物量
- 第二节 树高胸径异速关系
- 第三节 立地形
- 第四节 森林生产力

- Q8. 混交林立地质量评价采用哪种方法合适？其理论依据是什么？其方法有哪些缺点？

立地质量示范林


圪台林场66林班
10小班，辽东栎胸
径64cm树高18m


固定样地


延安市桥山林业局
栎类材积生长期近自然健康经营简介

Site form for pine-oak forest, con't

- $SF_{PT} = a_1 SF_{PA} + e_1$
- $SF_{PA} = a_2 SF_{QA} + b\ \text{Composition} + e_2$
- $SF_{QA} = a_3 SF_{PT} + c\ \text{DBH} + d\ \text{Density} + e_3$

Changes on site class

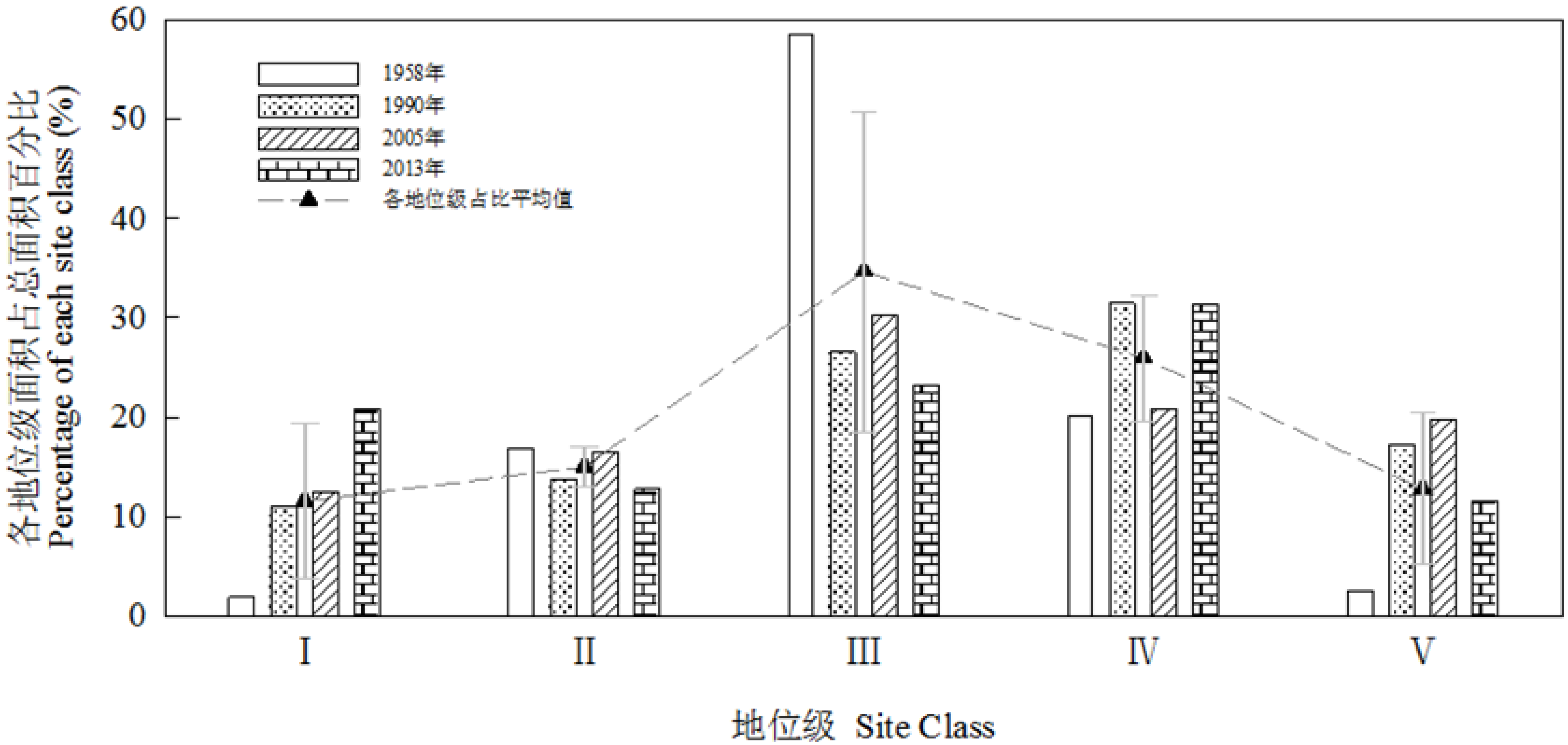
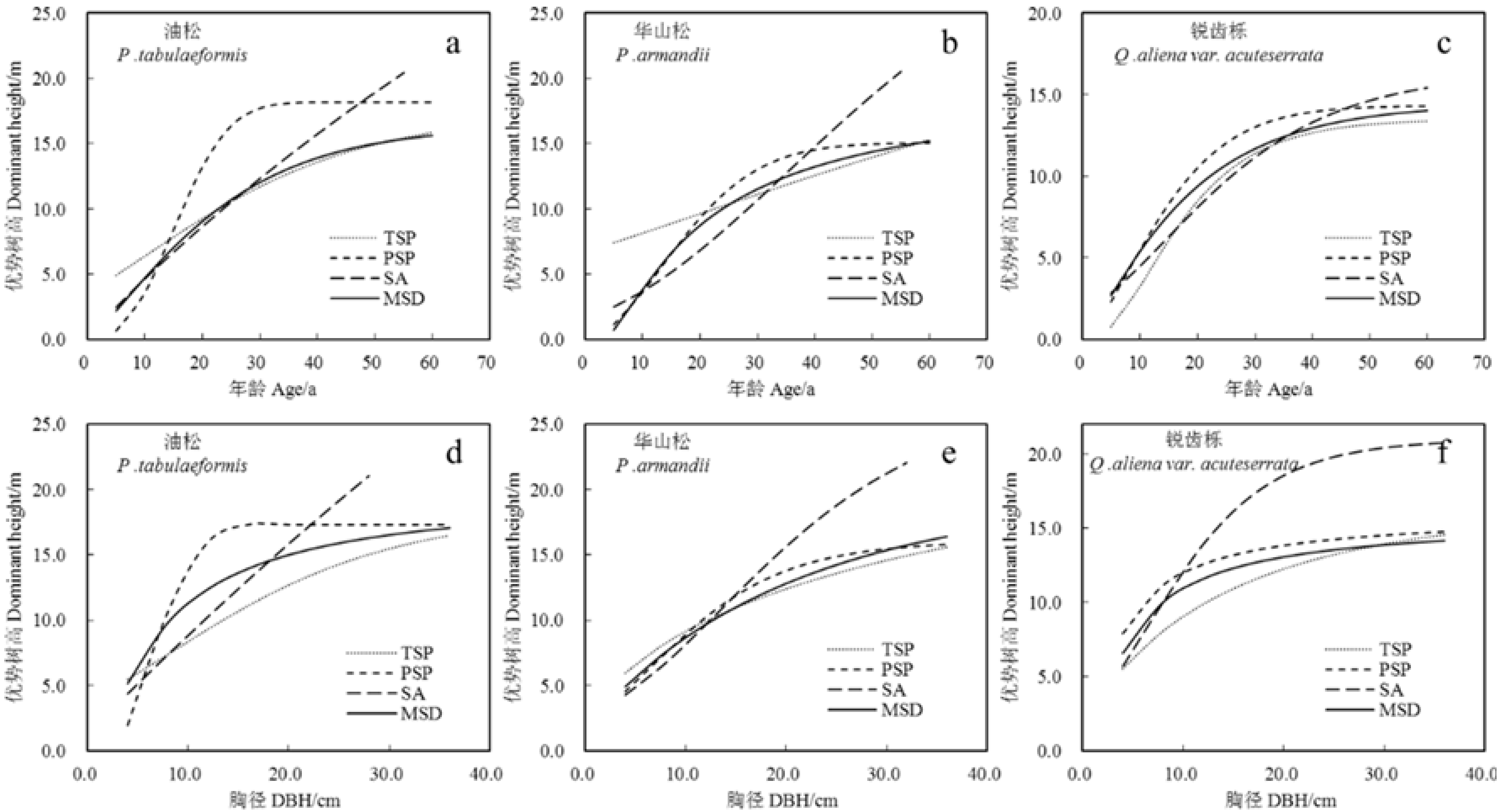


图 5-1 各地位级组成比例变化

Fig.5-1 Changes of each site class percentage

Multi-data and site evaluation



Height vs. Age

Theoretical growth equations

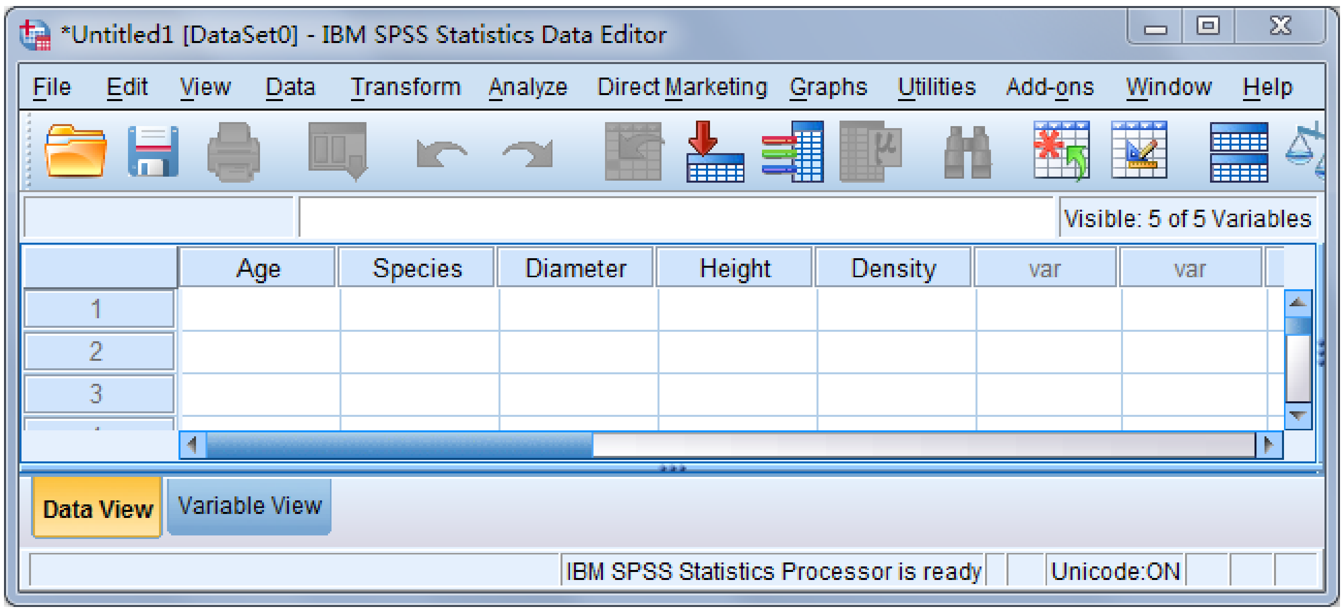
- Assume tree growth y (DBH, H, BA, or V) is a function of time, t
- $y = f(t)$

- Schumacher: $y = a*\exp(-b/t)$
- Mitscherlich: $y = a(1-\exp(-b*t))$
- Logistic: $y = a/(1+c*\exp(-b*t))$
- Gompertz: $y = a*\exp(-b*\exp(-c*t))$
- Korf: $y = a*\exp(-b*t^{(-c)})$
- Richards: $y = a(1-\exp(-b*t))^c$

- a, b, c, parameters

Computer programs for biometrics

- Statistical Package for the Social Sciences (SPSS)
- SAS
- R
- Python

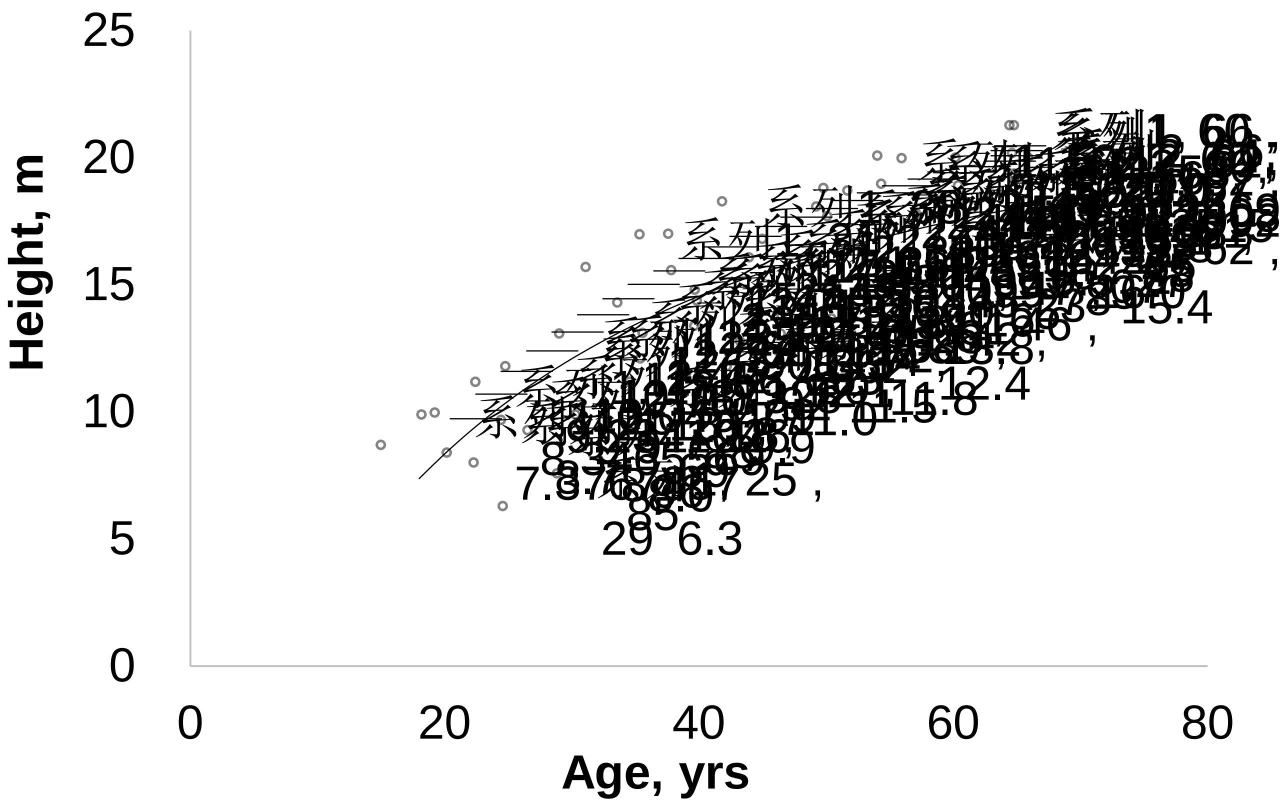


Iteration History

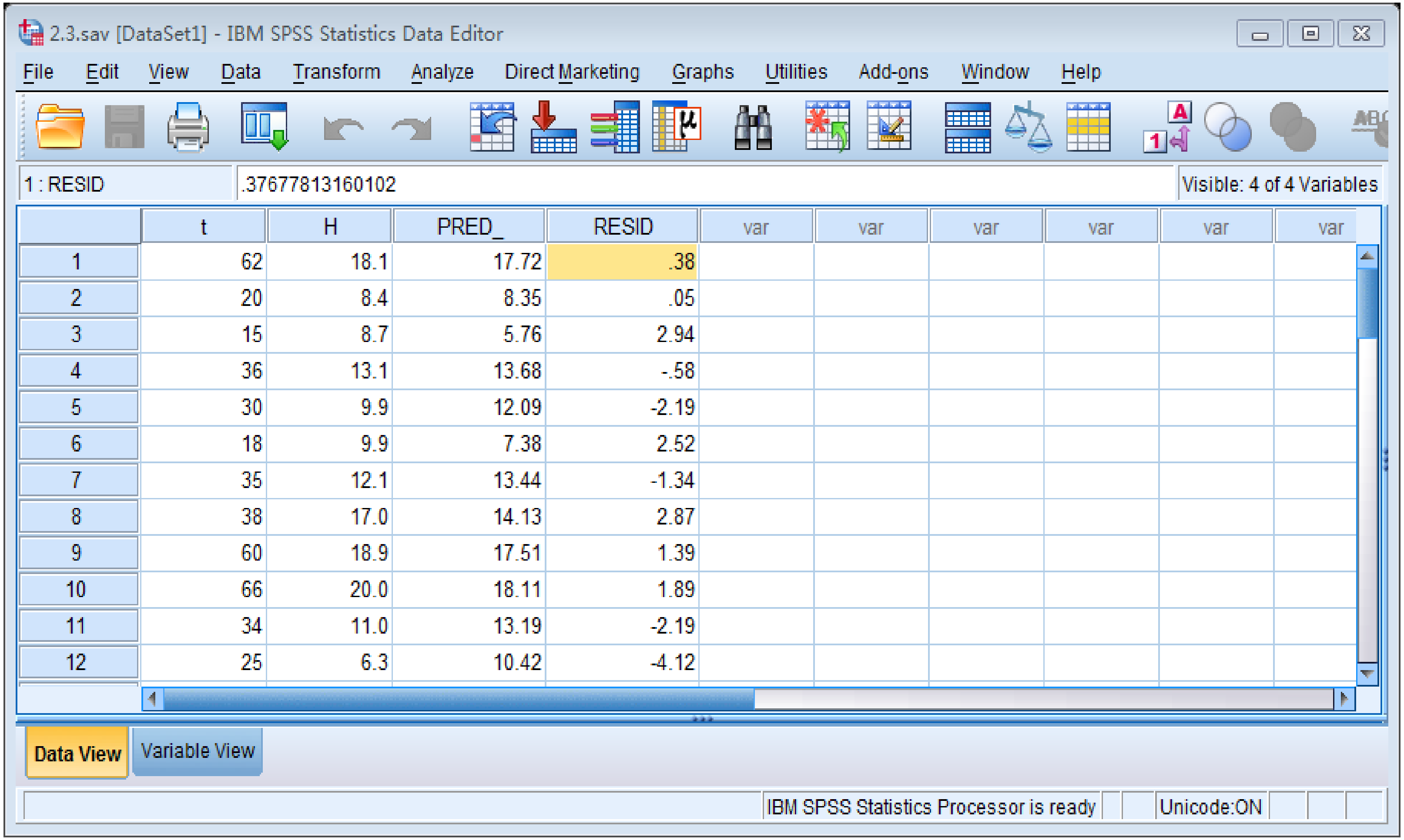
Iteration Number[a]	Residual Sum of Squares	Parameter	
		a	b
1.0	140.767	25.000	23.000
1.1	134.191	25.402	22.273
2.0	134.191	25.402	22.273
2.1	134.189	25.369	22.236
3.0	134.189	25.369	22.236
3.1	134.189	25.367	22.232
4.0	134.189	25.367	22.232
4.1	134.189	25.367	22.232

Predicting height growth

- H = 25.367*exp(-22.232/t)

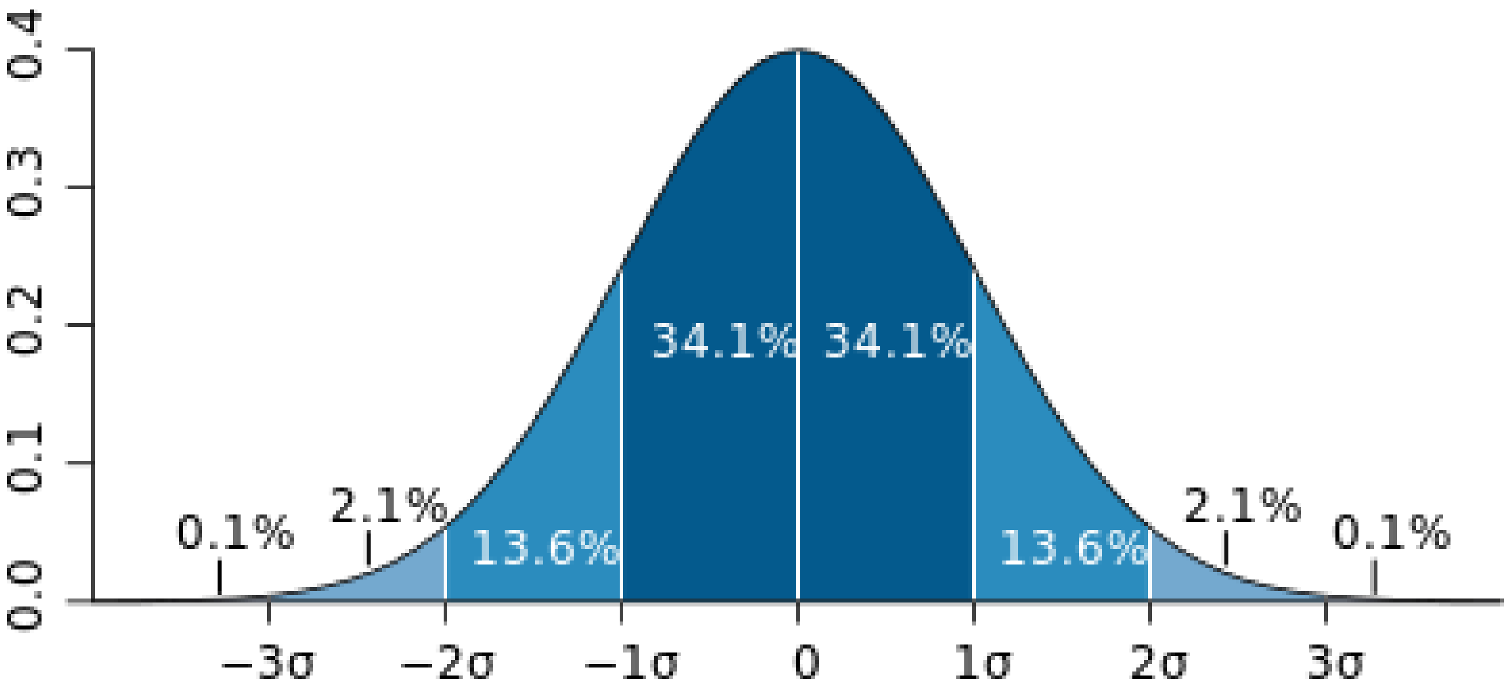


Predicted value and Residuals

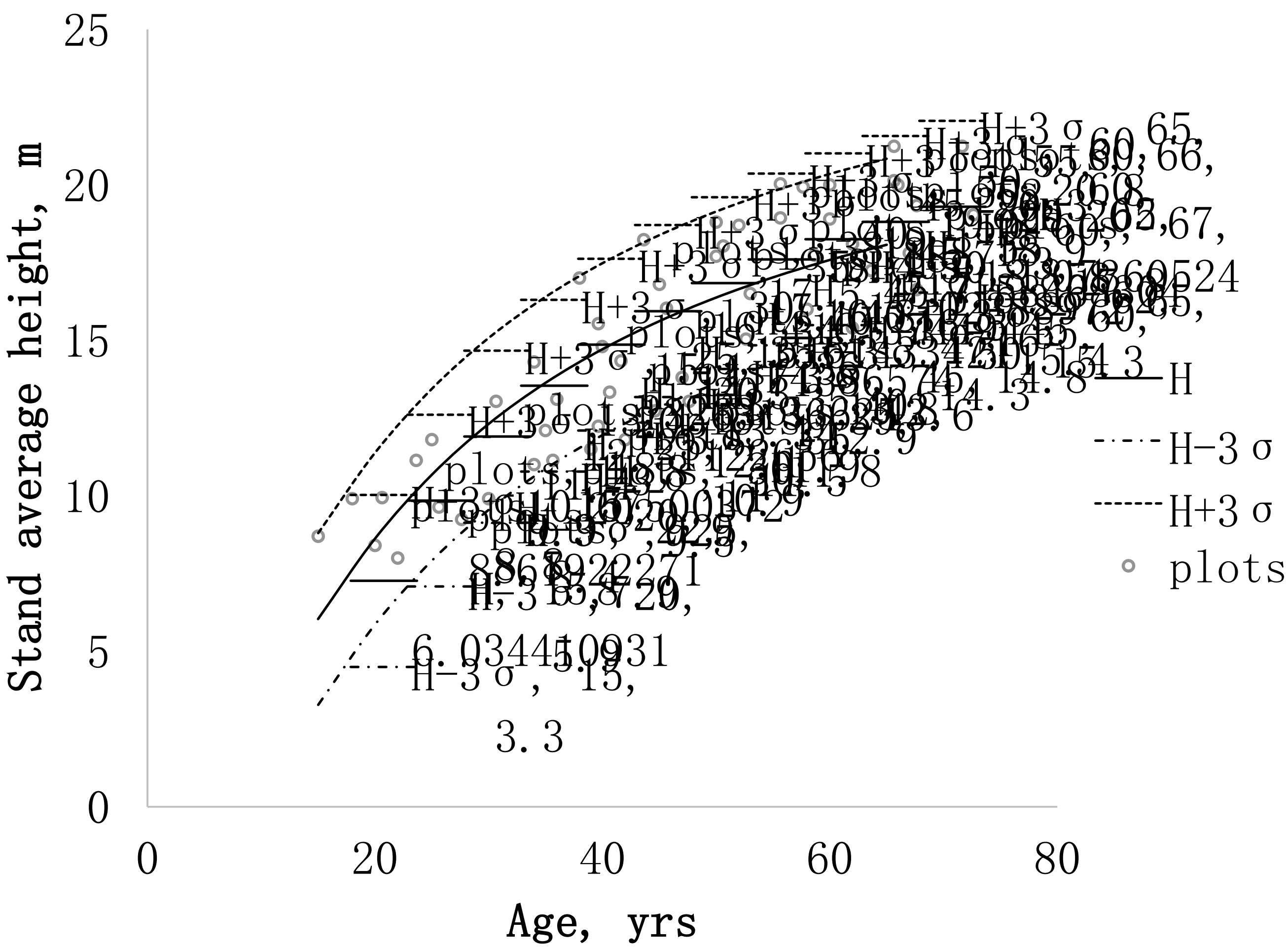


	t	H	PRED_	RESID	var	var	var	var	var	var
1	62	18.1	17.72	.38						
2	20	8.4	8.35	.05						
3	15	8.7	5.76	2.94						
4	36	13.1	13.68	-.58						
5	30	9.9	12.09	-2.19						
6	18	9.9	7.38	2.52						
7	35	12.1	13.44	-1.34						
8	38	17.0	14.13	2.87						
9	60	18.9	17.51	1.39						
10	66	20.0	18.11	1.89						
11	34	11.0	13.19	-2.19						
12	25	6.3	10.42	-4.12						

3*S.D.



Upper and lower bounds of site class



Site class table for *Pinus tabulaeformis*

Age, yrs	SC II, m	SC III, m	SC IV, m
20	9. 5–11. 4	7. 7–9. 4	5. 9–7. 6
30	13. 2–15. 1	11. 4–13. 1	9. 5–11. 3
40	15. 6–17. 5	13. 8–15. 5	11. 9–13. 7
50	17. 3–19. 1	15. 5–17. 2	13. 6–15. 4
60	18. 5–20. 3	16. 7–18. 4	14. 8–16. 6

Height-Diameter or Height-Age

1	Richard	$H_T = 1.3 + b \times [1 - \exp(-a \times DBH)]^c$
2	Weibull	$H_T = 1.3 + b \times [1 - \exp(-a \times DBH^c)]$
3	Logistic	$H_T = 1.3 + b / [1 + a \times \exp(-c \times DBH)]$
4	Korf	$H_T = 1.3 + b \times [\exp(-a / DBH^c)]$
5	Compertz	$H_T = 1.3 + b \times \exp[-a \times \exp(-c \times DBH)]$
6	Quadratic	$H_T = a + b \times Age + c \times Age^2$
7	Inverse	$H_T = a + b / Age$
8	Sigmodial	$H_T = b / \{1 + \exp[-(Age - a)/c]\}$
9	Logistic	$H_T = b / [1 + (Age/a)^c]$
10	Compertz	$H_T = b \times \exp\{-\exp[(a - Age)/c]\}$
11	Chapman	$H_T = b \times [1 - \exp(-a \times Age)]^c$
12	Hill	$H_T = b \times Age^a / (c^a + Age^a)$
13	Hyperbola	$H_T = a - b / (1 + c \times Age)^{1/d}$
14	Logarithm	$H_T = c + a \times \ln Age + b (\ln Age)^2$
15	Power	$H_T = c + a \times Age^b$
16	Mitscherlich	$H_T = b \times \{1 - \exp[(c - Age)/a]\}$
17	Modified Gaussian	$H_T = b \times \{1 - \exp(-[(Age - a)/c]^2)\}$
18	Richard	$H_T = b \times [1 - \exp(-a \times Age)]^c$
19	Schumacher	$H_T = b \times \exp[-c / (Age - a)]$

Fitting results

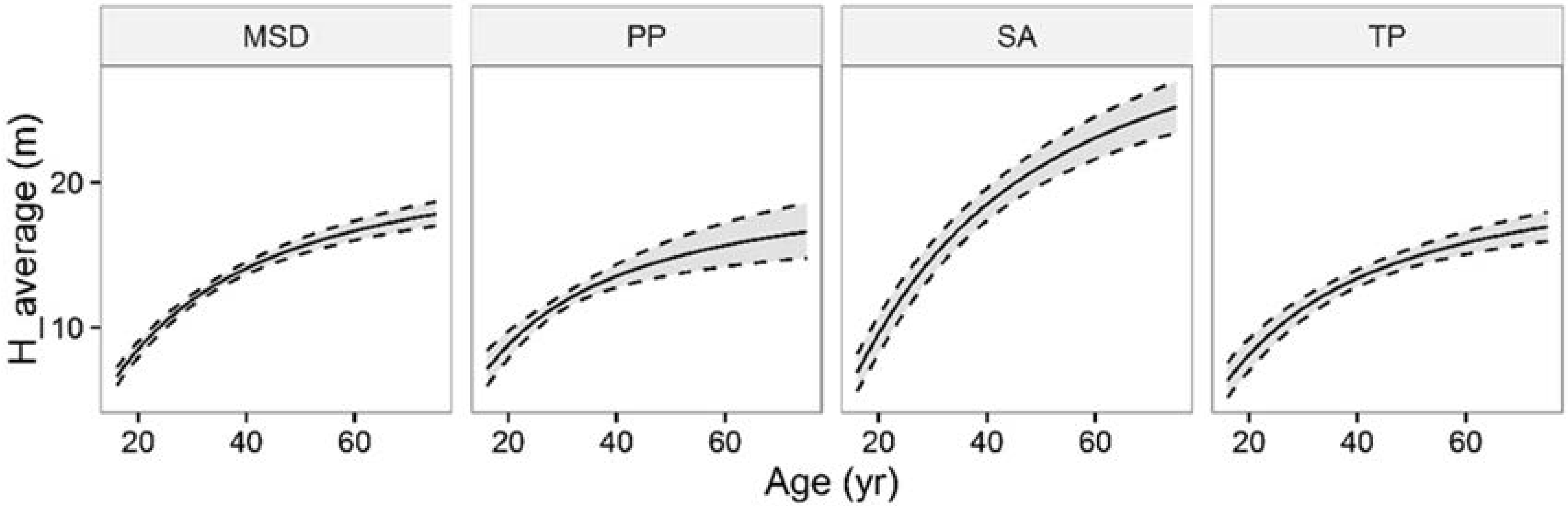
Tab. 4 Fitting results of guide curves

拟合结果 Fitting results	油松 *P. tabulaeformis*		华山松 *P. armandii*		落叶松 *L. principis-rupprechtii*		锐齿栎 *Q. aliena* var. *acuteserrata*	
	胸径 DBH	年龄 Age	胸径 DBH	年龄 Age	胸径 DBH	年龄 Age	胸径 DBH	年龄 Age
方程 Equation	Weibull	Gaussian	Korf	Logistic	Logistic	Sigmoidal	Weibull	Sigmoidal
n	245	245	631	631	249	249	458	458
a	0. 026 0	-11. 953 7	4. 146 1	62. 320 9	19. 071 5	25. 251 5	0. 174 7	15. 315 0
b	27. 042 9	17. 391 7	53. 928 8	30. 772 2	23. 251 9	27. 634 8	17. 501 2	13. 598 3
c	1. 024 3	38. 618 9	0. 324 8	-0. 743 1	0. 209 0	10. 176 7	0. 586 0	7. 966 1
R^2	0. 60	0. 50	0. 41	0. 40	0. 86	0. 89	0. 36	0. 39
SEE	2. 84	3. 16	2. 34	2. 40	2. 71	2. 38	2. 26	2. 20

①*n*：建模样本量 Number of observations for modelling；R^2：决定系数 Coefficient of determination；SEE：标准估计误差 Standard error.

Predicting average height with multi-data

The uncertainty of predictions, 95% Bayesian credible interval, were showed in grey area.
(SCI=11, SDI=600)



Parameter estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
a	25.367	2.013	21.244	29.491
b	22.232	3.243	15.590	28.874

ANOVA analysis

Source	Sum of Squares	df	Mean Squares
Regression	6330.471	2	3165.235
Residual	134.189	28	4.792
Uncorrected Total	6464.660	30	
Corrected Total	438.159	29	

Dependent variable: H
R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .694.

Competition

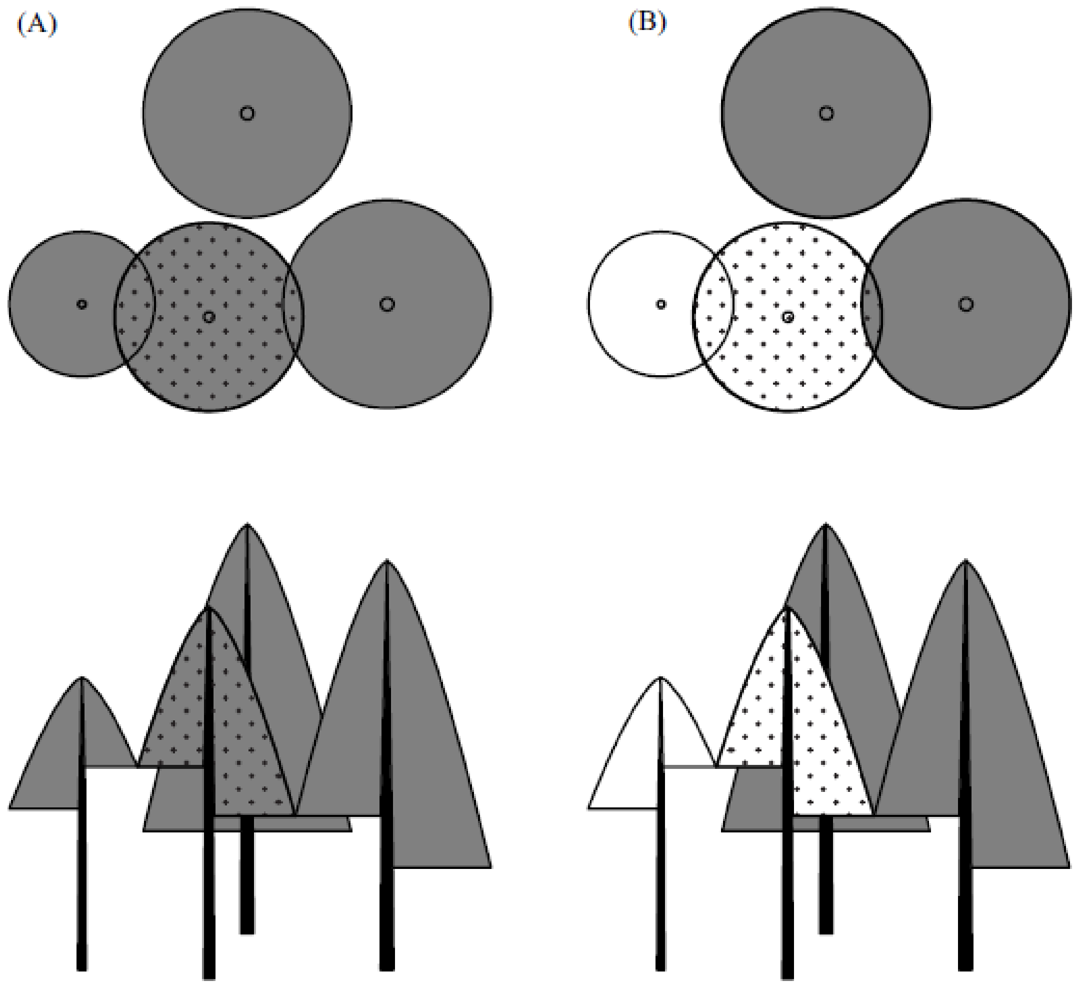


Figure 2.1 Illustration of one- (B) and two-sided (A) as well as distance-independent (top) and distance-dependent (bottom) measures of competition. The individual with the small dots is the subject tree, and all trees colored gray are considered competitors.

Competition

- Plants modify their environment as they grow, reducing the resources available for other plants.
- The primary mechanism of competition is spatial interaction.
- Plant death due to competition is a delayed reaction to the growth reduction following resource depletion.
- Plants adjust to environmental change, responding to competition and altering the nature of the competition.
- There are species differences in the competition process.

Competition index

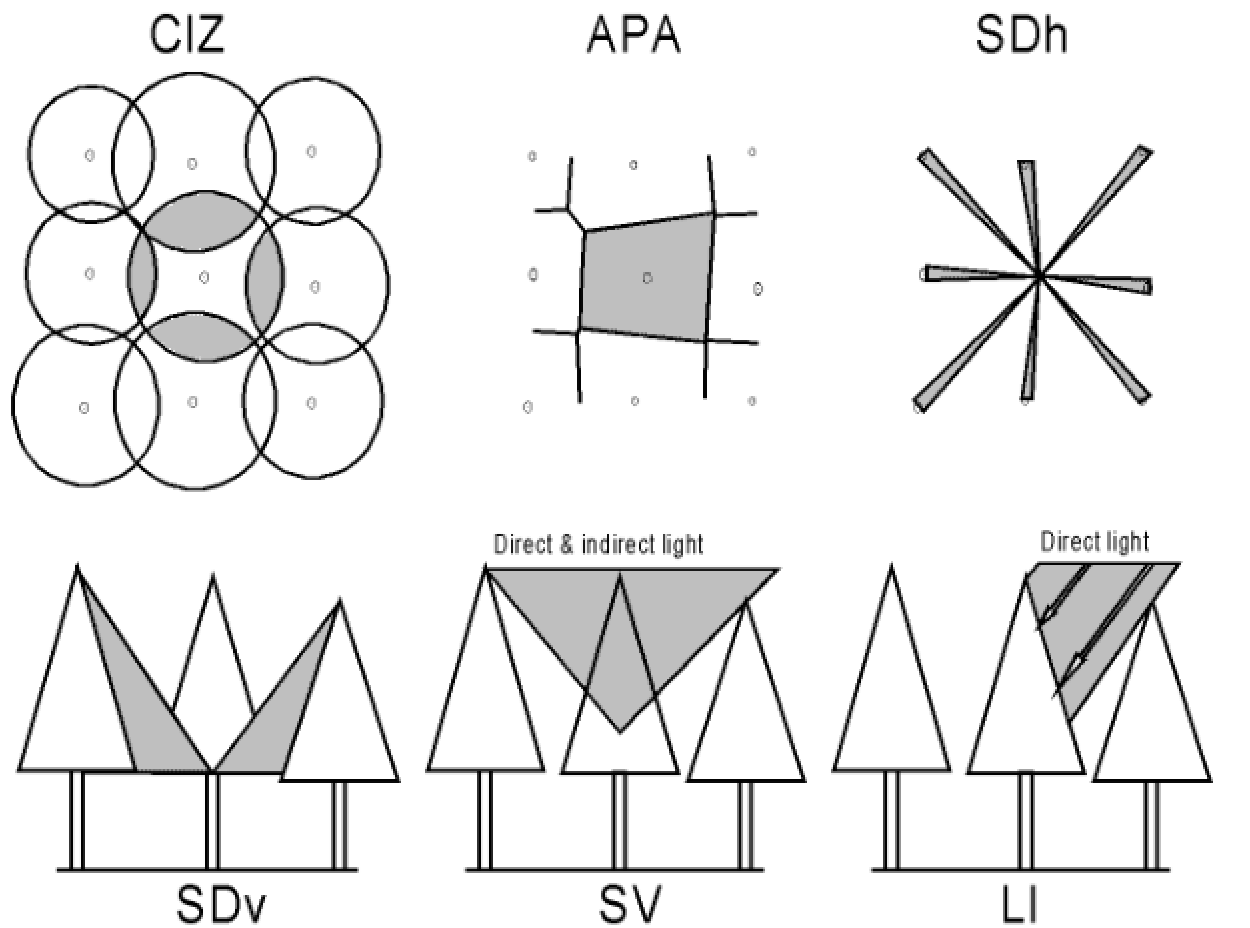


Fig. 4.1. Competition indices include the competitive influence zone (CIZ), area potentially available (APA), horizontal or vertical size–distance (SDh & SDv), sky view (SV) and light interception (LI) approaches.

Competition, con't

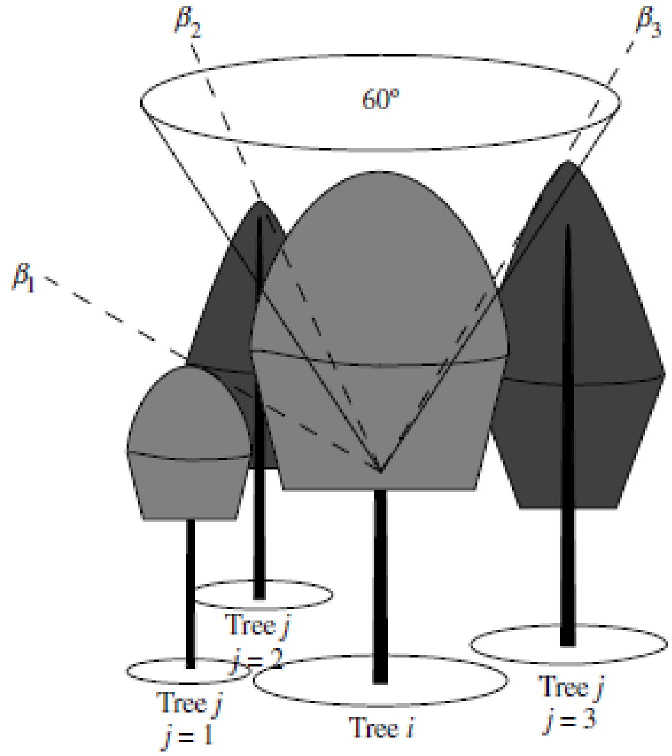
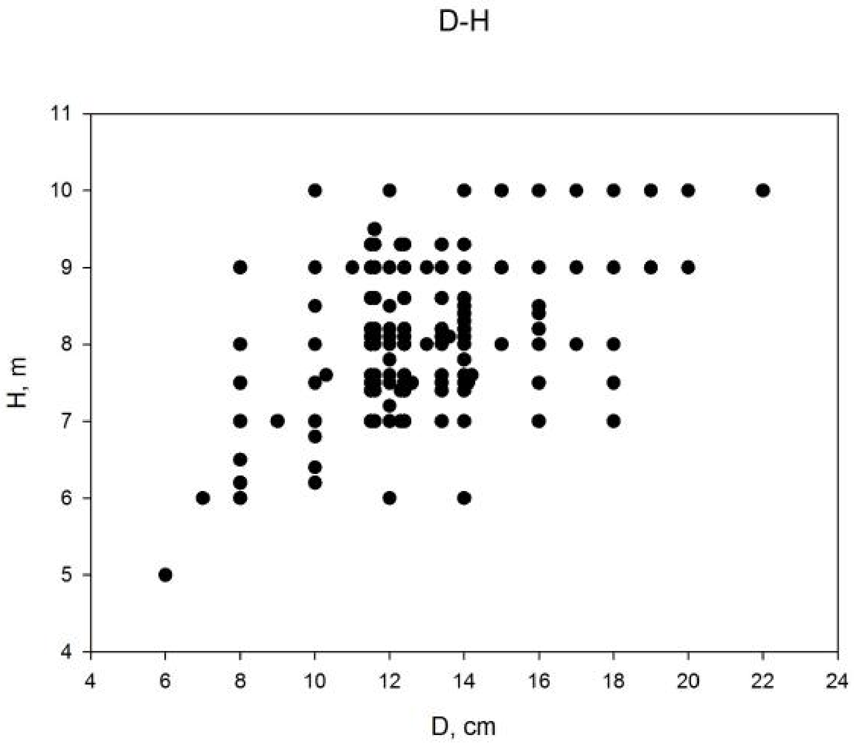
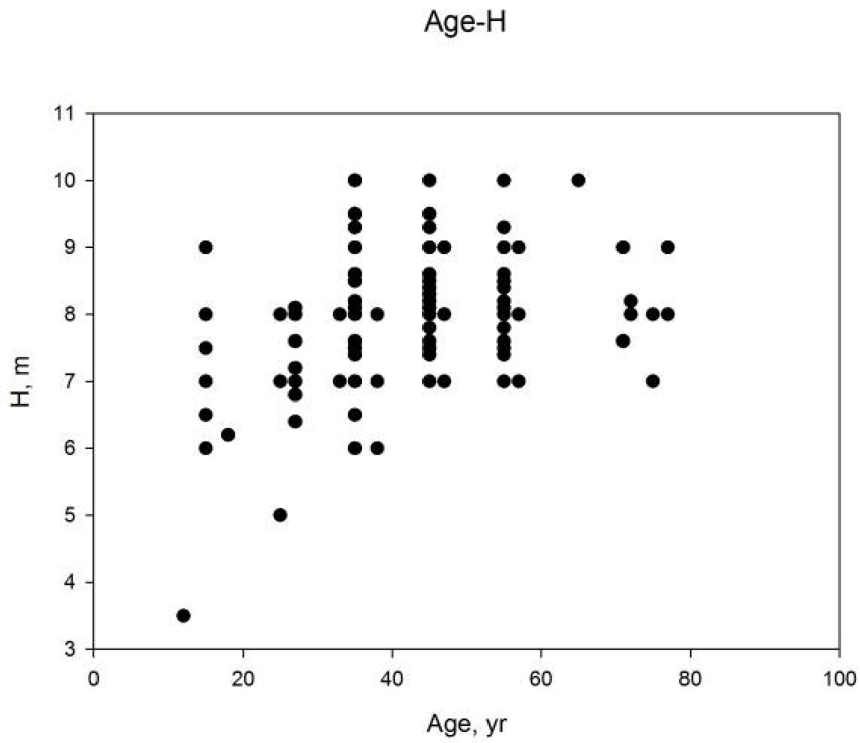


Figure 5.3 Virtual-reverse-cone method used in the SILVA distance-dependent, individual-tree growth model to calculate competition (Pretzsch *et al.*, 2002). Tree *i* is the subject tree and trees *j* ($j = 1, 3$) are potential competitors. The inverted cone, which is determined by species- and individual-specific parameters, defines a search area for competitors. Trees whose crown tips intersect the search area are competitors. Thus trees 2 and 3 are competitors of tree *i*.

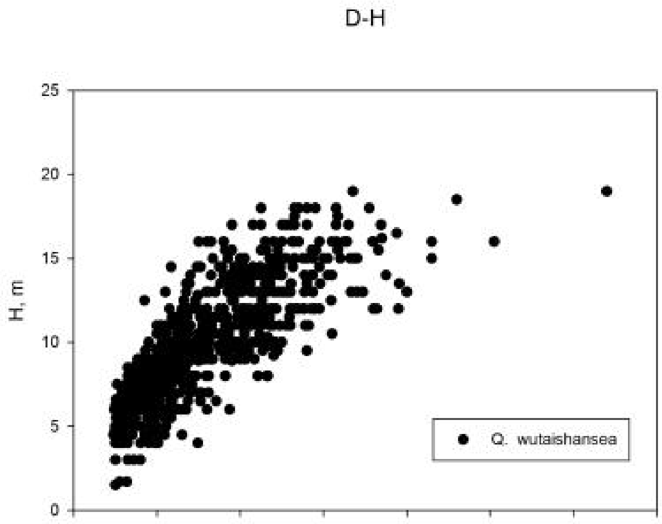
基于二类调查数据的栎类胸径-树高-年龄



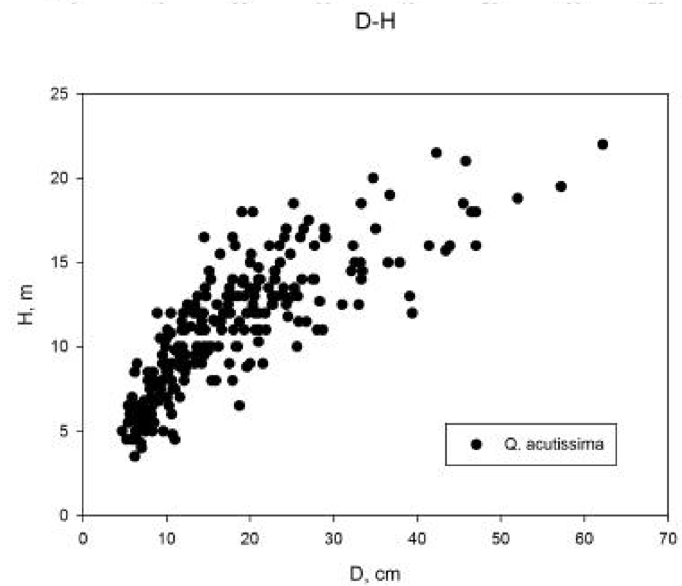


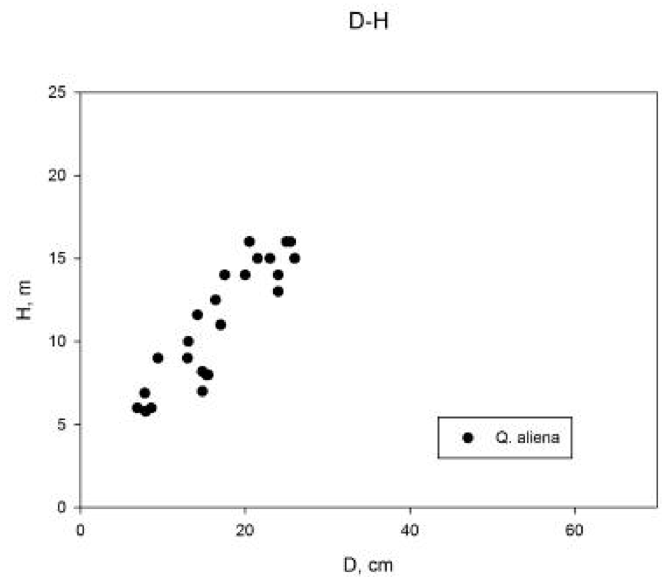
注：二类调查数据来源于黄龙山林业局 (2005), 桥山林业局 (2005, 2016)。栎类7成及以上。

数据采集分析

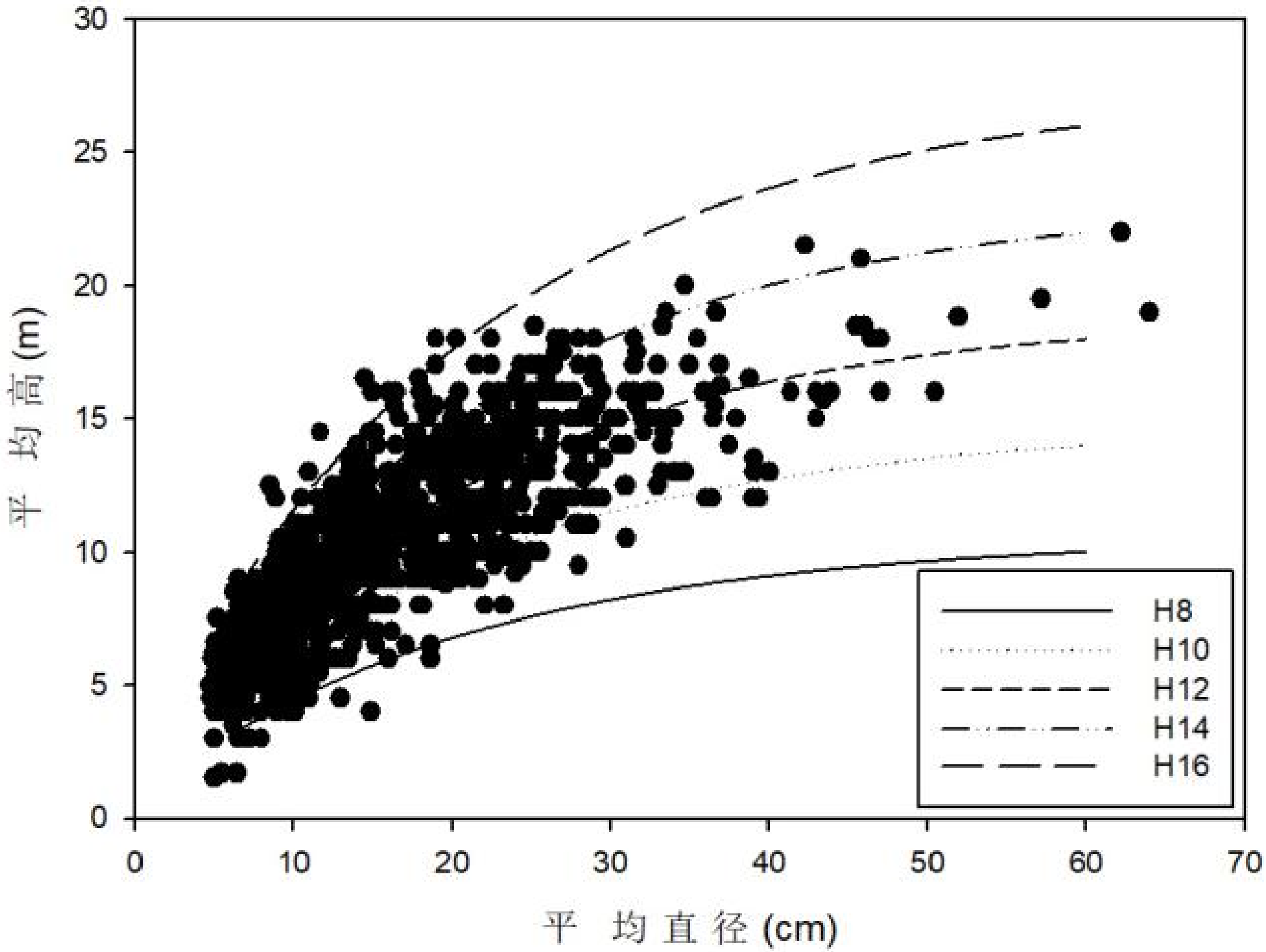


- 基于固定样地数据的树高-胸径关系最为稳定；
- 分树种的栎类树高-胸径关系基本一致，可以统一合并栎类处理计算。





立地形导向曲线分级



30
25
20
15
10
5
0
平 均 高 (m)
0
10
20
30
40
50
60
70
平 均 直 径 (cm)
H8
H10
H12
H14
H16

陕北栎类林立地形表，D12

基准胸径：12 cm

平均胸径	立地形 HD（m）				
D (cm)	5 m	7 m	9 m	11 m	13 m
6	2.5~3.7	3.8~5.0	5.1~6.2	6.3~7.5	7.6~8.7
8	3.1~4.5	4.6~6.0	6.1~7.6	7.7~9.1	9.2~10.6
10	3.6~5.2	5.3~7.0	7.1~8.8	8.9~10.6	10.7~12.3
12	4.0~5.9	6.0~7.9	8.0~9.9	10.0~11.9	12.0~13.8
14	4.4~6.5	6.6~8.7	8.8~10.9	11.0~13.1	13.2~15.3
16	4.8~7.1	7.2~9.4	9.5~11.8	11.9~14.2	14.3~16.6
18	5.1~7.6	7.7~10.1	10.2~12.7	12.8~15.2	15.3~17.8
20	5.4~8.0	8.1~10.7	10.8~13.4	13.5~16.1	16.2~18.8
22	5.7~8.4	8.5~11.3	11.4~14.1	14.2~17.0	17.1~19.8
24	5.9~8.8	8.9~11.8	11.9~14.7	14.8~17.7	17.8~20.7
26	6.2~9.2	9.3~12.2	12.3~15.3	15.4~18.4	18.5~21.5
28	6.4~9.5	9.6~12.7	12.8~15.8	15.9~19.0	19.1~22.2
30	6.6~9.7	9.8~13.0	13.1~16.3	16.4~19.6	19.7~22.9
32	6.7~10.0	10.1~13.4	13.5~16.7	16.8~20.1	20.2~23.5
34	6.9~10.2	10.3~13.7	13.8~17.1	17.2~20.6	20.7~24.0
36	7.0~10.4	10.5~14.0	14.1~17.5	17.6~21.0	21.1~24.5
38	7.2~10.6	10.7~14.2	14.3~17.8	17.9~21.4	21.5~25.0
40	7.3~10.8	10.9~14.5	14.6~18.1	18.2~21.7	21.8~25.4

林分密度理论

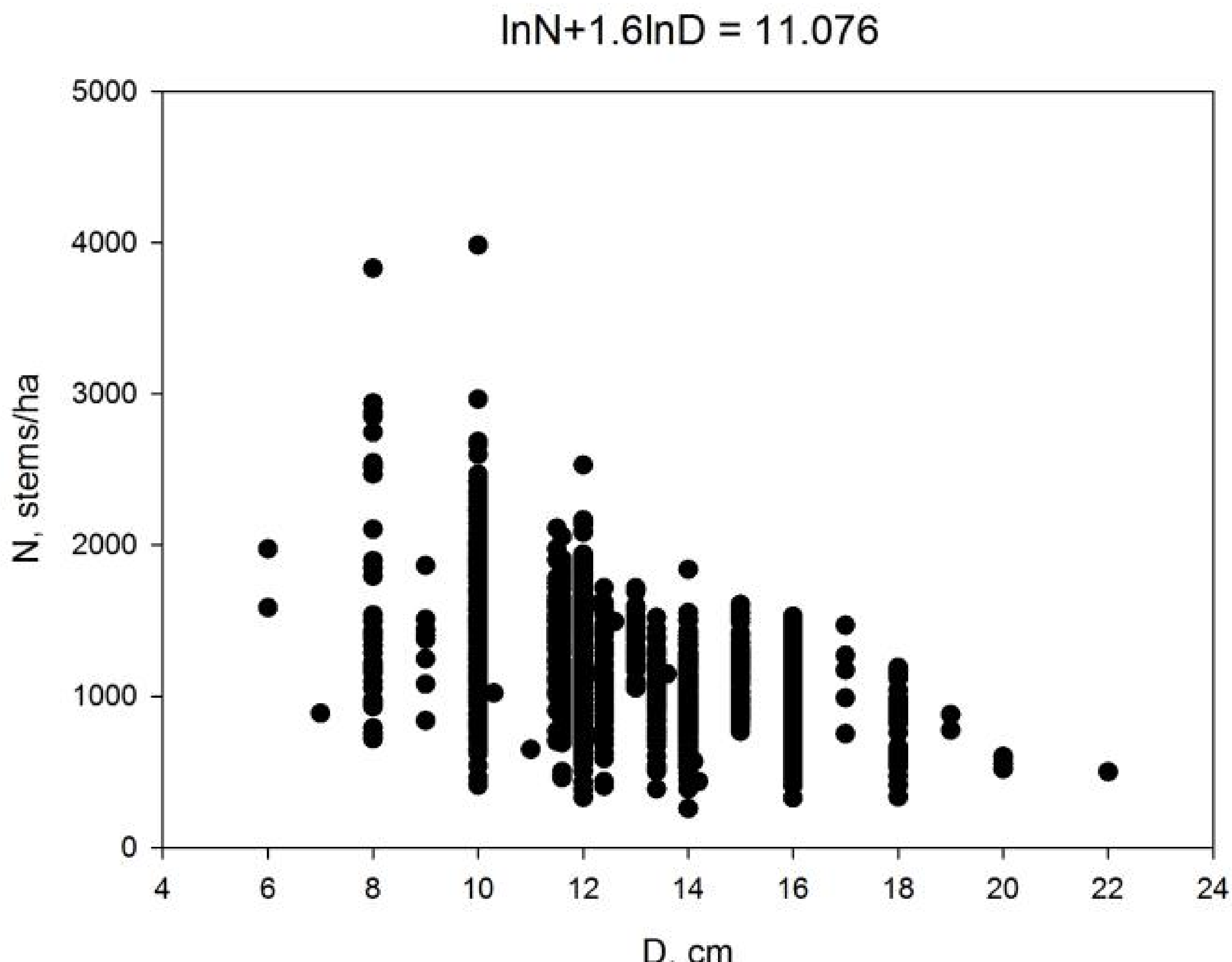
- 优势高理论 (Mitchell, 1975; Garcia, 2009)
- $\ln N = beta - 2 * \ln HT$

- 林分密度指数 (Reineke, 1933)
- $\ln N = beta - 1.6 * \ln D$

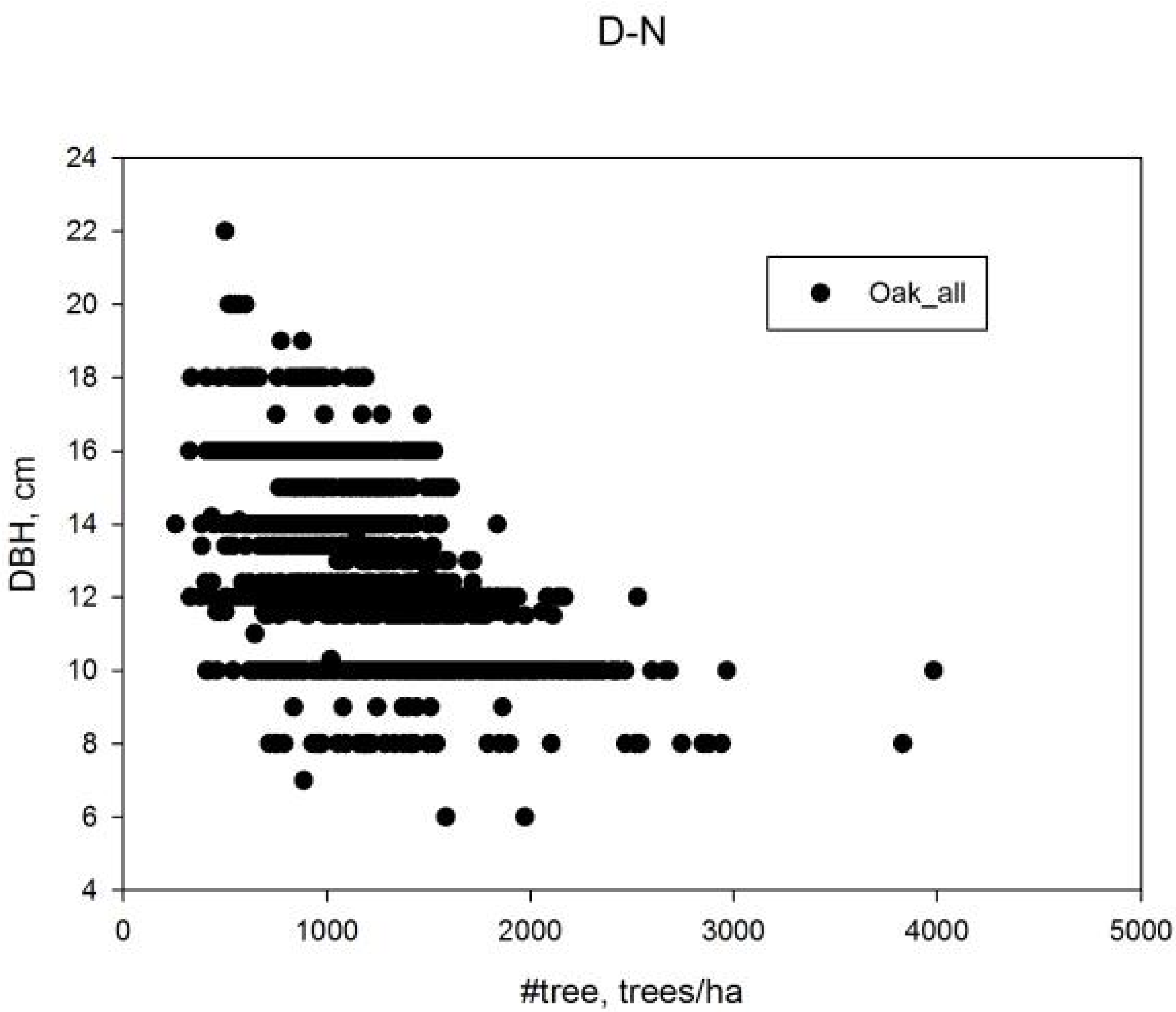
- 自疏伐线 (Yoda et al., 1963)
- $\ln N = beta - 2/3 * \ln V$

- 最大断面积(Assmann，1970；Steba and Monserud, 1993）
- $dN/N = -2 * (G/G_{max})^n * dD/D$, (Vanclay, 2010)
- 其中$G_{max} = G * (1 - (N/N_0)^n)^{(-1/n)}$

栎类林分密度-胸径关系，角规样地



林分密度指数与自疏伐


D-N
Oak_all
DBH, cm
#tree, trees/ha
24
22
20
18
16
14
12
10
8
6
4
0
1000
2000
3000
4000
5000

模型拟合结果

- 栎类树高-年龄生长
- H_tcore=1.543*(Age-0.5)^0.5
- HT=16.1456/(1+exp((-(Age-34.9889)/14.3188))
- H_ave=12.946/(1+exp((-Age+22.642)/18.909)), (陕西省林业厅，1964，1985）

- 栎类林分密度控制
- lnN_max=11.383-2*lnHT
- lnN_max=9.757-2/3*lnV
- lnN_max=11.076-1.6*lnD

基于树高-胸径的林分密度调整

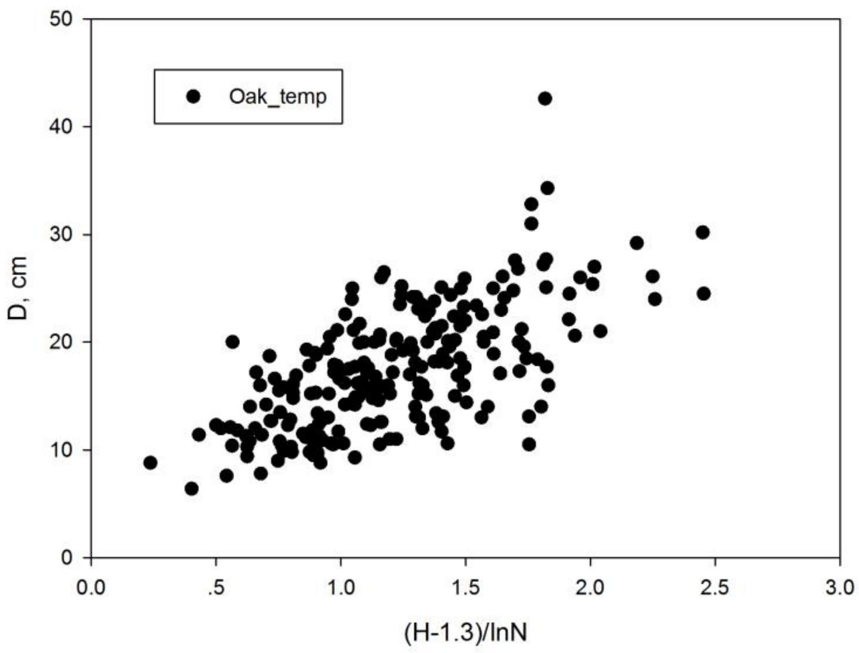
- 理论依据
- lnN=beta*(H-1.3)/D, (Vanclay, 2009)

- 备选模型
- lnN=13.622*(H-1.3)/D_all
- lnN=13.768*(H-1.3)/D_tcore

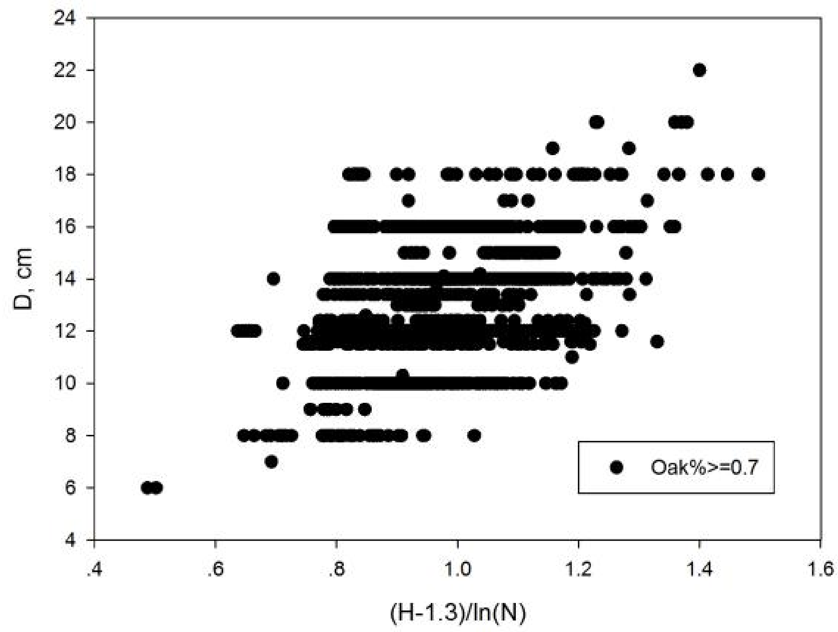
- 选用模型
- lnN=13.658*(H-1.3)/D_temp

树高和胸径对林分密度的双重影响

lnN=beta*(H-1.3)/D



D=beta(H-1.3)/lnN



基于数据更新的预测模型校正

- 例如树高生长模型校正 (Hynynen et al., 2002)。

- 树高生长模型校正步骤如下：
- 第一步，计算Bias=ln(H)-ln(H*),
- 第二步，计算H*(cal)=exp(ln(H*)+Bias*)，
- 第三步，计算校正后树高H(cal)=Cratio*H**exp(Bias*)，
- 其中Cratio=H(obs)_mean/H(cal)

陕北栎类林收获表, D12, HD=10m

立地形HD_{12} = 10m			D12	疏密度1.0
平均胸径D, cm	平均高H, m	林分密度N, stems/ha	蓄积V, m^3/ha	断面积G, m^2/ha
5.0	5.4	5476.1	36.0	10.8
7.0	6.8	3238.8	48.9	12.5
9.0	8.2	2183.3	62.0	13.9
11.0	9.4	1590.0	75.0	15.1
13.0	10.6	1218.7	87.8	16.2
15.0	11.6	968.7	100.1	17.1
17.0	12.6	791.3	112.0	18.0
19.0	13.5	660.3	123.4	18.7
21.0	14.3	560.3	134.3	19.4
23.0	15.0	482.2	144.6	20.0
25.0	15.7	419.8	154.3	20.6

陕北栎类示范林立地质量评价表

样地编号	平均胸径 cm	平均高 m	林分密度 trees/ha	林分断面积 m^2/ha	立地形，m	
					D12	D20
SL-104-12-1	12.5	8.1	2150	26.4	7.9	10.7
SL-169-9-1	12.0	7.5	1450	16.5	7.5	10.1
SL-136-3-4	17.3	10.4	875	20.7	8.3	11.3
SL-138-1-3	21.5	11.7	550	19.9	8.3	11.3
SL-104-11-1	11.5	9.7	1900	19.8	10.0	13.5
SL-136-3-1	18.5	11.0	625	16.8	8.5	11.5
SL-136-3-2	19.1	13.0	675	19.4	9.8	13.3
HGM-114-1-1	17.9	9.7	967	24.5	7.6	10.3
HGM-139-5-1	13.0	8.5	1100	14.6	8.1	10.9
CJC-134-9-1	20.8	14.0	833	28.4	10.1	13.7
CJC-143-6-1	19.3	14.2	750	22.0	10.7	14.5
GT-66-13-1	18.4	14.0	500	13.3	10.8	14.7
GT-66-10-1	18.9	15.5	667	18.7	11.8	16.0
DL-67-2-1	22.6	13.5	750	30.1	9.4	12.7
DL-64-2-1	18.8	14.3	983	27.4	10.9	14.8
DL-63-6-1	20.6	13.3	583	19.5	9.7	13.1
SB-14-5~2-1	16.0	9.9	1200	24.1	8.3	11.2

Mortality






Methods for modeling mortality

- Reineke (1933), Yoda et al. (1963), Curtis (1982)
  - Stand density index, self-thinning line, relative density

- Mäkelä and Hari (1986), Hawkes (2000)
  - Negative carbon balance

- Haenauer et al. (2001)
  - Neural networks, LOGIT model

- Flewelling and Monserud (2002)
  - Logit Model for Proportions, Least squares, Walker-Duncan algorithm, Weighted Least Squares, Maximum Likelihood

Markov process

- Mortality is not a Markov process, however, survival is.

- Survival = 1 – Mortality

  $P_s = 1 - P_m$
- 1-year: $P_{s1} = 1 - P_{m1}$
- n-year: $P_{sn} = (P_{s1})^n = (1 - P_{m1})^n$

  (The Markov property)
- 1-year: $P_{m1} = 1 - (P_{sn})^{(1/n)} = 1 - (1 - P_{mn})^{(1/n)}$
- $P_m = \exp(b'X)/(1 + \exp(b'X))$

(Flewelling and Monserud 2002)

A three-stage modeling approach: Mortality

- Stage 1. Empirical predictions based on observations
  - Stand density = f(DBH)
  - Stand density = f(BA)
- Stage 2. Fitting Step 1 with simulated data
  - Stand density index
  - Process-based
  - Artificial neural networks (ANN)
- Stage 3. Bayesian caliberation
  - Prior probability from Step 2
  - Markov Chain Monte Carlo (MCMC)
  - Posterior probability in the form of a mean vector and a variance matrix

Recruitment





Methods for modeling recruitment

- Buongiorno and Michie (1980), Liang (2010)
  - Assume observed reflect long-term ave.
  - Negatively correlated with stand density or BA

- Shifley et al. (1993)
  - Recruitment = f(CCF, diameter threshold)

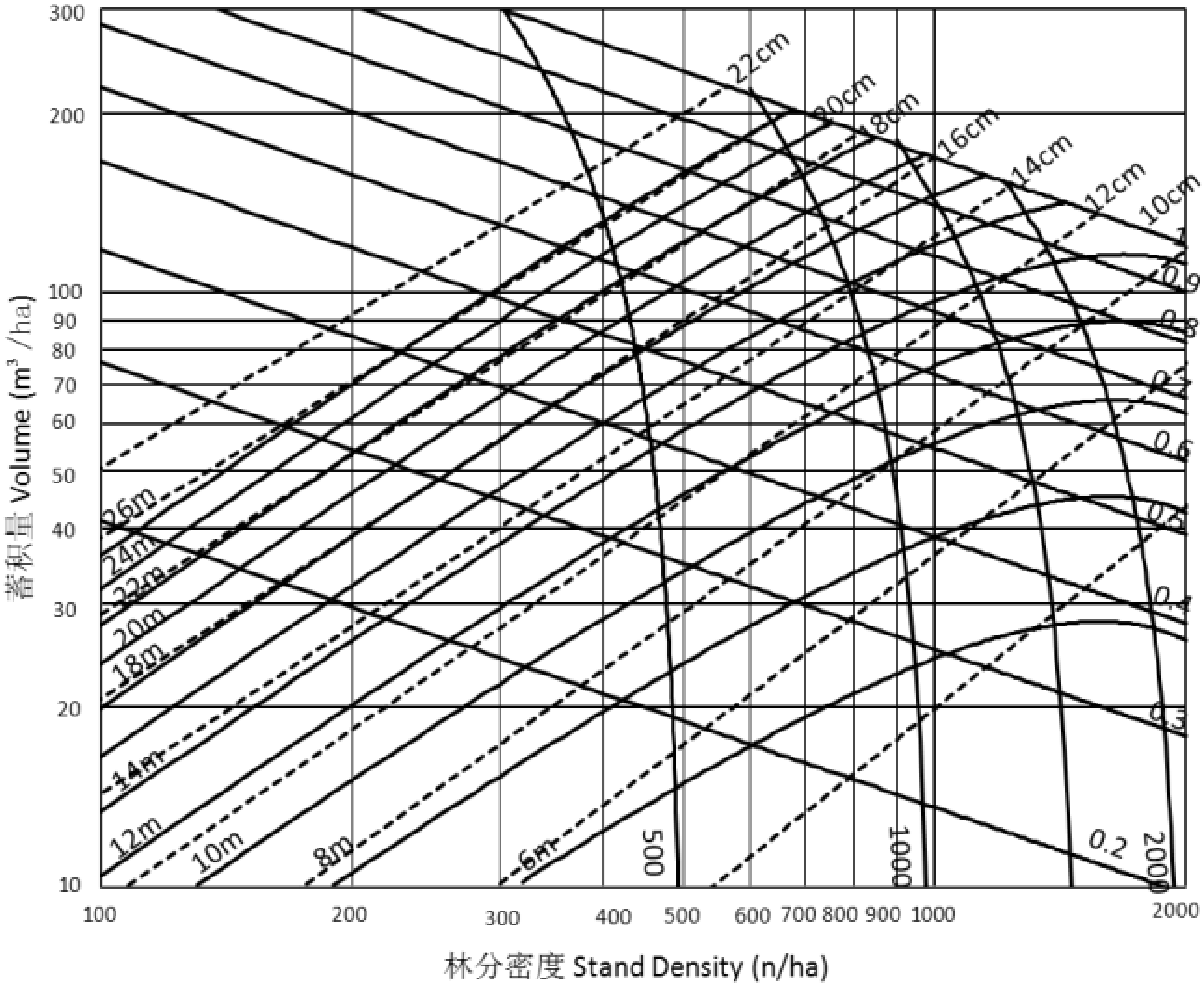
- Fergusen et al. (1986), Vanclay (1992)
  - 1) Logistic function, 2) conditional function

- Hasenauer and Kindermann (2002)
  - Neural networks
  - Juvenile height growth

A three-stage modeling approach: Recruitment

- Stage 1. Empirical predictions based on observations
  - Recruitment = f(BA, stand density)
  - Juvenile tree growth and mortality
- Stage 2. Simultaneous fitting Step 1 with simulated data
  - D-H equations
  - Juvenile tree height growth
  - ANN
- Stage 3. Bayesian caliberation
  - Prior probability from Step 2
  - MCMC
  - Posterior probability

林分密度控制图


300
200
100
90
80
70
60
50
40
30
20
10
蓄积量 Volume (m³/ha)
100
200
300
400
500
600
700
800
900
1000
2000
林分密度 Stand Density (n/ha)
22cm
20cm
18cm
16cm
14cm
12cm
10cm
26m
24m
22m
20m
18m
14m
12m
10m
8m
6m
500
1000
2000
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2

第九讲 纯林的林分蓄积

- 第一节 标准木
- 第二节 立木材积表
- 第三节 形高与形数
- 第四节 疏密度与标准表

- Q9. 标准木法计算材积的误差是如何产生的？

标准木法

- 平均标准木
  - 1. 设置标准地
  - 2. 计算D_ave, 查定H_ave
  - 3. 选定1-3株标准木（+-5%）
  - 4. 计算伐倒木材积 p.42, 或立木材积 p.49
  - 5. V=sigma(v_i)*G/sigma(gi)

- 分级标准木
  - 按胸径，分径级
  - 按断面积，分径级
  - 按径级比例

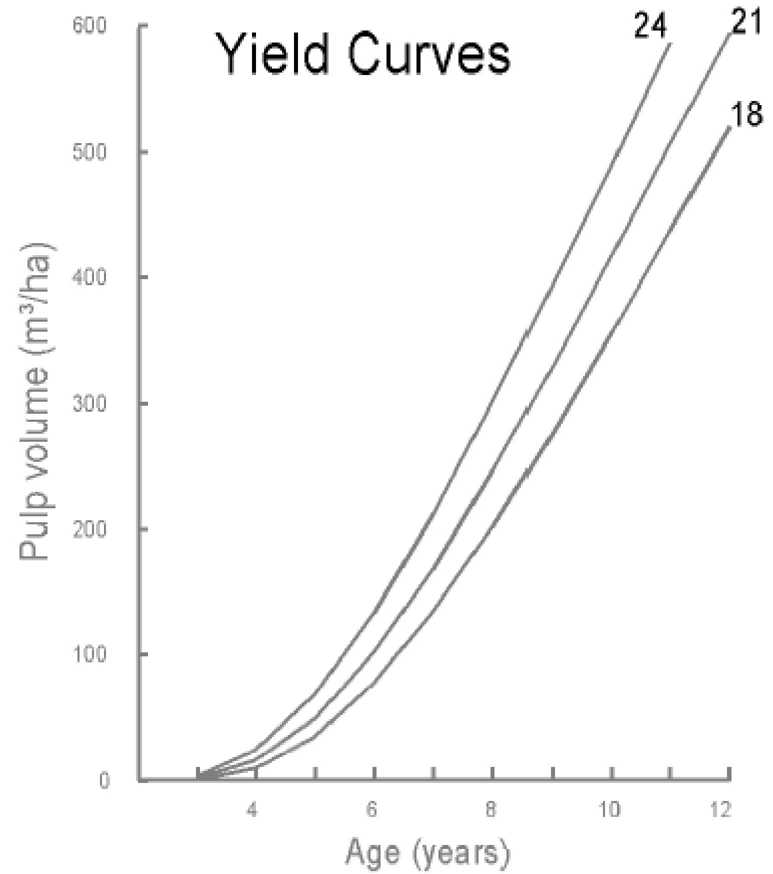
Yield tables 收获表

- A yield table presents the anticipated yields from an even-aged stand at various ages.
- One of the oldest approaches to yield estimation.
- Chinese “Lung Ch’uan codes” 龙泉码, some 350 yrs ago (Vuokila 1965).
- The first yield tables were published in Germany in 1787.
- Various approaches used in Europe (Vuokila 1965) and North America (Spurr 1952)

Growth and yield tables

Yield Table

Age (y)	Site Index (m) 18	21	24
3	1	2	4
4	11	17	25
5	36	50	69
6	78	102	133
7	134	169	212
8	201	246	301
9	276	330	395
10	356	418	491
11	438	507	586
12	520	594	679



Yield Equation: $\log(V+1) = 3.534 - 14.02/t + 0.2314\ S/t$

TABLE 1. *Experience table for the yield of various species for light thinning (Von Cotta, 1821, p. 34)*

Tafel V. A. Fichten.

Jahre.	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.
20	269	450	632	813	994	1175	1356	1538	1719	1900
21	290	485	680	875	1071	1266	1461	1656	1851	2047
22	311	520	730	939	1149	1358	1568	1777	1987	2196
23	333	557	781	1005	1229	1453	1677	1901	2124	2349
24	355	593	832	1071	1310	1549	1788	2026	2265	2504
25	377	631	885	1139	1393	1646	1900	2154	2408	2662
26	400	669	939	1208	1477	1747	2016	2285	2555	2824
27	423	708	993	1278	1563	1848	2133	2418	2703	2989
28	447	748	1049	1350	1651	1952	2233	2554	2855	3156
29	471	788	1106	1423	1740	2057	2375	2692	3009	3327
30	495	830	1163	1497	1831	2165	2499	2832	3166	3500
31	520	871	1222	1573	1923	2274	2625	2975	3326	3677
32	546	914	1282	1649	2017	2385	2753	3120	3488	3856
33	572	957	1342	1728	2113	2498	2883	3268	3653	4039
34	598	1001	1404	1807	2210	2613	3015	3418	3821	4224
35	625	1046	1467	1887	2308	2729	3150	3571	3992	4413
36	652	1091	1530	1969	2408	2848	3287	3726	4165	4604
37	679	1137	1595	2053	2510	2968	3426	3883	4341	4799
38	707	1183	1660	2137	2613	3089	3566	4042	4519	4995
39	735	1231	1726	2222	2717	3213	3709	4205	4701	5197
40	764	1279	1793	2308	2822	3338	3853	4369	4884	5400
41	794	1328	1861	2395	2928	3464	4000	4534	5070	5606
42	823	1377	1929	2481	3035	3590	4145	4701	5256	5812
43	853	1426	1998	2570	3143	3718	4295	4870	5445	6020
44	882	1475	2067	2660	3252	3847	4443	5038	5633	6229
45	912	1525	2137	2750	3362	3977	4593	5208	5824	6438
46	942	1575	2207	2840	3472	4107	4743	5378	6013	6649

收获表 （杉木, 地位级II）

Age, yr	H, m	D, cm	N, n/ha	V, m3/ha	V_ave, m3/ha/yr	ΔV, m3/ha/yr	V%, %
5	4.0	5.0	2400				
10	8.8	10.0	2100	75	7.5	15	
15	12.4	14.0	2100	165	11.0	18	15.0
20	14.5	18.0	1500	240	12.0	15	7.41
25	16.0	21.0	1500	300	12.0	12	4.4
30	17.0	23.0	1500	351	11.7	10.2	3.13

Source: 陈平留等(2010), p. 76

收获表1

- 某地15年生的杉木林经调查其平均树高为12.0 m，平均胸径为12 cm，蓄积量为150 m3/ha。
- 试计算其30年生时的平均胸径、评价树高，和林分蓄积。
- 疏密度 P=G/Gmax, 蓄积量 V=P*Vmax

- 根据该林分平均高资料，该林分属于II地位级，采用杉木II地位级生长过程表。
- 查表得知II地位级杉木林分15年生时平均树高为12.4 m，平均胸径14.0 cm，蓄积量165 m3/ha。
- 查表得知II地位级杉木林分30年生时平均树高为17.0 m，平均胸径23.0 cm，蓄积量351 m3/ha。

收获表2

- 秦岭火地塘油松天然林现实生长收获表

- 现有30年生油松林经调查其平均树高为10.6 m，平均胸径为18.5 cm，蓄积量为81.0 m3/ha，

- 预测其55年生时的平均胸径、树高、蓄积量。

实验形数法

- v=g*(h+3)*f_epsilon
- f_epsilon= h/(h+3)*f_1.3

- 主要乔木树种平均实验形数

0.45 云南松、冷杉
0.43 云杉、杉木（实生）
0.42 杉木、红松、华山松、黄山松
0.41 杉木（扦插）、天山云杉、落叶松、樟子松、油松、赤松、黑松
0.40 杨树、桦树、柳树、椴树、栎树、槐树、榆树、樟树、桉树
0.39 马尾松
0.38 侧柏

陕西省二元立木材积方程

基于材积方程可计算单木材积与林分蓄积。二元材积模型是根据材积与胸径、树高两个因子的回归关系而拟合的树木单株材积模型，是编制二元材积表的基础。二元材积方程基于形数计算方法：$V = G \cdot H \cdot f_{1.3}$

其中 V 为材积，$f_{1.3}$ 为 1.3m 高度的形数。

（1）秦岭、巴山、关山地区油松：$f_{1.3} = 0.71900D^{-0.09214}H^{-0.03059}$

（2）秦岭、巴山、关山地区华山松：$f_{1.3} = 0.68917D^{-0.18723}H^{0.10529}$

（3）秦岭、巴山、关山地区栎类：$f_{1.3} = 0.72770D^{-0.16639}H^{0.01493}$

（4）秦岭、巴山、关山地区桦类：$f_{1.3} = 0.05243D^{-0.13367}H^{0.14526}$

（5）秦岭、巴山、关山地区杨类：$f_{1.3} = 0.99575D^{-0.00885}H^{-0.24569}$

（6）秦岭、巴山、关山地区阔杂：$f_{1.3} = 0.66275D^{-0.18862}H^{-0.00755}$

（7）桥山、黄龙山地区栎类：$f_{1.3} = 0.77267D^{-0.010067}H^{-0.05273}$

（8）桥山、黄龙山地区杨类：$f_{1.3} = 0.78438D^{-0.07453}H^{-0.09236}$

（9）桥山、黄龙山地区白桦：$f_{1.3} = 0.7391D^{-0.22027}H^{0.064443}$

（10）杉木：$f_{1.3} = 0.53643 - 0.0013223D + 0.77058\frac{1}{H} - 0.046331\log D$

（11）马尾松：$f_{1.3} = 0.77825D^{-0.16660}H^{-0.01591}$

（以上选自《陕西省二元立木材积表》 陕西省林业勘察设计院编 1975 年）

削度方程法

- 削度方程 p.205-208
- 削度方程 (taper curve) > 干形（form factor）
- d_i => h_i, 任意d_i 估算 h_i
- h_i => d_i,任意h_i 估算 d_i
- v_i=(pi/40000)*int(hi-1_hi)di^2*dhi, 计算任意分段v_i

第十讲 混交林林分蓄积

- 第一节 树种组成与林分结构
- 第二节 角规原理与技术
- 第三节 林分断面积
- 第四节 林分株树密度与蓄积

- Q10. 角规技术的精度问题，在林分断面积，林分株数，蓄积计算上，其误差产生的原理是什么？

林分蓄积计算方法

- 方法一
  - 解析木，标准木（人工林）
  - 材积表，一元材积表，二元材积表，f_1.3 （纯林）
  - 削度方程
- 方法二：角规测树，林分断面积，G=Fg*Zn (p.179-180)
- 方法三：疏密度，标准表，生长过程表，林分生长模型估算
- 方法四：遥感估算

角规测树法

- 角规测树，p.178
- 角规点数的确定, Tab. 6-15, p. 183
- 角规常数（F）的选择, (F=0.5, 1, 2, 4), p.182

- 角规绕测技术
- 角规控制检尺，R= 50d/sq(Fg)

- 林缘误差的消除
- 胸径和树高的测定
- 年龄、地理及林下因子的测定
- 角规调查小组

角规系数

- G = Fg*Z
- Rj = (L/l)*Dj
- gj = Zj*(pi/4)*Dj^2

- Fg = 2500(l/L)^2
- Fg = 0.5, R = 70.70d, 中龄林 D=8-16cm
- Fg = 1, R = 50d, 近熟林 D=17-28cm
- Fg = 2, R = 35.35d， 过熟林 D>28cm
- Fg = 4, R = 25d， 过熟林 D>28cm

- Fg=1, ha/n
- 1/5, 2/7, 3/9, 4/11, 5/12, 6/14, 7-8/15, 9-10/16, 11-15/17, >16/18

遥感数据

- 如果因只采用森林测量而没有足够的样地来获得很好的调查结果，我们可以利用与森林变量有关的辅助变量。例如通过RS或GIS所获得的变量。
- 对林业调查估计值校正产生样地变量的加权，其中权重为与样地相似的总体林分面积。
- 在森林调查中总体是一个区域，其单位为图像的像元或可能的样地。
- 假定一个调查样地为一个相关的像元给出森林变量数值。每一个单元 j 与一个变量 y_j 和一个辅助变量 x_j 相关。
- y 变量在森林调查中为森林变量，x 变量是从遥感或气象变量中获得的光谱变量，而这些变量又是从地理信息系统数据库中获得的。

遥感林分蓄积

- Forest Inventory, p. 18-19，利用航空影像将同样100 ha面积进行分层。3层分别定义为：

	A(ha)	n	V(m3/ha)	SD(m3/ha)	Vtot(m3)	SD(m3)
开阔地	18.0	18	42	6.7	756	121
中龄林	33.3	35	167	10.0	5557	344
成熟林	48.7	49	268	13.3	13033	649

- V_ave = 0.180*41.976+0.333*166.84+0.486*267.67=193m3/ha
- SD=sqr(0.180^2*45.437+0.33362*100.27+0.487^2*177.72)=7.4 m3/ha
- Vtot=755.6+5557.1+13033.4=19346 m3
- SD_tot=sqr(14722+111246+421372)=740 m3

遥感林分蓄积 , con't

- 由各种公式（Forest Inventory, p. 77-78) 计算获得的小面积估计值如下:

Area	n	NIR	y_i	s_e	y_iSYN	y_iREG	y_iSUR	s_e
1	7	0.22893	169.2	13.79	115.6	151.4	158.5	11.387
2	5	0.25104	92.5	25.35	115.6	134.1	102.0	31.773
3	6	0.26008	120.8	20.36	115.6	127.0	123.0	20.389
4	22	0.28201	113.5	9.45	115.6	109.8	116.3	6.946
5	10	0.31497	91.4	12.21	115.6	84.0	83.1	8.346
mean		0.27802	115.6	6.91	115.6	112.9	112.9	5.216
sum	50							

- y_i　　区域 i 的传统局部估计
- y_iSYN　　区域 i 的平均整体值估计
- y_iREG　　区域 i 内自变量的平均值*相关系数
- y_iSUR　　整体估计量

标准误

- 每公顷平均林木蓄积为：

  y_ave = 1/n * sigma_i=1_n(y_i)

  = 1/102 * sigma_i=1_102(y_i) = 193 m3/ha

  其中y_i 指样地 i 每公顷蓄积。为了求出平均标准误，我们首先必须确定总体 N 和样地 n 的大小。

- 近似抽样比率 f = n/N

  f = sigma_i=1_n(a_i/A) = sigma_i=1_102(a_i/100) = 0.02

- 总体方差估计值:

  s_y^2 = (1/(n-1))*(sigma_i=1_n(y_i^2)-(sigma_i=1_n(y_i^2))^2/n) = 12601 (m3/ha)^2

- 求每公顷平均林木蓄积的标准误：

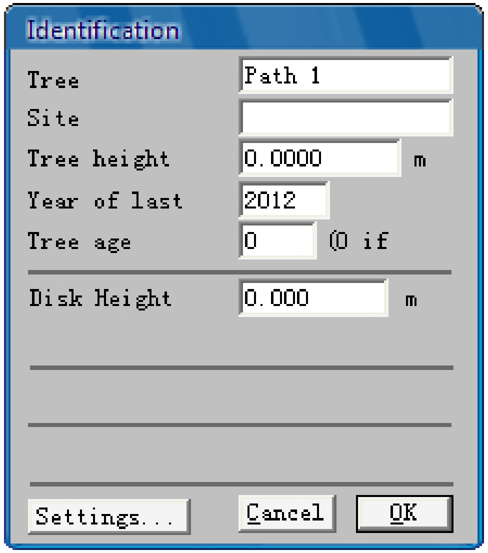
  s_y_hat = sqr((1-n/N)(s_y^2/n))

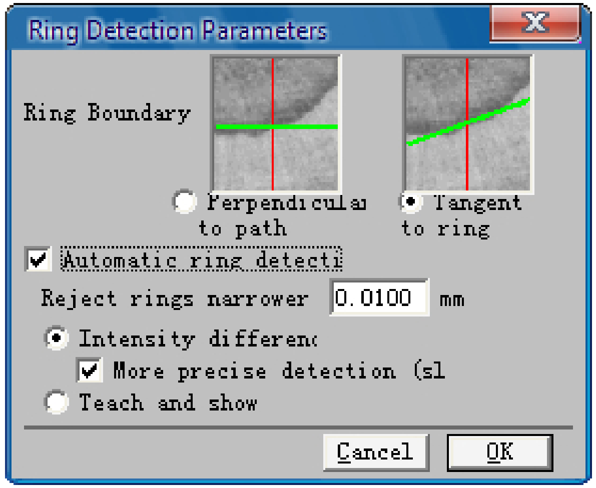
第十一讲 林木动态生长

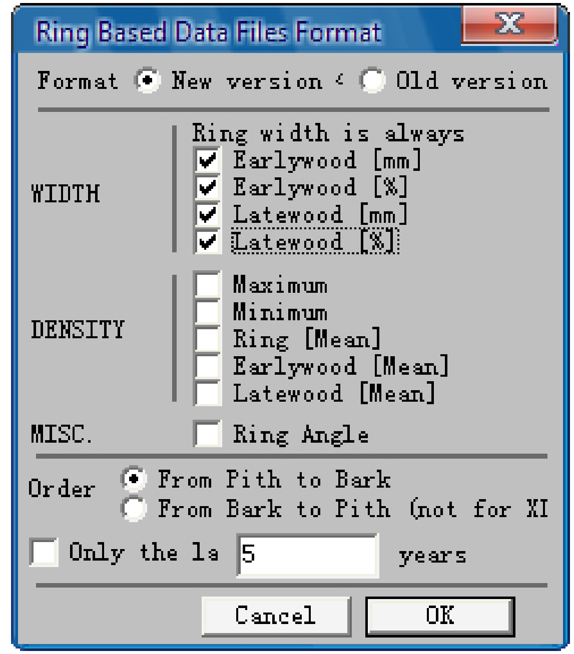
- 第一节 树木生长量与生长率
- 第二节 平均生长量与连年生长量
- 第三节 树木生长方程
- 第四节 代谢尺度理论

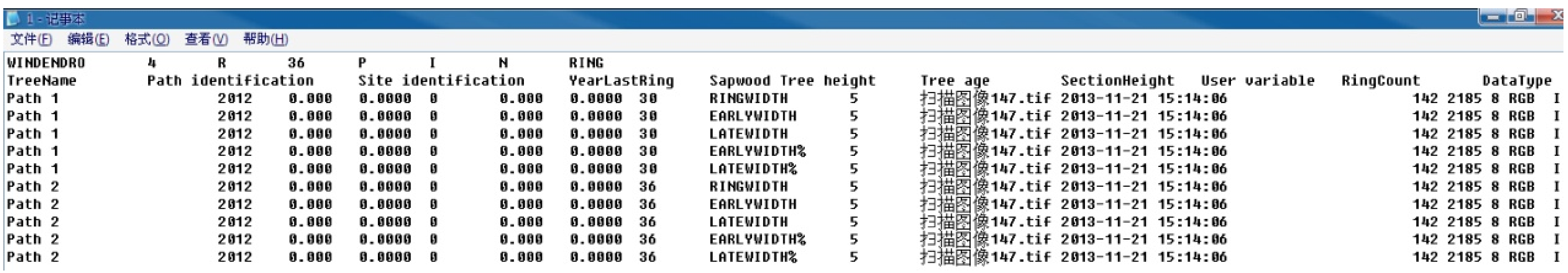
- Q11. 树木生长，生长率，生长方程的变量及其生物学原理是什么？

WinDENDRO 年轮分析系统










```
WINDENDRO      4        R        36       P        I        N        RING
TreeName       Path identification        Site identification        YearLastRing       Sapwood Tree height         Tree age         SectionHeight   User variable   RingCount        DataType
Path 1                  2012     0.000    0.0000   0        0.000    0.0000  30         RINGWIDTH        5         扫描图像147.tif 2013-11-21 15:14:06                          142 2185 8 RGB   I
Path 1                  2012     0.000    0.0000   0        0.000    0.0000  30         EARLYWIDTH       5         扫描图像147.tif 2013-11-21 15:14:06                          142 2185 8 RGB   I
Path 1                  2012     0.000    0.0000   0        0.000    0.0000  30         LATEWIDTH        5         扫描图像147.tif 2013-11-21 15:14:06                          142 2185 8 RGB   I
Path 1                  2012     0.000    0.0000   0        0.000    0.0000  30         EARLYWIDTH%      5         扫描图像147.tif 2013-11-21 15:14:06                          142 2185 8 RGB   I
Path 1                  2012     0.000    0.0000   0        0.000    0.0000  30         LATEWIDTH%       5         扫描图像147.tif 2013-11-21 15:14:06                          142 2185 8 RGB   I
Path 2                  2012     0.000    0.0000   0        0.000    0.0000  36         RINGWIDTH        5         扫描图像147.tif 2013-11-21 15:14:06                          142 2185 8 RGB   I
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Path 2                  2012     0.000    0.0000   0        0.000    0.0000  36         LATEWIDTH        5         扫描图像147.tif 2013-11-21 15:14:06                          142 2185 8 RGB   I
Path 2                  2012     0.000    0.0000   0        0.000    0.0000  36         EARLYWIDTH%      5         扫描图像147.tif 2013-11-21 15:14:06                          142 2185 8 RGB   I
Path 2                  2012     0.000    0.0000   0        0.000    0.0000  36         LATEWIDTH%       5         扫描图像147.tif 2013-11-21 15:14:06                          142 2185 8 RGB   I
```

Table 2.1 Example growth and yield models, the competition variables used, and the type of model form in which the competition is used.

Growth model	Competition variable[a]		Model form
	One sided	Two sided	
Whole stand			
DFSIM (Curtis *et al.*, 1981)	—	BA, RD	Realized
Scube (García, 2011)	—	BA, TPH, CC	Realized
Size class			
FIBER (Solomon *et al.*, 1986)	—	BA_I, BA_R	Realized
Vanclay (1989a)	—	BA	Realized
Distance-dependent individual tree			
SILVA (Pretzsch *et al.*, 2002)	KKL, KMA, NDIST	—	Potential × modifier
TASS (Mitchell, 1975)	FV/FV_{max}	TPH	Realized
Distance-independent individual tree			
ORGANON (Hann, 2011)	CCFL, BAL, CCH	BA	Realized, potential × modifier
PROGNAUS (Monserud *et al.*, 1997)	BAL	BA	Realized
CACTOS (Wensel *et al.*, 1987)	CC_{66}	BA	Potential × modifier

[a] Where BA is total basal area; BA_I is total initial basal area before harvest; BA_R is total basal area after removal; BAL is basal area in larger trees; CCFL is crown competition factor in larger trees; CC is canopy crown closure; CCF is crown competition factor; CCH is crown closure at the top of the subject tree; CC_{66} is crown closure at 66% of subject tree's height; FV is tree foliar volume; FV_{max} is the tree foliar volume in the absence of competition; KKL is the crown competition index of Pretzsch *et al.* (2002); KMA is the ratio between the sum of crown surface area of coniferous competitors to that of all competitors; NDIST is the horizontal distance between the competition center of gravity to the stem center of a subject tree; RD is Curtis (1982) relative density; and TPH is trees per hectare.

Data and Models

- Like chickens and eggs, it is not obvious which comes first.
- Modeling and definition and collection of data should form an iterative process, commencing with the model formulation.
- Most modeling efforts commence with and data available
- The modeling approach often may be dictated by limitations of the data.

Project 3. Stand dynamics

- 1.Based on the transition matrix model (Cao et al. 2016, p. 58-60), predict forest dynamics at the stand level for 50 years.
- 2.Define the timing of forest succession up to the climax community.
- 3.Estimate the stand DBH and BA when it reaches a stable ecosystem.
- 4.Compute the mortality rate (self-thinning rate) during the succession.

Project 3, con't

- 5.Processing the data of 40 pine stands (Cao et al. 2016, p.57) with a diameter size class 10 cm, calculate number of trees N_i (trees/size class), mean diameter D_i, and basal area BA_i for each size class.
- 6.Using the matrix model (example 4.2), predict 20 years growth for the pine forests (suppose 40 plots as a whole forest), computer mean DBH and BA at forest level.
- 7.Based on the whole stand model (example 4.1), predict 20 years growth for the 40 pine stands, respectively. Then, summarize to forest level, calculate forest level D and BA.
- 8.Compare and analyze the matrix model and the whole stand model, in terms of growth predictions, statistic bias, and the underlying reasons.

Models and data 模型与数据

- Like chickens and eggs, it is not obvious which comes first.
- Modeling and definition and collection of data should form an iterative process, commencing with the model formulation.
- Most modeling efforts commence with and data available
- The modeling approach often may be dictated by limitations of the data.

Life span

Bacteria	10^-2 yrs
Insects	10^-1 yrs
Grasses, herbs	10^0 yrs
Large mammals	10^1 yrs
Humans	10^2 yrs
Trees	10^4 yrs

Processes in forest ecosystems

	Process	Duration	Spatial	Pattern
+4	Evolution	Millenniums	Continents	genotypes
+3	Succession	Centuries	Landscapes	community
+2	System renewal	Decades +	Ecosystems	regeneration
+1	Stand development	Decades	Stands	Age class
0	Element cycle	Year	Tree-tree	Matter budget
-1	leafs, fine roots,...	Week-month	Tree+vegetation	Tree foliation
-1	Decomposition	Week-month	Soil horizon	Humus form
-2	Assimilation-matter	Hours-weeks	Leaf-root	Carbon and ion
-2	Mineralisation	hours-weeks	Soil aggregate	Soil solution
-3	Biochemical reaction	Minutes	Cell	Biochemical
-3	Soilchemical	Seconds	Mineral surface	

Spatial and temporal aggregation

Spatial scale

Biome shift models

Landscape — Landscape models

Community — Succession models

Population — Stand models

Organism — Individual tree models

Organ — Ecophysioligical models

Cell

Second Day Year Decade Century Century Millenium

Temporal scale

Models for forest ecosystem management

- Forest yield models (e.g., CACTOS, FPS, FVS, ORGANON, SPS)
- Ecological gap models (e.g., JABOWA, FORET)
- Ecological compartment models (e.g., CENTURY, FOREST-BGC)
- Process/mechanistic models (e.g., PnET, PipeStem, ECOPHYS, FOREST-BGC)
- Vegetation distribution models (e.g., Monserud et al. 1993)
- Hybrid models (e.g., PipeQual/CROBAS, Mäkelä for Finland; 3-PG, Landsberg & Waring; Ågren for Sweden; FOREST 5: Robinson)

Source: Monserud (2003), Pretzsch et al. (2008)

From primary production to growth and yield

- Gross primary productivity (GPP, t/ha/yr) refers to the total biomass produced in photosynthesis over a given time period for a given area.
- Net primary productivity (NPP, t/ha/yr) is defined as the biomass remaining after subtracting the continuous losses through respiration.

- GPP = NPP + sigma(Respiration)
- GPP = NPP * f_resipiration
- NPP = net biomass growth + plant organs and whole plant losses
- Gross growth = net growth + losses + mortality = NPP

Growth and yield

- Growth rfers to the increase in dimensions of one or more individuals in a forest stand over a given period of time
  - e.g. m^3/ha/yr

- Yield refers to their final dimensions at the end of a certain period
  - e.g. m^3/ha

- if yield is y, growth is the derivative dy/dt

第十二讲 林分动态生长

- 第一节 解析木数据与年轮气象学
- 第二节 木芯数据与径向生长
- 第三节 单木水平长期复位监测
- 第四节 径阶净增量与转移概率

- Q12. 解析木数据可以提供哪些对林业生产和科研有用的信息？

Model classification by scales and purposes

Use	Resolution	Driving variables	Example
Empirical models			
Atmospheric studies	Global primary production	Evapo-transpiration	Lieth & Box (1972)
National forest planning	Stand variables	Age, stand basal area	Clutter (1963)
Regional planning	Individual trees	Tree species & sizes	Prognosis (Stage 1973)
Silvicultural studies	Tree crowns	Tree & branch variables	TASS (Mitchell 1975)
Silvicultural & conversion studies	Wood characteristics	Branches, ring width & density	SYLVER (Mitchell 1988)
Succession & Process models			
Ecological studies	Individual trees	Tree species & sizes	JABOWA (Botkin 1993)
Nutrient cycling	Individual trees	Trees, nutrients	FORCYTE (Kimmins 1988)
Physiological studies	Mass of foliage, branches, roots	Biomass, photosynthesis, respiration	Sievänen *et al.* (1988)

Models for forest ecosystem management

- Forest yield models (CACTOS, FPS, FVS, ORGANON, SPS)
- Ecological gap models (JABOWA, FORET)
- Ecological compartment models (CENTURY, FOREST-BGC)
- Process/mechanistic models (PnET, PipeStem, ECOPHYS, FOREST-BGC)
- Vegetation distribution models (Monserud et al. 1993)
- Hybrid models (PipeQual/CROBAS, Mäkelä for Finland; 3-PG, Landsberg & Waring; Ågren for Sweden; FOREST 5: Robinson)

Source: Monserud (2003), Pretzsch et al. (2008)

QUASSI 森林动态预测模型

- Publications:

  吴恒等（2015）

  廖梓延等（2017）

  郭小阳等（2017）

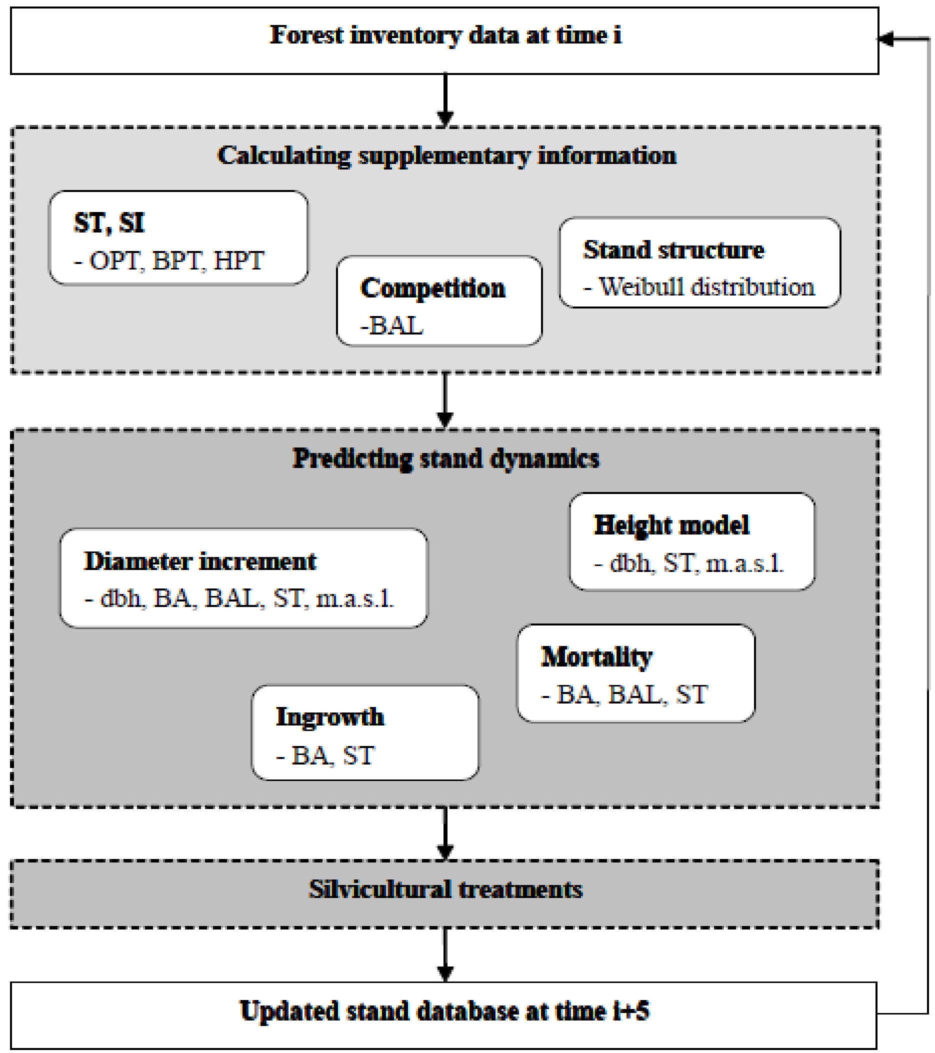
  郭嘉等 (2019)

  Sun et al. (2019 a,b)

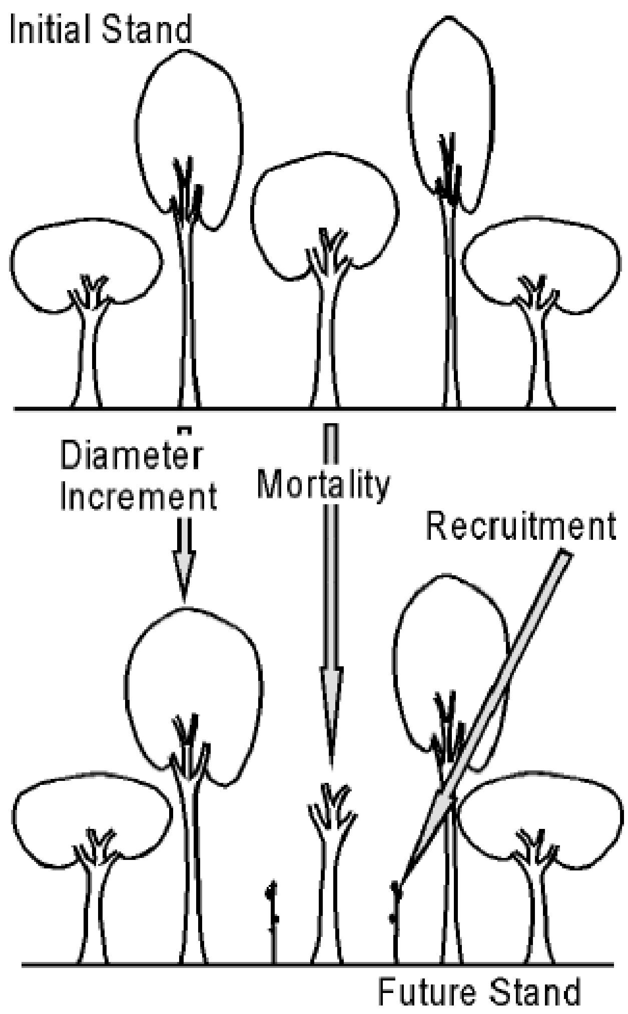
  Tian et al. (2020 a,b)

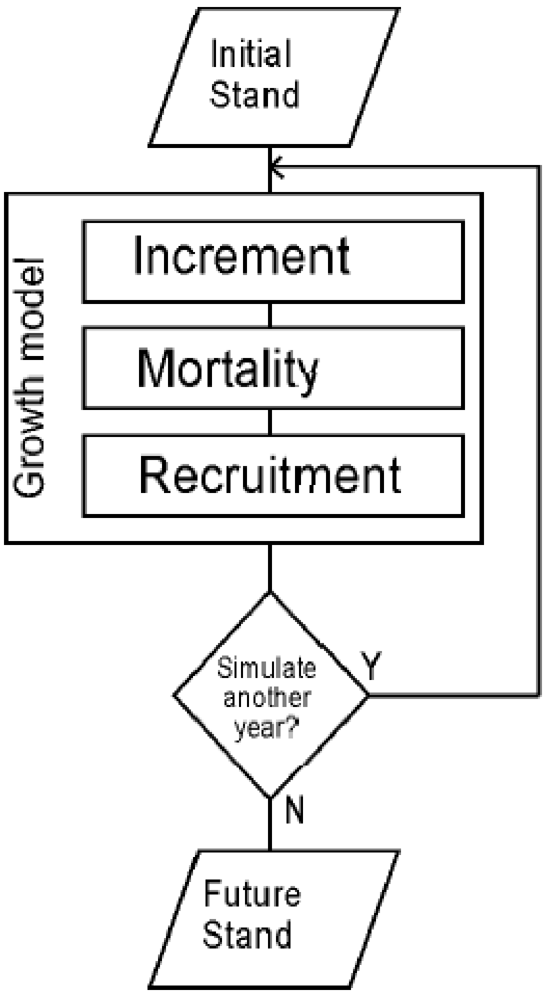
  王彬等 (2020 a,b)

  薛海连等 （2021）



Components of forest growth





第十三讲 经验生长模型

- 第一节 全林生长模型
- 第二节 径阶生长模型
- 第三节 单木生长模型
- 第四节 林分密度控制图

- Q13. 经验模型按尺度分，需要哪类森林调查/测树/建模数据？

Whole stand models

- Whole stand models are those growth and yield models in which the basic units of modelling are stand parameters such as basal area, stocking, stand volume and parameters characterizing the diameter distribution.

- They require relatively little information to simulate the growth of a stand, but consequently yield rather general information about the future stand.

Example, Growth and yield table

- 15 years Chinese fir stand, H_ave 12.0 m， D_ave 12 cm， V=150 m3/ha，
- Try to predict its H_ave, D_ave, V at age 30.

- H_ave = 17.0 * (12/12.4) = 16.5 m
- D_ave = 23.0 cm * (12/14) = 19.78 cm
- V = 351 * (150/165) = 319.4 m3/ha

Growth tables and percentages

- Yield tables => require data: stand age,
  => uneven-aged ?
- Growth tables => volume, density, height, average diameter, and crown class, other than age
- Growth percentages => expected growth expressed as a percentage rather than in absolute terms.
- Short-term or long-term?
- Other stands?

Growth and yield equations

- Delta_Vn = V2 – V1 + Vc
- ln(Vt) = 1.34 + 0.394lnG0 + 0.346lnt + 0.00275SC(t^-1)
- Delta_v = beta_0 + beta_1(d) + beta_2(d)^2
- Delta_G = beta_0 + beta_1*G(t^-1)+(beta_2+beta_3(t^-1)+beta_4*SI)*G^2
- ln(delta_G) = -3.071+1.094lnG+0.007402G*SF-0.2258G

Lab exercise, whole stand model

- Suppose H, D, G growth is a function of t,
- Select the theoretical equation, Schumacher formula, for regression analysis.
- Constructing H-t, D-t, G-t regression model.

Pinus tabulaeformis, SC II

No.	t	H	D	G	No.	t	H	D	G
1	60	19.2	29.0	26.0	21	58	16.5	22.5	23.8
2	36	11.6	21.4	20.6	22	34	12.8	19.1	24.4
3	37	13.9	14.1	26.2	23	25	11.1	14.0	20.0
4	59	16.4	21.8	23.3	24	46	16.1	19.6	26.1
5	62	15.0	21.1	27.4	25	45	15.3	18.9	21.6
6	20	11.4	14.1	18.2	26	56	16.9	23.9	28.7
7	63	17.3	27.8	27.9	27	57	16.1	21.6	27.5
8	48	14.1	22.9	21.1	28	20	9.3	11.3	12.9
9	46	15.6	22.0	25.5	29	46	14.9	24.1	24.0
10	67	18.5	23.8	22.5	30	53	13.8	20.6	27.2
11	72	19.1	32.5	30.8	31	25	12.2	19.2	15.0
12	42	15.2	21.6	20.5	32	33	12.6	18.0	17.4
13	26	9.9	12.2	16.6	33	43	15.1	17.5	21.6
14	38	12.4	15.2	23.4	34	35	12.7	21.6	27.3
15	24	8.0	8.2	16.7	35	43	15.3	23.9	23.0
16	54	16.8	23.8	22.1	36	66	17.2	23.2	23.1
17	45	13.4	19.7	21.9	37	31	12.2	14.4	19.2
18	58	16.5	26.4	27.9	38	54	13.7	19.9	26.8
19	41	13.8	18.3	22.9	39	64	16.7	23.3	26.9
20	40	13.0	16.6	27.4	40	31	12.7	16.3	23.3

The whole stand model

- H = 22.841*exp(-19.284/t)
- D = 36.149*exp(-24.507/t)
- G = 33.767*exp(-15.443/t)

- N = 40000*(G/(pi*D^2))
- V_pinus_t = 0.33123*(D^2)*H+0.00805*D*H-0.00274*D^2+0.00002
- V_pinus_t = (H+3)G*f_pinus_t, f_pinus_t = 0.41

The yield table

年龄 (a)	树高 (m)	平均胸径 (cm)	林分密度 (株/ha)	林分断面积 (m^2/ha)	单木材积 (m^3)	林分蓄积 (m^3)
15	6. 3	7. 1	3086	12. 1	0. 0140	43. 2
20	8. 7	10. 6	1764	15. 6	0. 0399	70. 4
25	10. 6	13. 6	1261	18. 2	0. 0759	95. 6
30	12. 0	16. 0	1008	20. 2	0. 1169	117. 8
35	13. 2	17. 9	859	21. 7	0. 1594	136. 9
40	14. 1	19. 6	762	23. 0	0. 2014	153. 5
45	14. 9	21. 0	694	24. 0	0. 2417	167. 8
50	15. 5	22. 1	644	24. 8	0. 2798	180. 3
55	16. 1	23. 2	606	25. 5	0. 3154	191. 2
60	16. 6	24. 0	576	26. 1	0. 3486	200. 8
65	17. 0	24. 8	552	26. 6	0. 3794	209. 4

Growth and yield equations

- Delta_Vn = V2 – V1 + Vc
- ln(Vt) = 1.34 + 0.394lnG0 + 0.346lnt + 0.00275SC(t^-1)
- Delta_v = beta_0 + beta_1(d) + beta_2(d)^2
- Delta_G = beta_0 + beta_1*G(t^-1)+(beta_2+beta_3(t^-1)+beta_4*SI)*G^2
- ln(delta_G) = -3.071+1.094lnG+0.007402G*SF-0.2258G

Optimization of Weibull parameters

Objective function:

$$\min Z = \frac{\sum(D_i - \hat{D}_i)^2}{\hat{\sigma}_D^2} + \frac{\sum(B_i - \hat{B}_i)^2}{\hat{\sigma}_B^2} + \frac{\sum(N_i - \hat{N}_i)^2}{\hat{\sigma}_N^2} \quad (3)$$

where D is diameter, B is basal area, N is density, $\hat{\sigma}$ is estimated value of the standard deviation.

- stand attributes then can be predicted by m tree species and n diameter classes with stand-level data

s.t. E_Dg <= 0.25

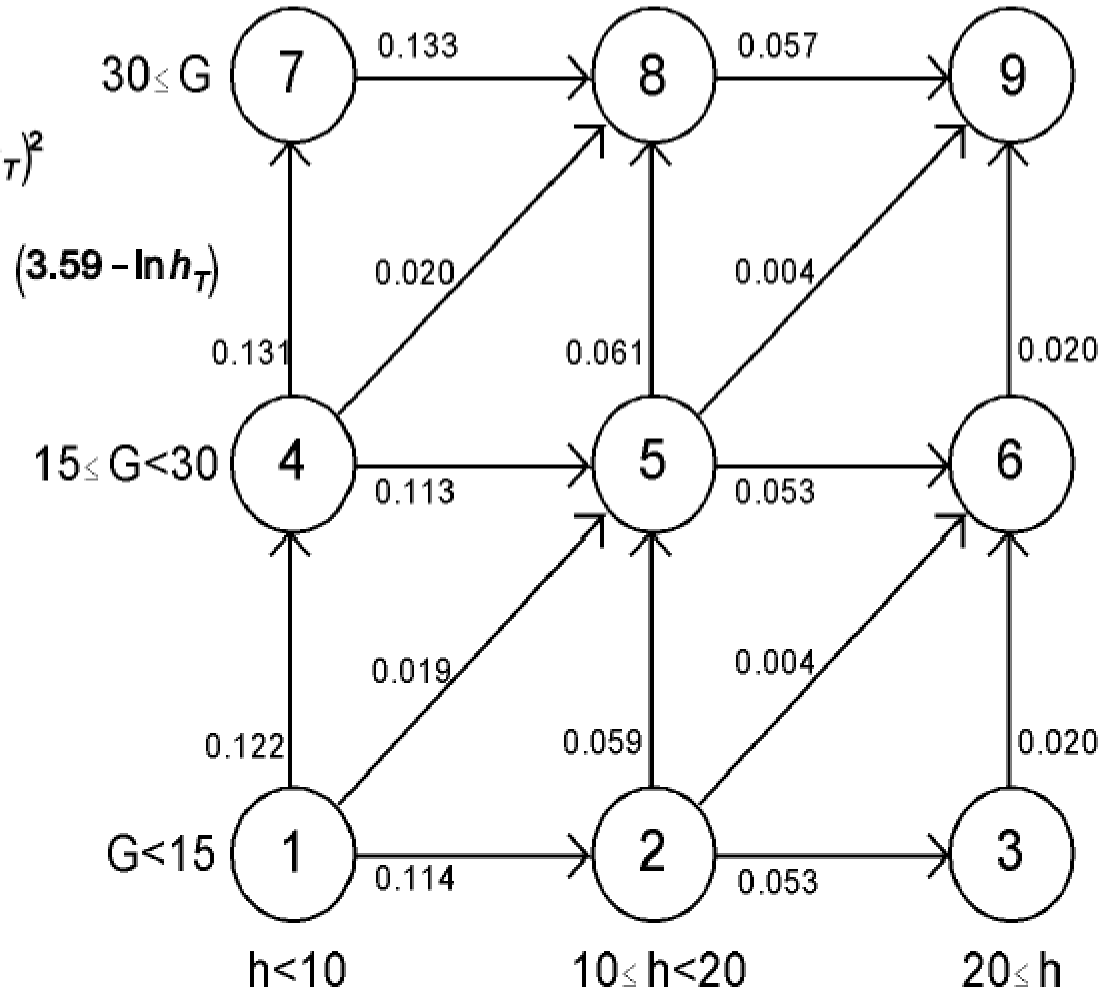
E_BA_i <= 0.1, for all i = 1, ..., m

d_ij >= 0, for all i =1, ..., m; j = 1, ..., n

Whole-stand transition matrices

$$dh_T/dt = 0.0752\, h_T (3.59 - \ln h_T)^2$$

$$dG/dt = 0.0752\, G\, (4.08 - \ln G)\, (3.59 - \ln h_T)$$



Stand table projection

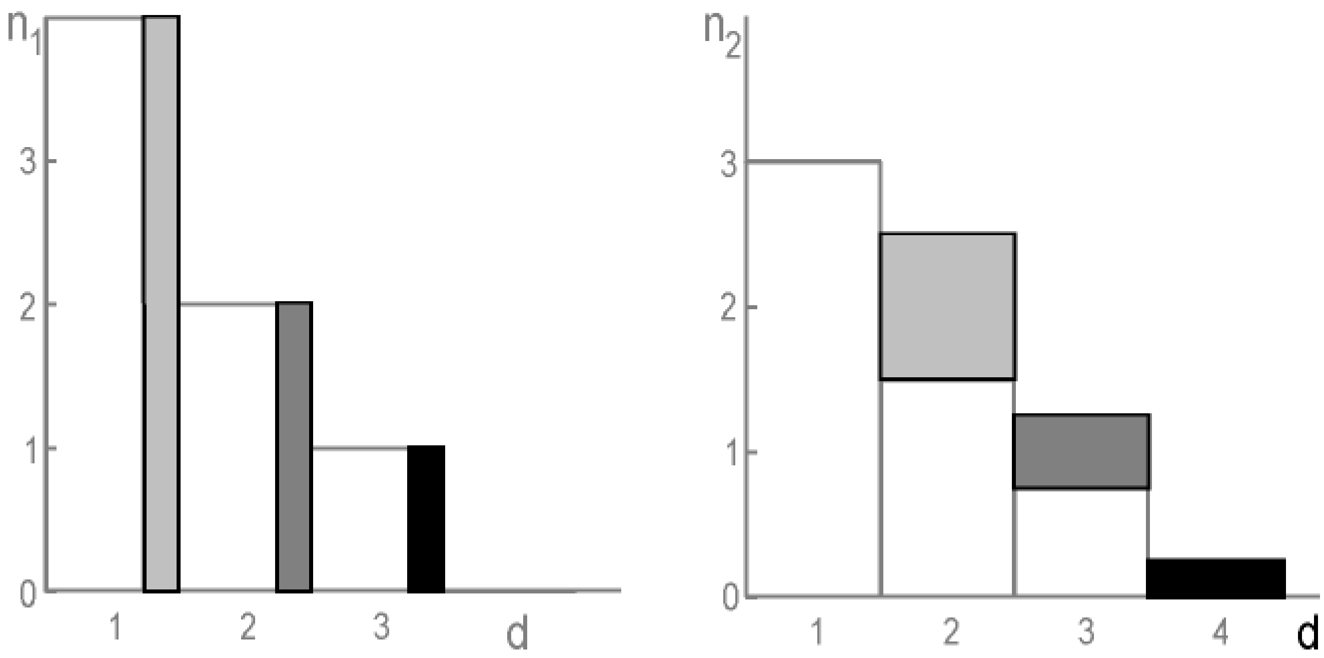


Fig. 3.1. Stand table projection with movement ratio 0.25, so that 25% of each class moves up to the next class.

Transition Matrices

- Consider a hypothetical system S, with n distinct states $S_1, S_2, \ldots, S_n$. If the system starts in state S_i, then in a single time interval, it has probability P_{ij} of moving to state S_j.

- Provided that these P_{ij} depend only on the current state S_i and not on any historic events,

- These probabilities can be expressed in a square matrix, termed the transition probability matrix or stationary Markov chain.

Size class model: diameter distribution

size class	DBH, cm	N, trees/ha	d_ave, cm	ba_ave, m2	BA, m2/ha
1	[10,20)	840	15	0.02	14.8
2	[20,35)	234	27	0.06	13.4
3	[35,)	14	40	0.13	1.8
tot		1088			30

Transition matrix

- $y_{1,t+1} = a_1*y_{1t} + R_t$
- $y_{2,t+1} = b_1*y_{1t} + a_2*y_{2t}$
- $y_{3,t+1} = b_2*y_{2t} + a_3*y_{3t}$

- y_{it}, number of trees per ha in size class i at time t
- a_i, ratio of trees remains in class i during time t to t+1
- b_i, ratio of trees moves to class i+1 during time t to t+1
- $1-a_i-b_i$, mortality of trees (%) in class i during time t to t+1

Size class transition and ingrowth

- Known:
  - $R_t = 109 - 9.7G_t + 0.3N_t$
  - $N_t = y_{1t} + y_{2t} + y_{3t}$
  - $G_t = 0.02y_{1t} + 0.06y_{2t} + 0.13y_{3t}$
- Solutions:
  - R_t, recruits during time t to t+1
  - $R_t = 109 - 9.7(0.02y_{1t} + 0.06y_{2t} + 0.13y_{3t}) + 0.3(y_{1t} + y_{2t} + y_{3t})$
  - $R_t = 109 + 0.106y_{1t} - 0.282y_{2t} - 0.961y_{3t}$
  - $y_{1,t+1} = 109 + 0.906y_{1t} - 0.282y_{2t} - 0.961y_{3t}$
  - $y_{2,t+1} = 0.04y_{1t} + 0.9y_{2t}$
  - $y_{3,t+1} = 0.02y_{2t} + 0.9y_{3t}$

Size class model: transition probability

size class	a_i	b_i	1-a_i-b_i		
1	0.8	0.04	0.16		0.96
2	0.9	0.02	0.08		0.98
3	0.9	0	0.1		1

	size class				
Year	i_1	i_2	i_3	BA	V
0	840	234	14	32.66	299
5	790.598	244.2	17.28	32.71036	297.4996
10	739.8113	251.4039	20.436	32.53714	294.1002
15	688.7341	255.856	23.42048	32.1707	289.0953
20	638.3347	257.8197	26.19555	31.6413	282.7724
25	589.4521	257.5712	28.73239	30.97852	275.4084
30	542.7967	255.3921	31.01057	30.21084	267.266
35	498.9521	251.5648	33.01736	29.36519	258.5902
40	458.3796	246.3664	34.74692	28.46668	249.606
45	421.4248	240.0649	36.19956	27.53834	240.517
50	388.3248	232.9154	37.3809	26.60094	231.5036
55	359.2171	225.1569	38.30112	25.6729	222.723
60	334.1491	217.0099	38.97414	24.77021	214.3089
65	313.0881	208.6749	39.41693	23.90645	206.372
70	295.9319	200.3309	39.64873	23.09283	199.0006
75	282.5185	192.1351	39.69048	22.33824	192.2617
80	272.6371	184.2223	39.56413	21.64942	186.2027
85	266.0374	176.7056	39.29216	21.03106	180.8524
90	262.4392	169.6765	38.89706	20.48599	176.2231
95	261.541	163.2064	38.40088	20.01532	172.3123
100	263.0287	157.3474	37.82492	19.61866	169.1044

Individual-tree models

- delta(DBH)=f(DBH,BA,SI,...)
- delta(HT)=f(HT,BA,SI,...)
- P_s=f(DBH,HT,BA,SI,...)
- R=f(BA,SI,...)

- Tree Records

- Spp, DBH, HT, n

↓

- Spp,DBH+delta(DBH),HT+delta(HT), p_s*n

Tree list models

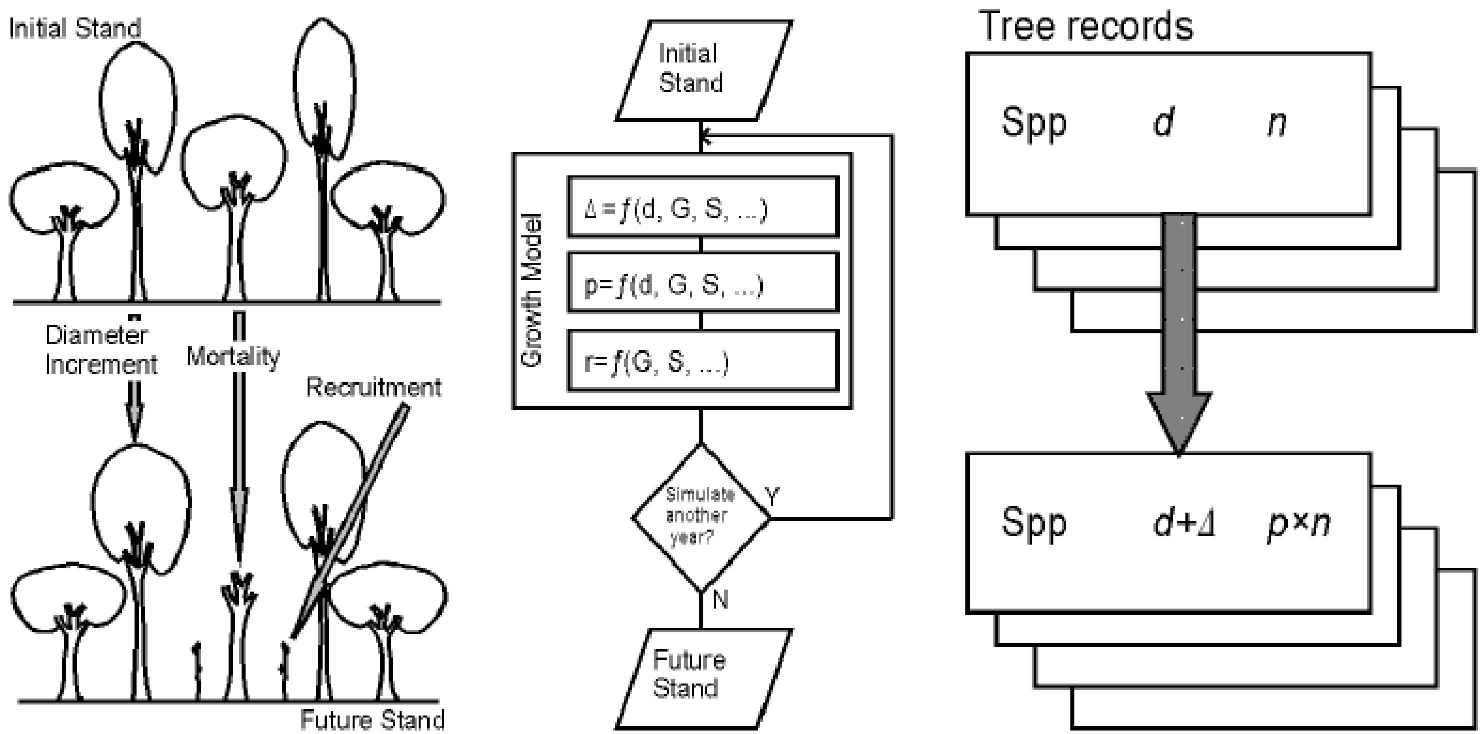


Fig. 4.3. Tree records representing a forest stand. Growth is modelled by incrementing the diameters in each record ($d+\Delta$) and mortality is accommodated by reducing expansion factors ($p \times n$).

Basal area increment model

- ln(BAI) = a + b*SIZE + c*COMP + s*SITE

- b*SIZE = b_1*ln(DBH) + b_2*DBH^2 + b_3*ln(CR)
- c*COMP = c_1*BAL + c_2*CCF
- s*SITE = d*SITE_1 + e*SITE_2 + f*SITE_3

- d*SITE_1 = d_1(ELEV-d_2)^2 + d_3*SL^2 + d_4*SL*sin(AZ) + d_5*SL*cos(AZ)
- e*SITE_2 = e_1*HF + e_2*HH
- f*SITE_3 = f_1*DP + f_2*M + f_3*P + sigma(f_4i*S_i) + sigma(f_5i*V_i) + sigma(f_6i*GD_i)

Modeling forest regeneration

- Uncertainty of forest regeneration
- Juvenile tree height growth model
- Forest recruitment simulation

Neural networks

Advantages:

- Neural networks are a viable alternative to the conventional LOGIT approach for estimating tree mortality.
- Artificial neural networks to be more effective at predicting regeneration establishment than regression equations.
- Artificial neural networks were effective predictors when regeneration data were not available.

(Hasenauer et al. 2001, Hasenauer and Merkl 2001, Hasenauer and Kindermann 2002)

Bayesian calibration

- Many parameters
- Many output variables
- Relatively few measured data available

Quantifying uncertainty rather than maximizing fit

- p(theta|D) = cp(D|theta)p(theta)
- p(D|theta) = p(E = D – M(theta))
- theta' = theta_t + epsilon
- beta = p(theta'|D) / p(theta_t|D)
  = p(D|theta')p(theta') / p(D|theta_t)p(theta_t)

(Van Oijen et al. 2005)

Markov Chain Monte Carlo

- Bayesian calibration cannot be performed analytically
- The posterior parameter distribution must be approximated in the form of a representative sample of parameter values

↓

- MCMC does not require advance knowledge of the shape of the posterior distribution
- MCMC: Metropolis-Hastings sampling

(Van Oijen et al. 2005)

第十四讲 过程生长模型

- 第一节 林窗理论
- 第二节 过程机理模型
- 第三节 半经验半机理混合模型
- 第四节 平行系统模型

- Q14. 如何提高过程模型的准确性和普适性？

Process-based models

- Light interception

  LI_N=LI_0*exp(1-(k*LAI/N))
- Photosynthesis = f(carboxylation, ribulose) = f(CO2, leaf nutrition, leaf temperature)
- Stomatal conductance

  g_s = g_max*f_1(APAR)*f_2(T)*f_3(VPD)*f_4(C_i)*f_5(theta)
- Respiration
- Carbon allocation
- Soil water and nutrients

基于过程的单木模型 CROBAS

$$G = \sum_i G_i = Y^{-1}(P-R)$$

$$P = P_0(1-e^{-kl})/N$$

$$R_m = r_1(W_f + W_r) + r_2(W_s + W_b + W_t)$$

- *G*为树木总生长量，*i*代表树木不同器官，*P*指光合作用生产量，R_m为维持呼吸作用，*R*指呼吸作用消耗量，*Y*为转化因子，P_0为单位面积最大光合利用率，*N*为每单位林木株数，*K*为消光系数，*L*为叶面积指数，*W*为干重，r_1、r_2为经验参数。

Source: Mäkelä (1997)

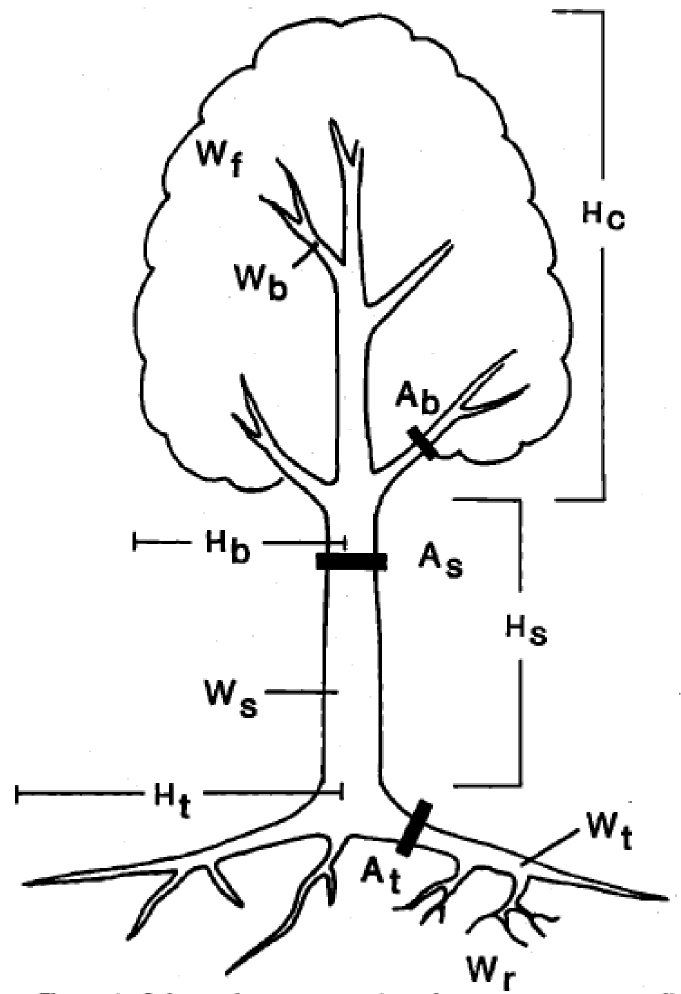
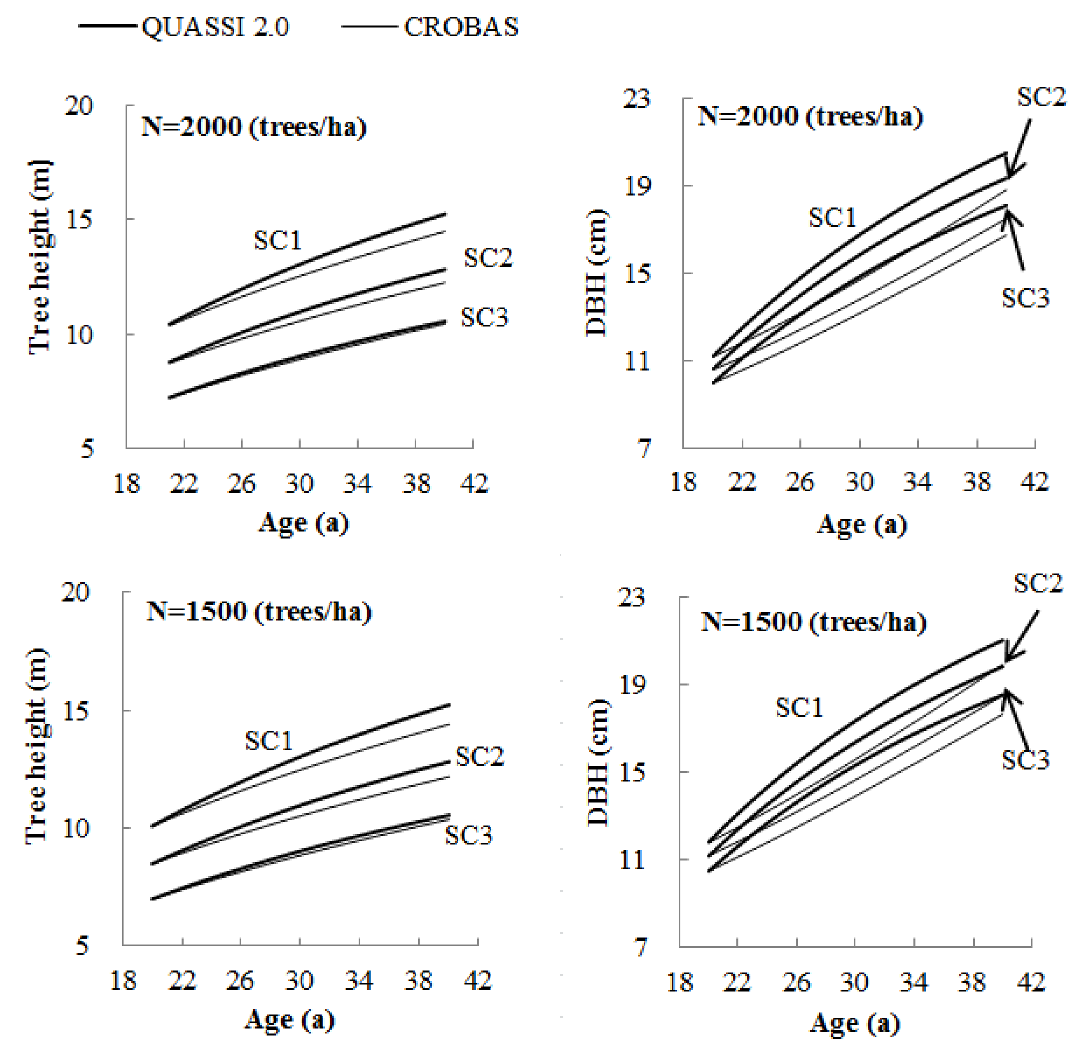
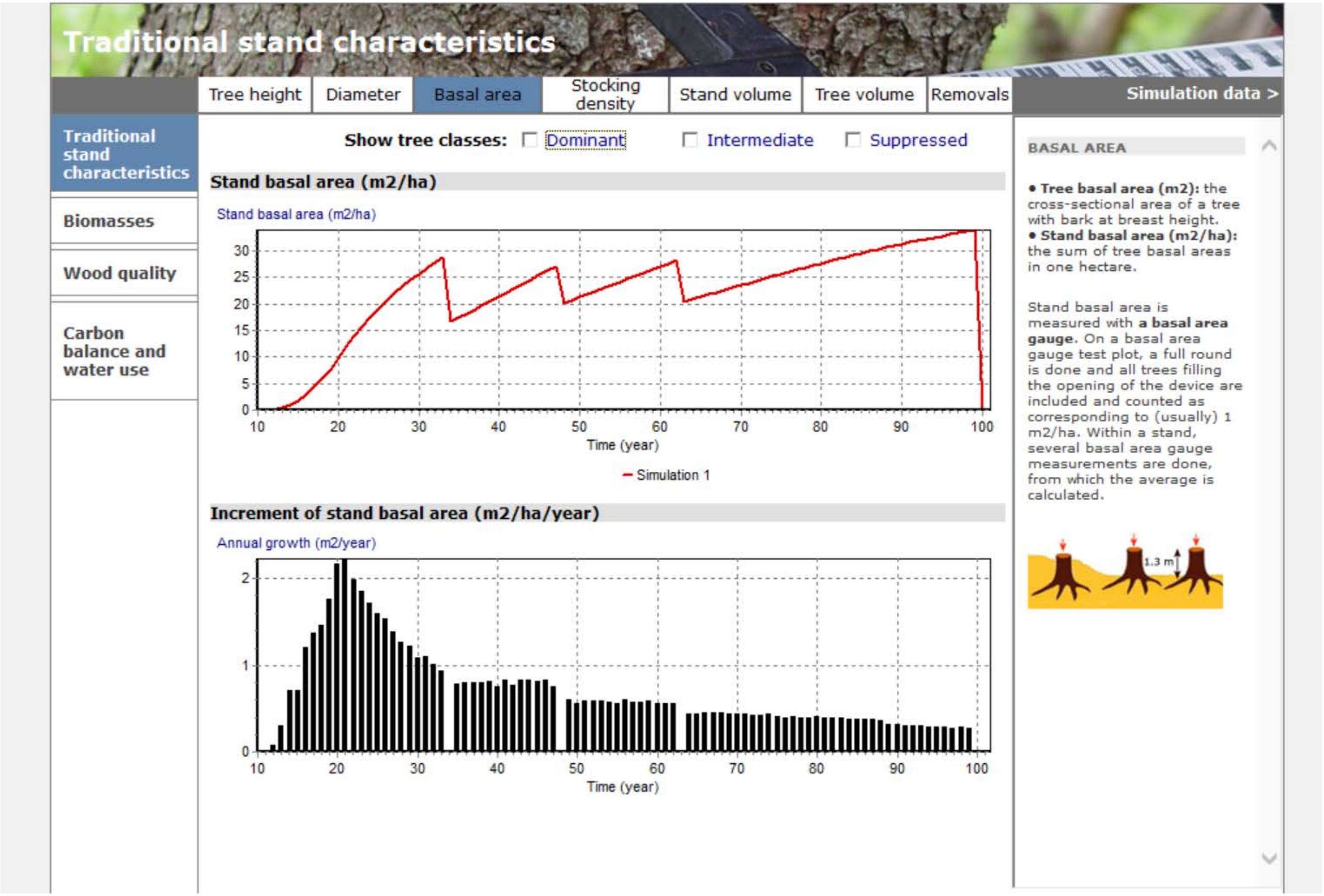


Figure 1. Schematic representation of tree structure as applie
in the model.

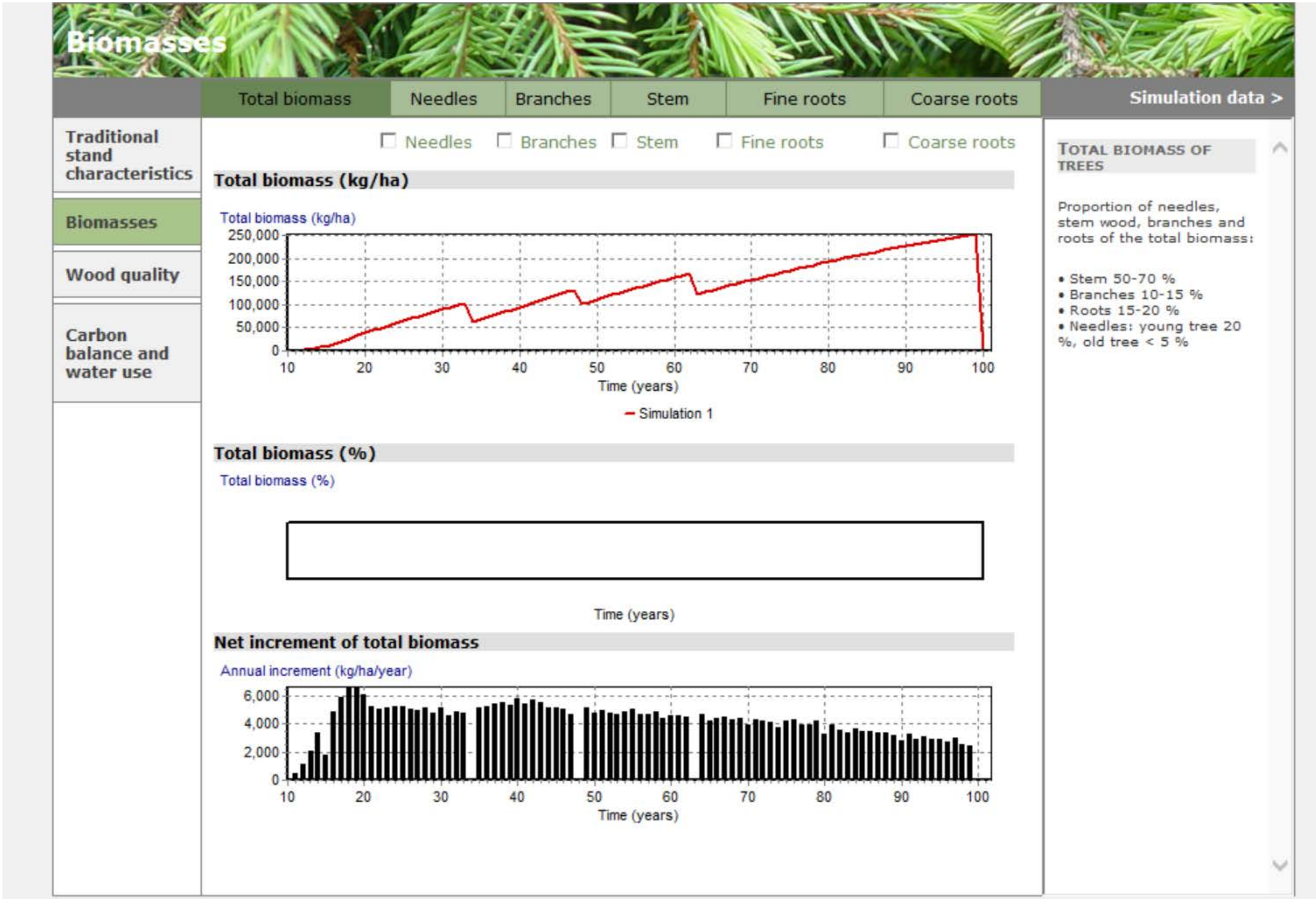
QUASSI vs. CROBAS (Xue et al. 2021)



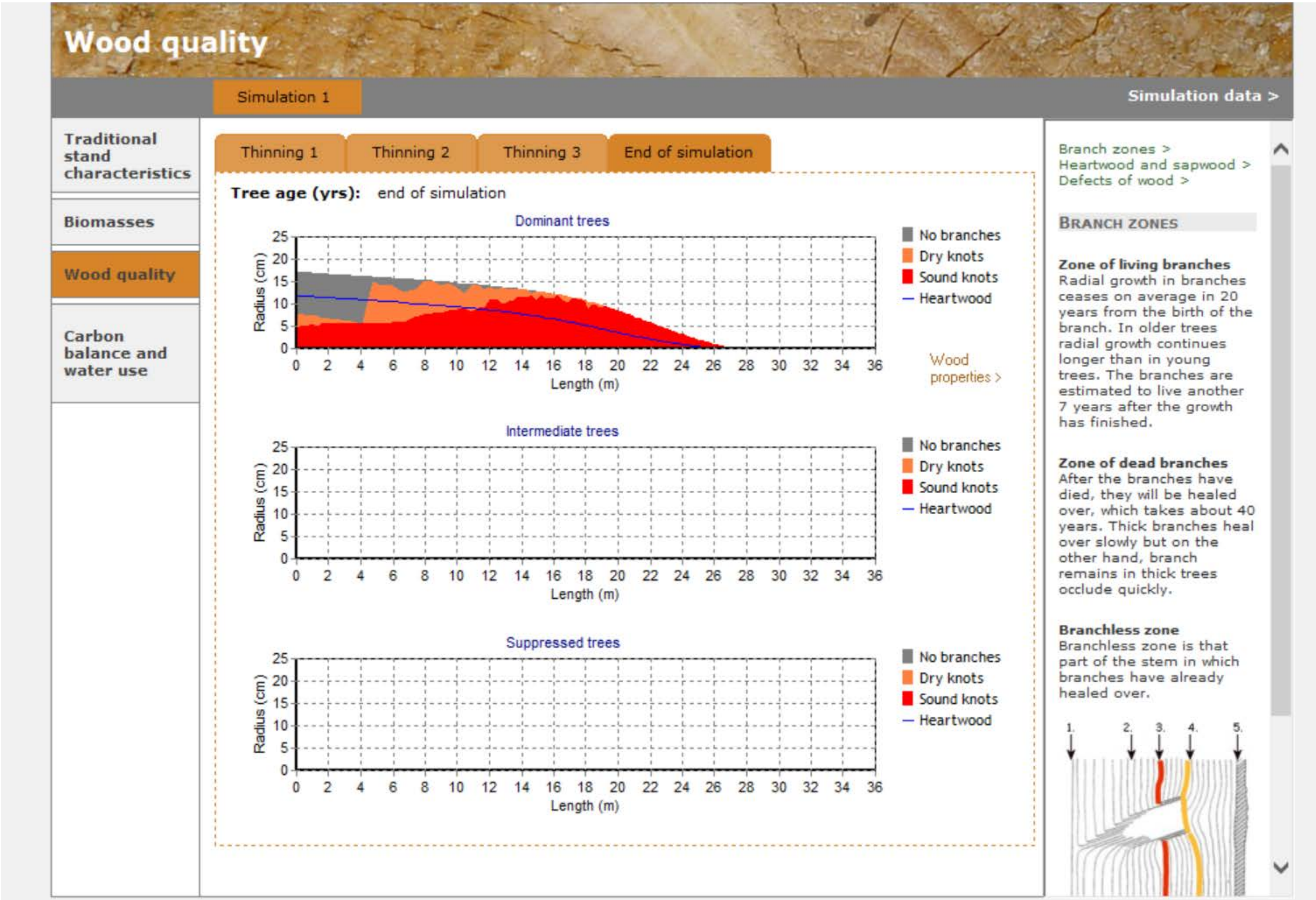
Silvicultural recommendations



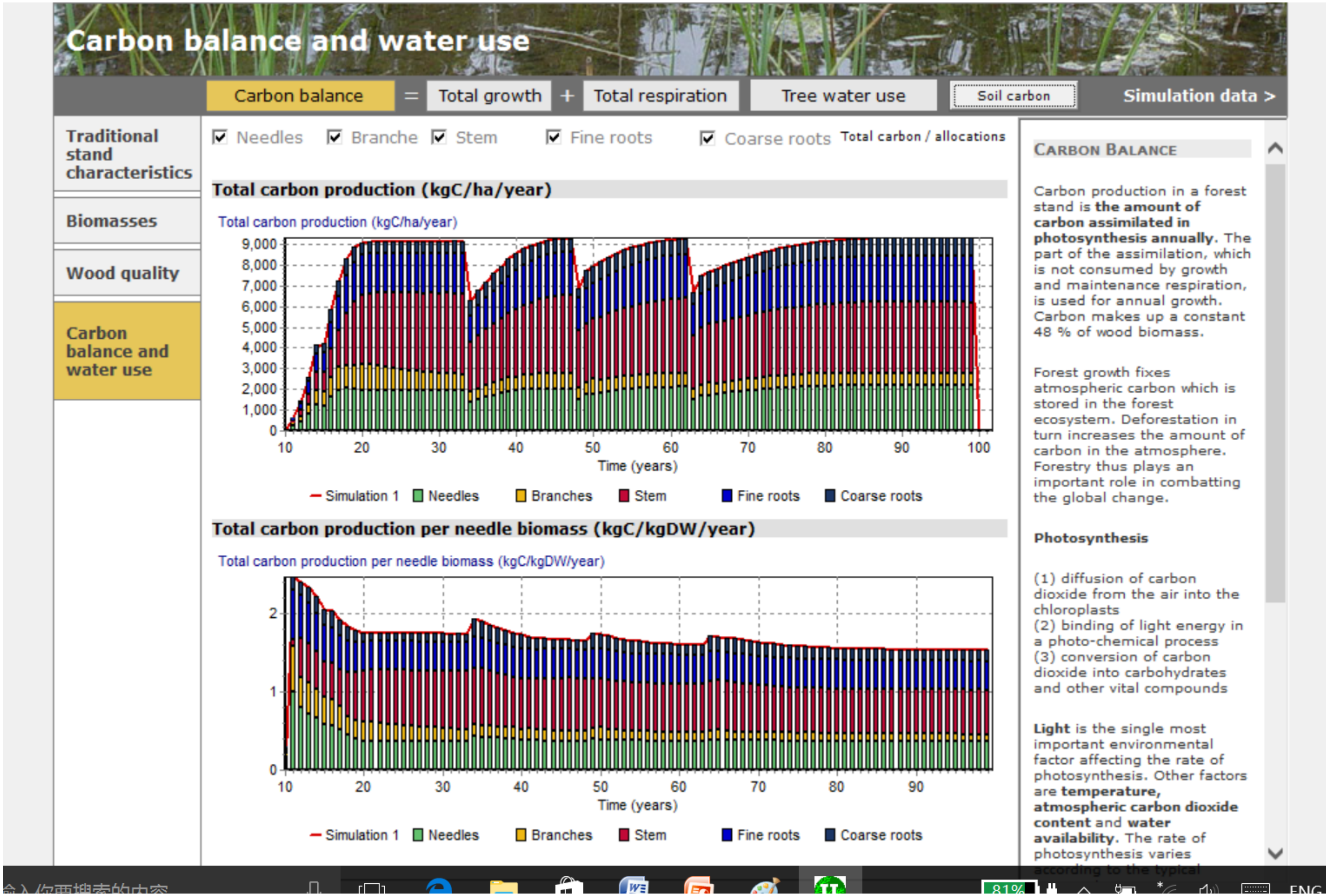
Biomass production



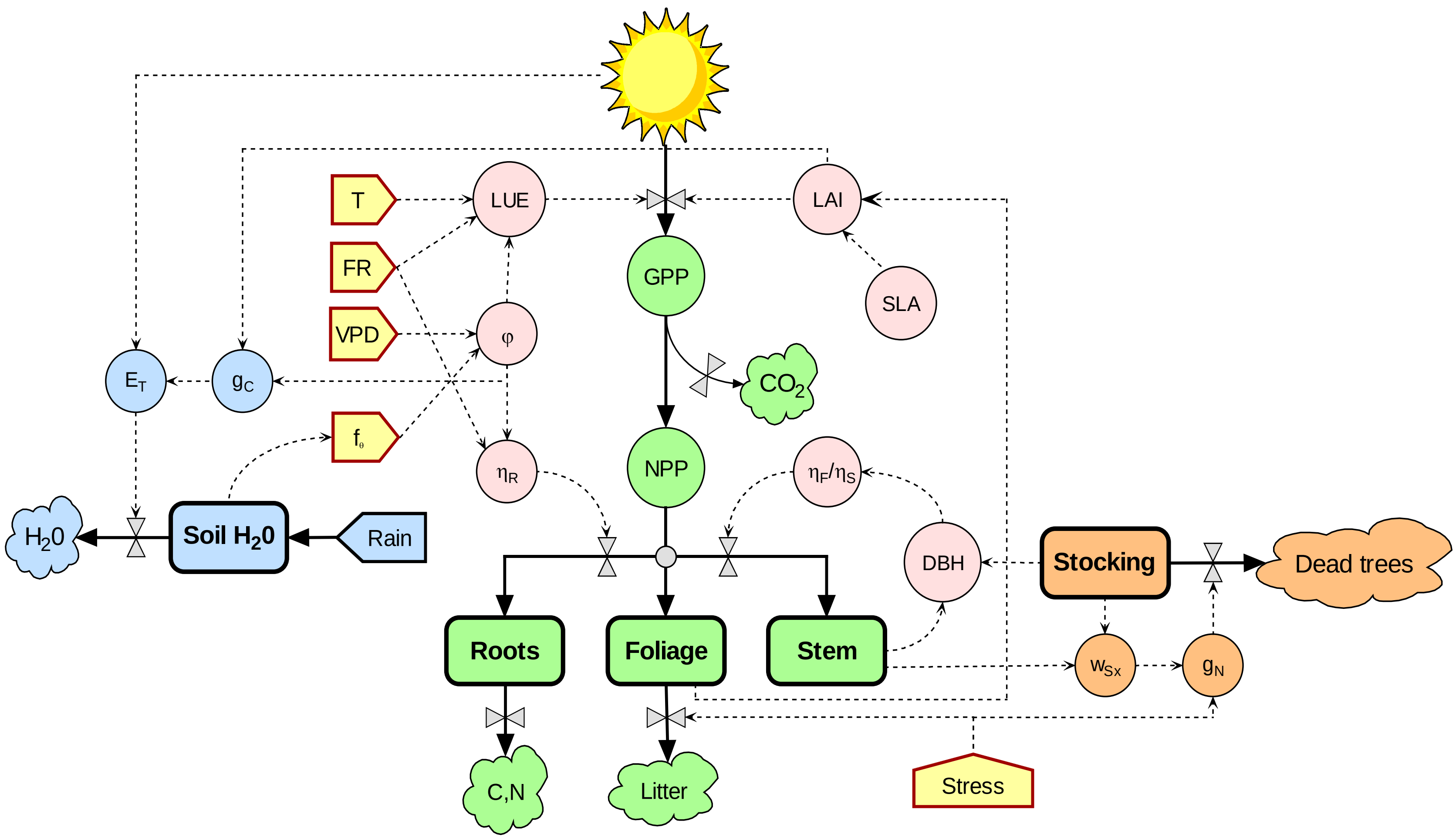
Wood quality

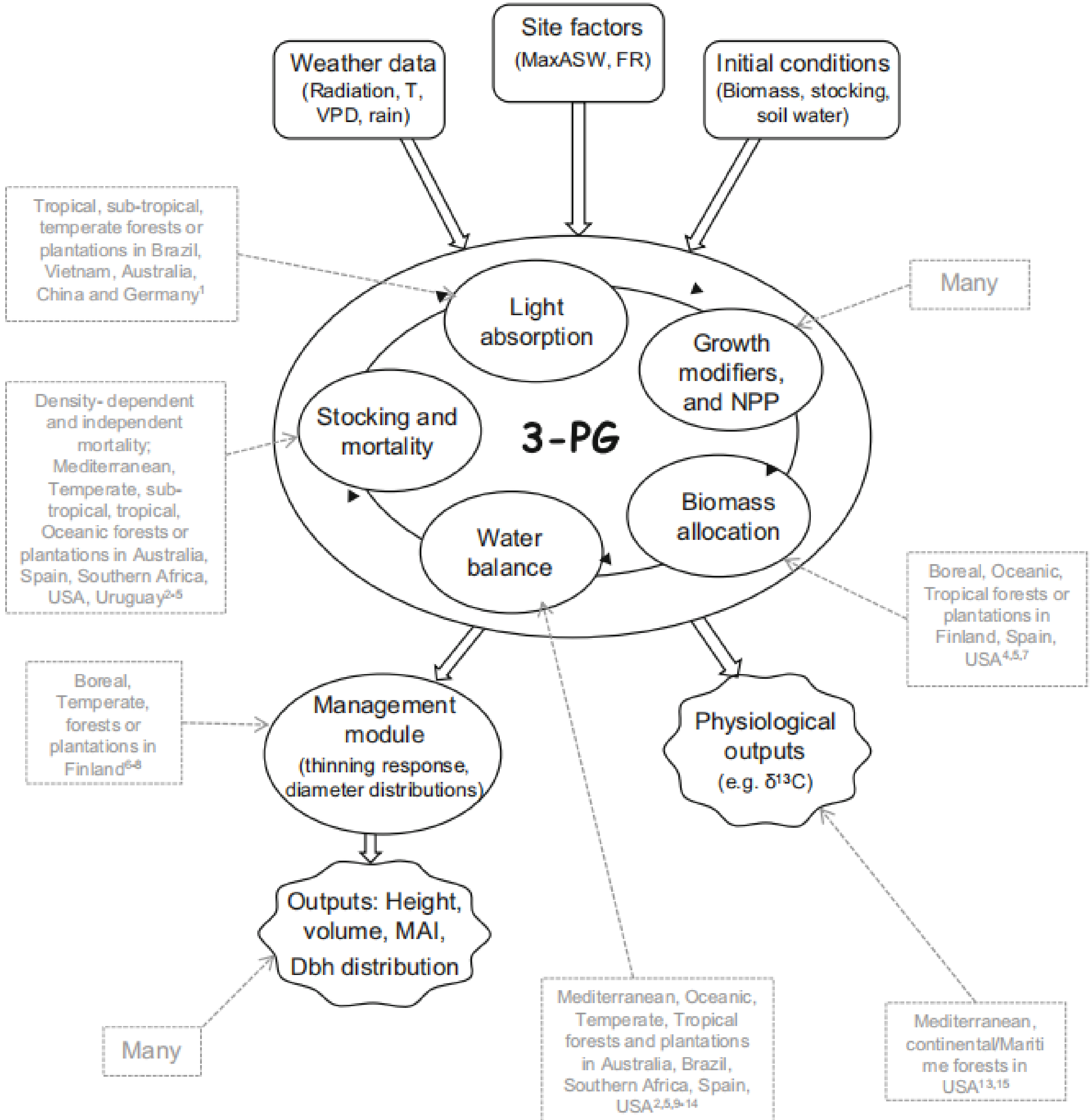


Carbon balance and water use

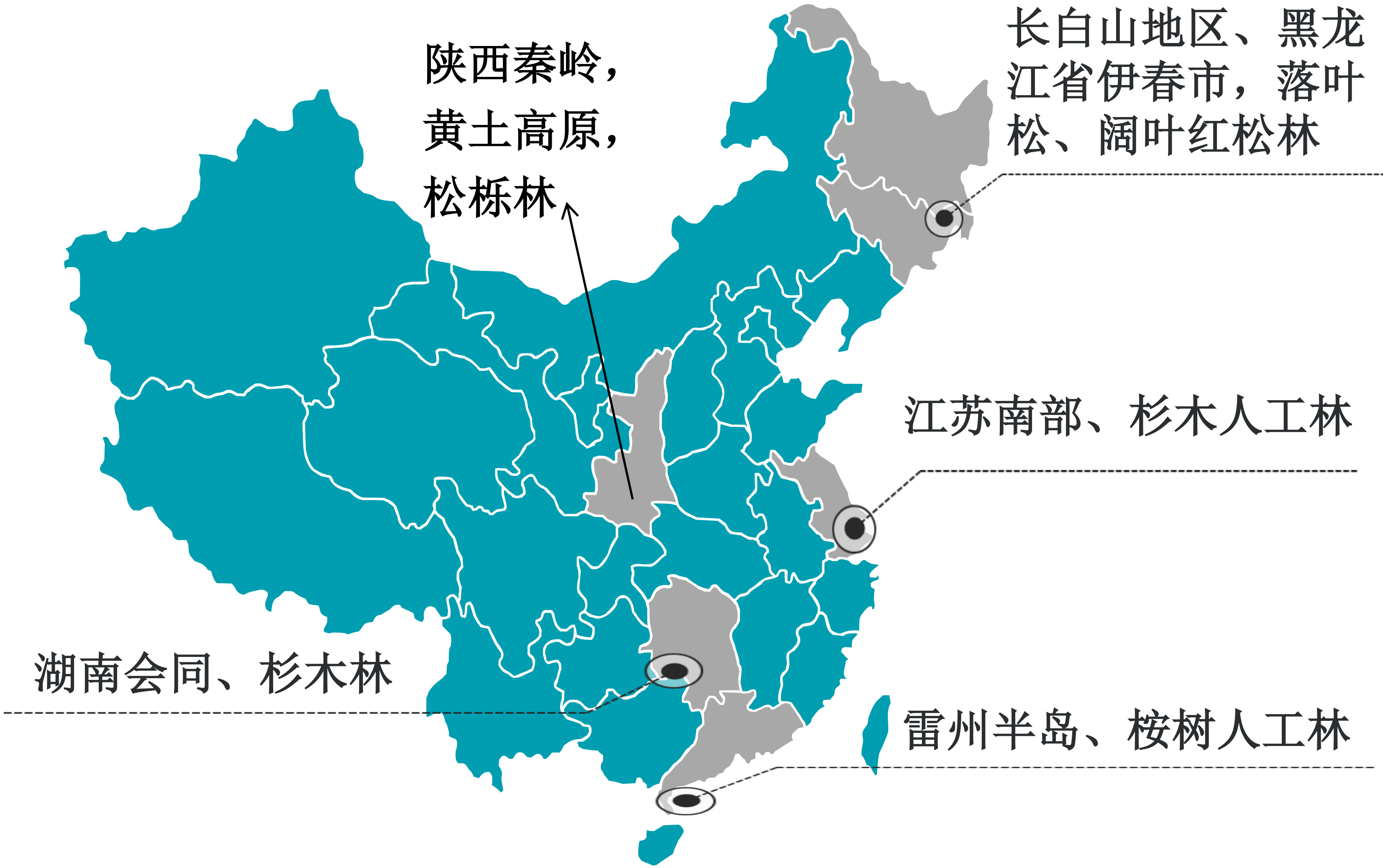


The 3-PG model




Weather data
(Radiation, T, VPD, rain)
Site factors
(MaxASW, FR)
Initial conditions
(Biomass, stocking, soil water)
Tropical, sub-tropical, temperate forests or plantations in Brazil, Vietnam, Australia, China and Germany[1]
Many
Light absorption
Growth modifiers, and NPP
Stocking and mortality
3-PG
Biomass allocation
Water balance
Density-dependent and independent mortality; Mediterranean, Temperate, sub-tropical, tropical, Oceanic forests or plantations in Australia, Spain, Southern Africa, USA, Uruguay[2-5]
Boreal, Oceanic, Tropical forests or plantations in Finland, Spain, USA[4,5,7]
Boreal, Temperate, forests or plantations in Finland[6-8]
Management module
(thinning response, diameter distributions)
Physiological outputs
(e.g. δ13C)
Outputs: Height, volume, MAI, Dbh distribution
Many
Mediterranean, Oceanic, Temperate, Tropical forests and plantations in Australia, Brazil, Southern Africa, Spain, USA[2,5,9-14]
Mediterranean, continental/Maritime forests in USA[13,15]

QUASSI 3-PG


陕西秦岭，
黄土高原，
松栎林
长白山地区、黑龙
江省伊春市，落叶
松、阔叶红松林
江苏南部、杉木人工林
湖南会同、杉木林
雷州半岛、桉树人工林

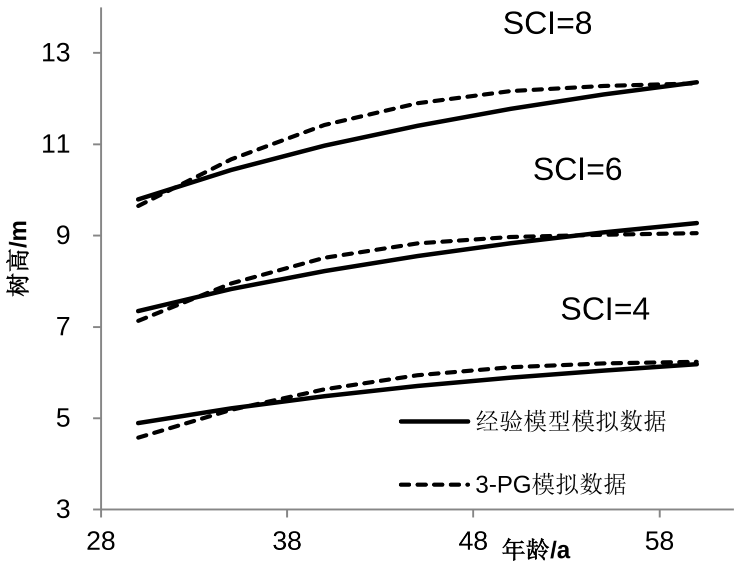
过程模型建模

- 碳，LUE and carbon allocation
- 氮，NUE, site quality, crown-root ratio, foliage mass : fine roots
- 水，WUE and water balance

- 混合建模 Hybrid modelling approach
- 模型结构混合：半经验半机理模型
- 建模方法混合：经验约束优化过程

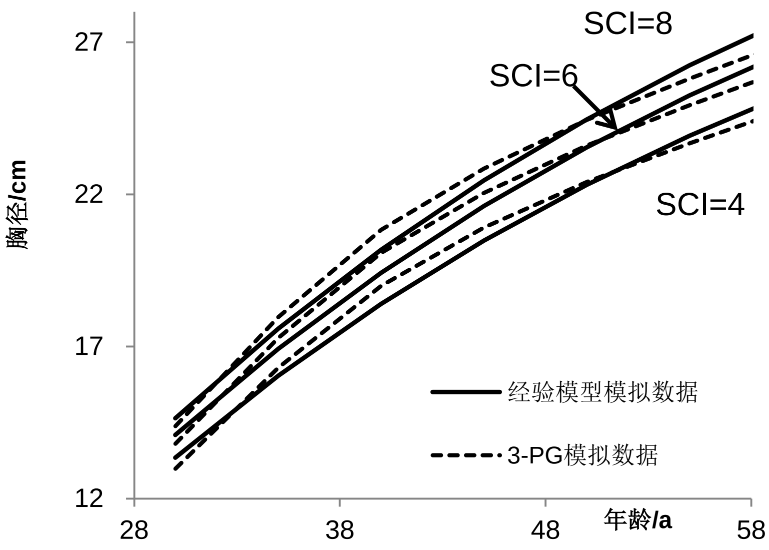
- 敏感性：单因素敏感性分析，相对敏感性分析，全局敏感性分析
- 不确定性：蒙特卡洛 Monte Carlo，马尔科夫链蒙特卡洛MCMC，贝叶斯分析 Bayesian analysis

3-PG 锐齿栎，秦岭



（a）树高模拟结果

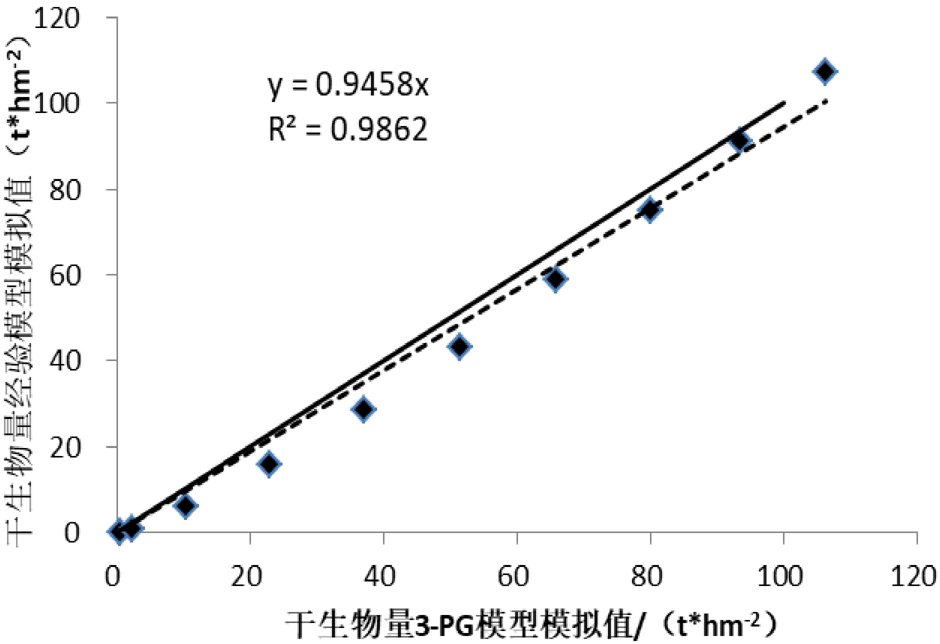
模拟精度 97.77%



（b）胸径模拟结果

模拟精度 98.10%

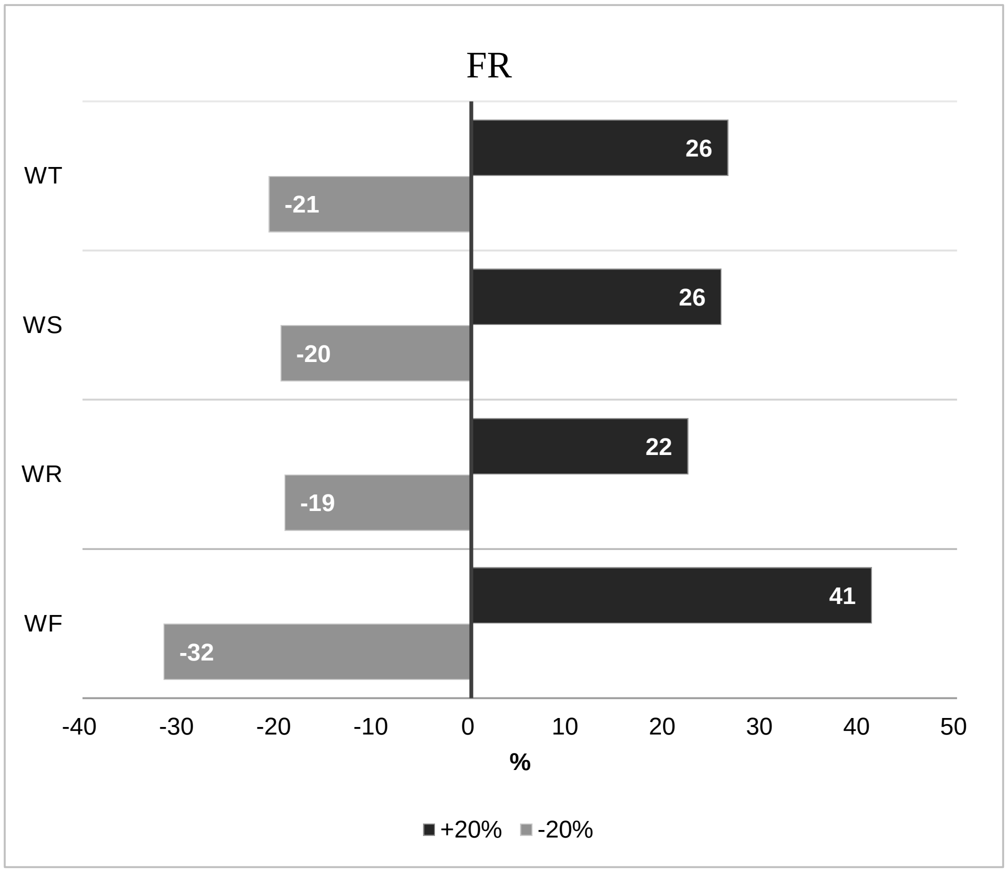
干生物量模拟值对比



Multiple R	0.996258
R Square	0.992531
Adjusted R Square	0.991597
标准误差	3.569435

干生物量积累速度在25到28林龄时逐渐增大，后续趋于平稳，林龄为34年后干生物量积累速度有下降趋势

3-PG 辽东栎，黄土高原



林分叶生物量、根生物量、干生物量均随FR增加而增大，随FR减少而减小。

叶生物量对土壤肥力等级变化的响应程度显著强于根生物量和干生物量（FR增加20%，叶生物量增加41%；FR减少20%，叶生物量减少32%）；

根生物量、干生物量和总生物量对FR变化的响应程度相差不大，增加和减少的百分数均在20%左右。

CROBAS 华山松，秦岭

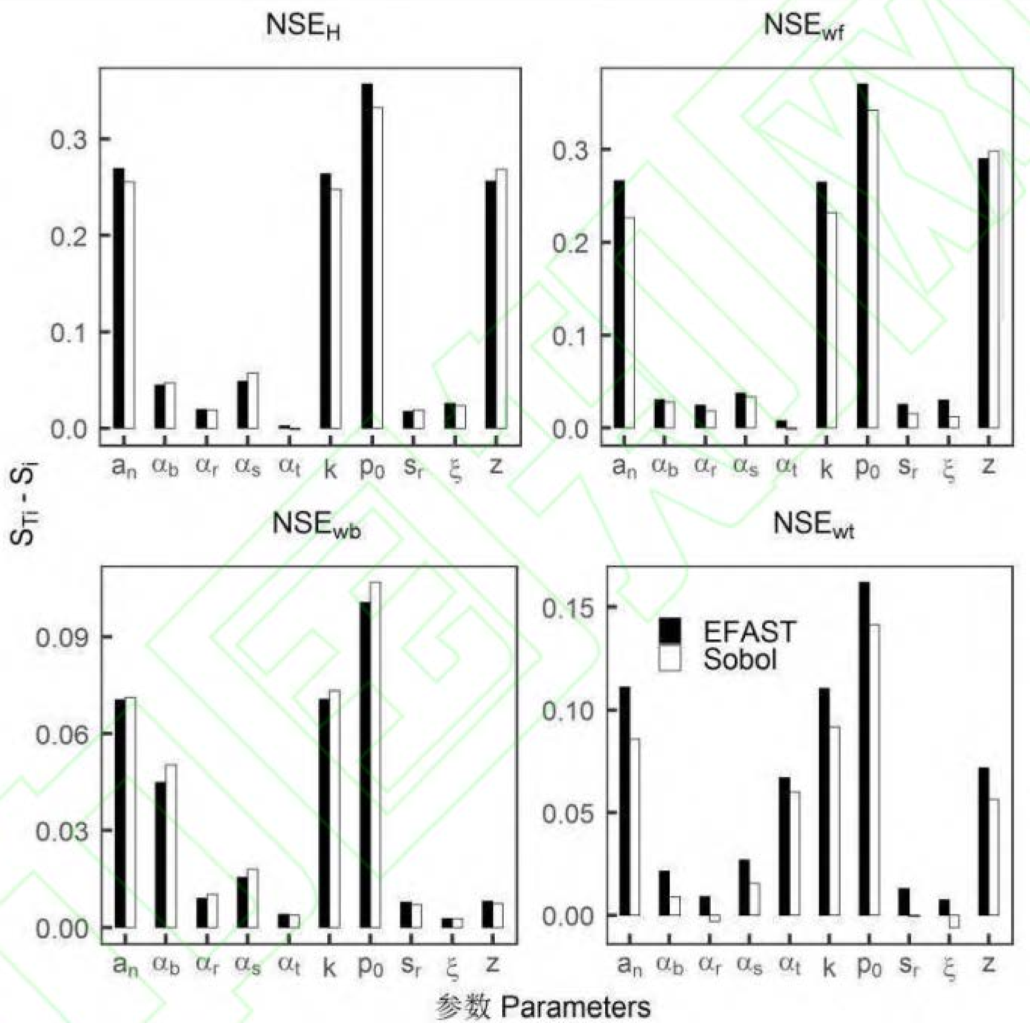


图 3 Sobol 和 EFAST 参数间相互作用的比较

Fig.3 Comparison of parameter interactions by Sobol and EFAST.

参数 p0 与其他参数之间相互作用对各个输出变量影响均最高，an、z 和 k 与其他参数相互作用对树高、叶生物量影响较高，an、k、αb 与其他参数相互作用对枝生物量影响较高，z、an、k、αt 与其他参数的相互作用对根生物量的影响较高。

EFAST 所得结果与 Sobol 略有不同，对于树高，Sobol 与 EFAST 的相互作用较高的参数分别是 z、k，且二者差值很小。

第十五讲 生物量与碳计量

- 第一节 碳平衡理论
- 第二节 森林碳汇计量方法与数据采集
- 第三节 森林乔木层和草灌层的碳计量
- 第四节 森林土壤碳的动态预估

- Q15. 森林生产力与森林生物量的计算，如何考虑年龄因素的影响？如果是异龄林？

Farquhar 光合作用公式

$$A_n = \min\left(\left(\frac{(V_{c\max}\cdot(C_i-\Gamma^*))}{C_i+K_C\cdot(1+(\frac{O_i}{K_O}))}\right),\left(\left(\frac{J}{4}\right)\cdot\left(\frac{(C_i-\Gamma^*)}{C_i+2\cdot\Gamma^*}\right)\right)\right)-R_d$$

- An, net photosynthesis
- Vcmax, carboxylation
- Jmax, regeneration of ribulose
- Ci, ambient CO2 concentration
- Oi, ambient O2 concentration
- GAMMA*, CO2 compensation point in the absence of mitochondrial respiration
- J, rate of electron transport
- Rd, rate of mitochondrial respiration
- KC and KO, the Michaelis-Menten coefficients of Rubisco activity for CO2 and O2

生物量与碳计量

- 森林碳汇计量的经验方法 Empirical approaches
- 自下而上 Bottom-up
- 原理：林木结构的异速生长关系

- 森林碳汇计量的过程方法 Process-based approaches
- 自上而下 Top-down
- 原理：光合作用与碳平衡理论

碳平衡理论

- $W_r = \alpha_r * W_f$
- $W_f = \xi' * A_c^{\zeta}$
- $dW_i/dt = G_i - S_i$

- $G = \sigma_i(G_i) = (P-R)*Y^{(-1)}$
- $R_m = r_1(W_f+W_r)+r_2(W_s+W_b+W_t)$

- G为树木总生长量，i代表树木不同器官，
- P指光合作用生产量，
- Rm为维持呼吸作用，R指呼吸作用消耗量，
- Y为转化因子，P0为单位面积最大光合利用率，N为每单位林木株数，K为消光系数，L为叶面积指数，W为干重，r1、r2为经验参数。

森林碳汇计量方法

- 遥感估算法
- 蓄积-生物量法 $W_{tot} = f(V)$

  $W_i = f_i(D)$

  $W_i = f_i(D,H)$
- 生物扩展因子法 BEF (Biomass Expansion Factor)

  $BEF_i = W_i/V$

  $BEF(t) = a+b*\exp(-0.01*t)$
- 过程机理模型法

$NPP = r_{NPP}*GPP$

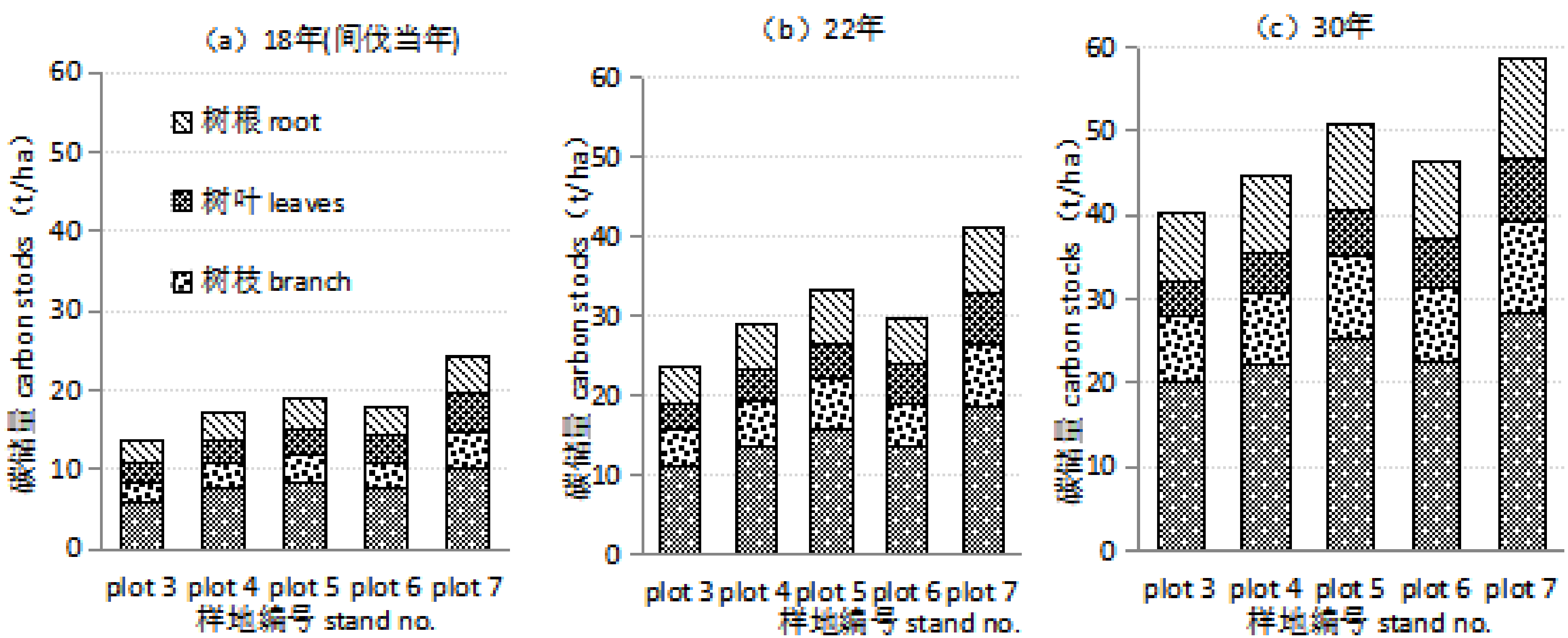
$G_t = NPP/C_c, C_c \approx 0.5$

$GPP = f_{APAR}*GPP_{max}$

$f_{APAR} = (1-\exp(-k*LAI))$

$GPP_{max} = \sum_{i=1}^{365}(LUE_i,PAR_i,f_{iPAR},f_{iTemp},f_{iVPD})$

间伐对油松林碳储量的影响



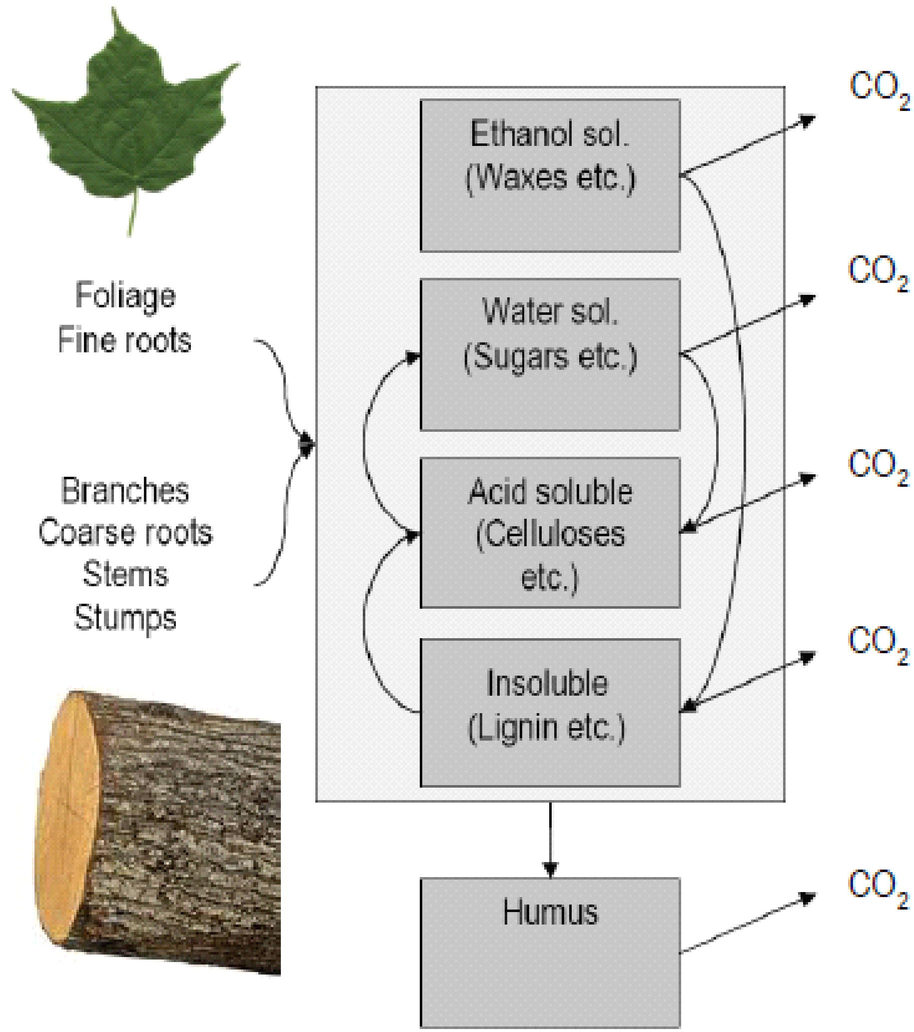
The soil carbon model YASSO (Cao et al. 2010)

Input

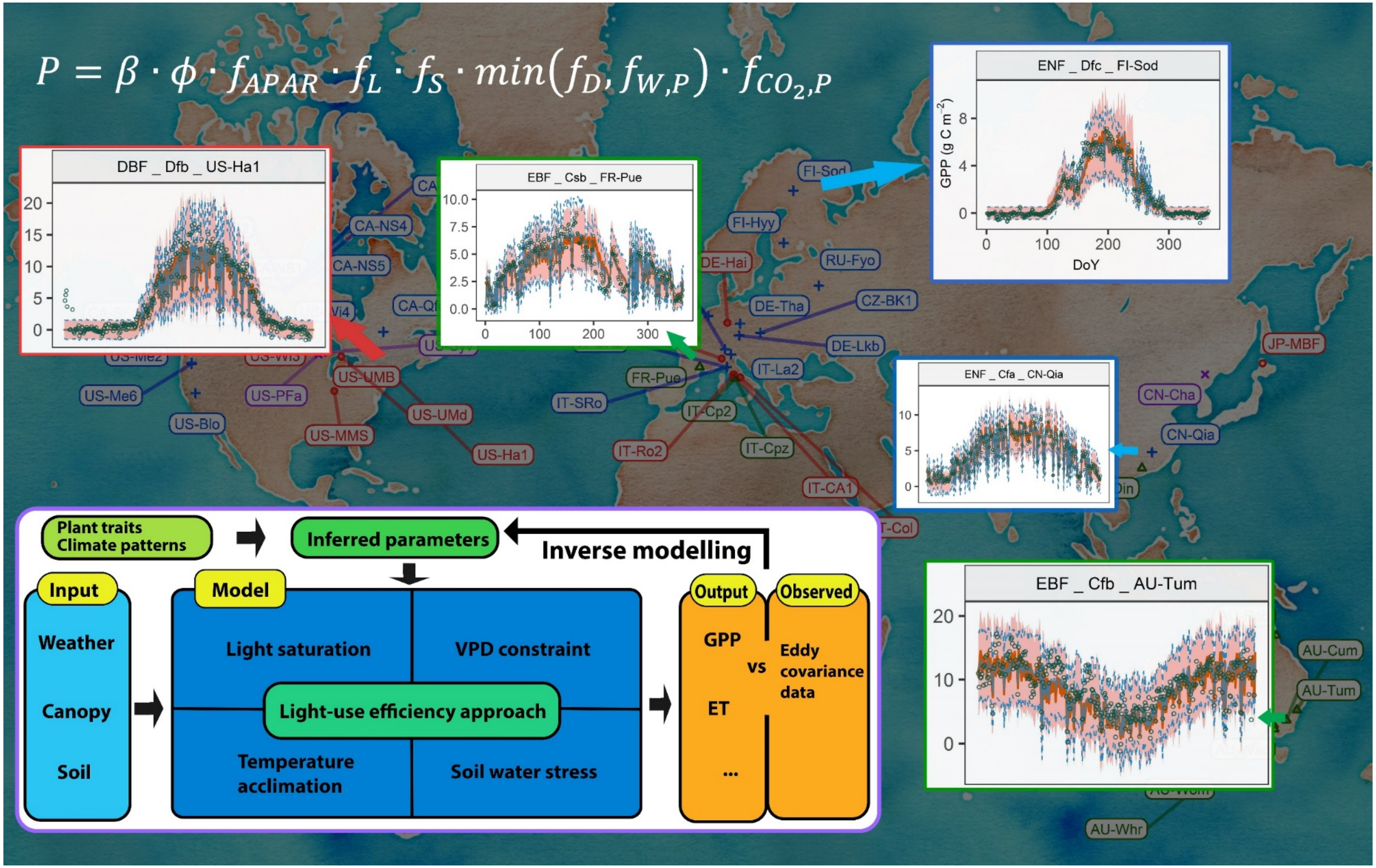
- Carbon input to soil: quantity, chemical quality, diameter of woody litter
- Climate: temperature, precipitation, annually or monthly

Output

- Variables: soil carbon stock, change in soil carbon stock, carbon flux out of soil
- Mean estimate and uncertainty



The PRELES model (Tian et al. 2020)



The PRELES Model

Input

Daily meteorological observations
Photosynthetic photon flux density (PPFD) above the canopy (μmol m^{-2} s^{-1})
Air temperature (° C)
Vapour pressure deficit (VPD, kPa)
Precipitation (mm)

Soil property
soil depth exploited by roots (mm)
soil field water capacity (mm)
soil wilting point (mm)

Canopy Information
Fraction of absorbed photosynthetically active radiation **(f_{APAR})**

Output

GPP (*P*, g C m^{-2})， Daily gross

primary production；

ET (*E*, mm) Evapotranspiration；

$f_{W,P}$ (θ, mm)， Soil water

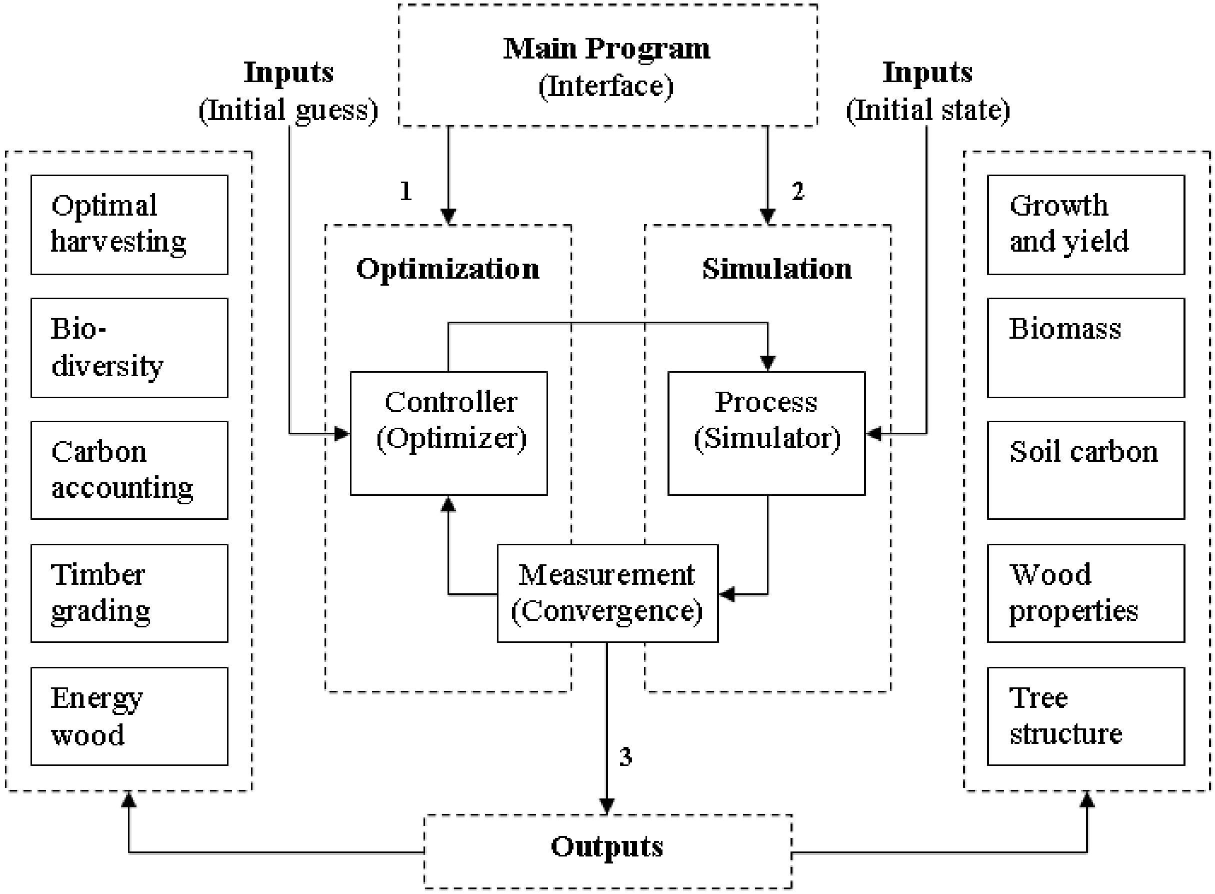
Framework of the LUE approach

$$P = \beta \phi f_{\mathrm{APAR}} f_L f_S \min(f_D, f_{WP})$$

- P - Daily photosynthetic production (g C m^{-2})
- β - The potential light use efficiency (g C mol^{-1} m^{-2})
- ϕ - The photosynthetic photon flux density (mol m^{-2} day^{-1})
- f_{APAR} - The fraction of ϕ absorbed by the canopy

- f_L - Modifier that account for light saturation
- f_S - Modifier that account for temperature acclimation
- f_D - Modifiers for vapour pressure deficit
- $f_{W,P}$- Modifiers for soil water stress
- All modifiers are constrained between 0 and 1

OPTIFOR 1.0 (Cao, 2010)



Simulation models in OPTIFOR 1.0

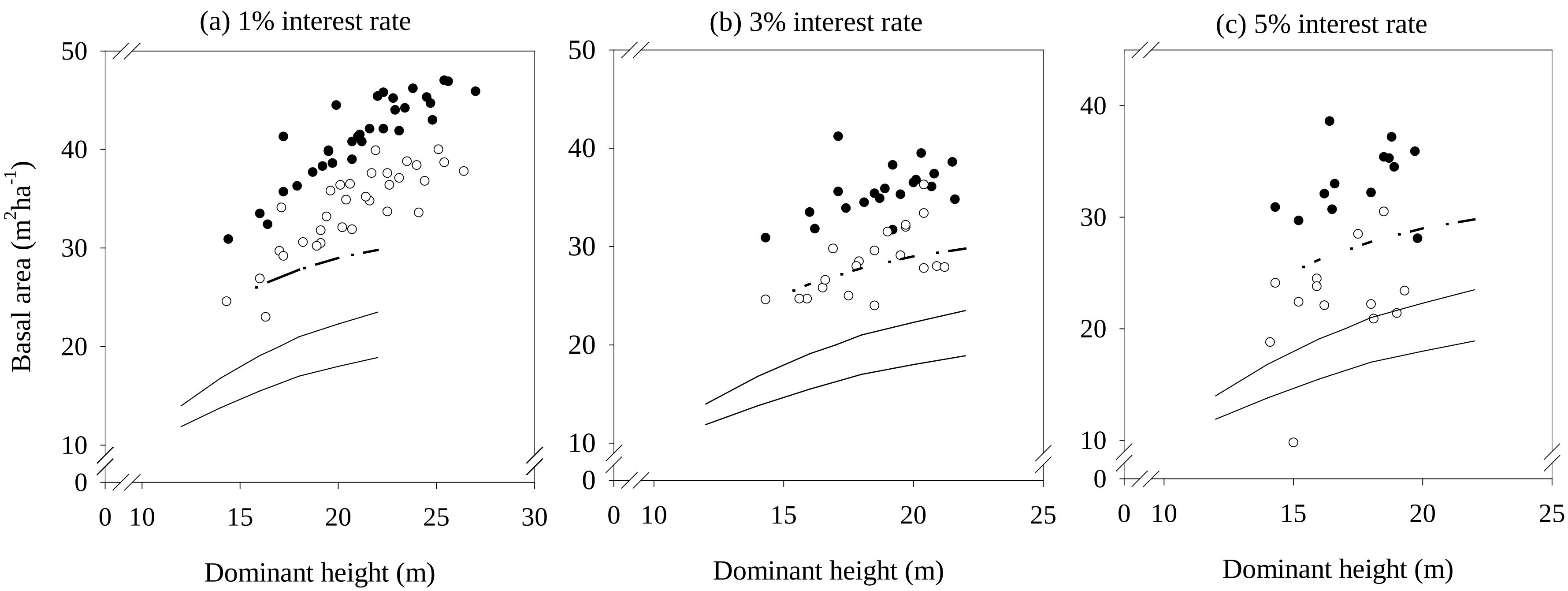
- MOTTI (Hynynen et al. 2002, 2005)
- Crobas/PipeQual (Mäkelä 1997, Mäkelä and Mäkinen 2003)
- Yasso (Liski et al. 2005)
- Wood quality (Mäkinen et al. 2007)

Applications of OPTIFOR 1.0

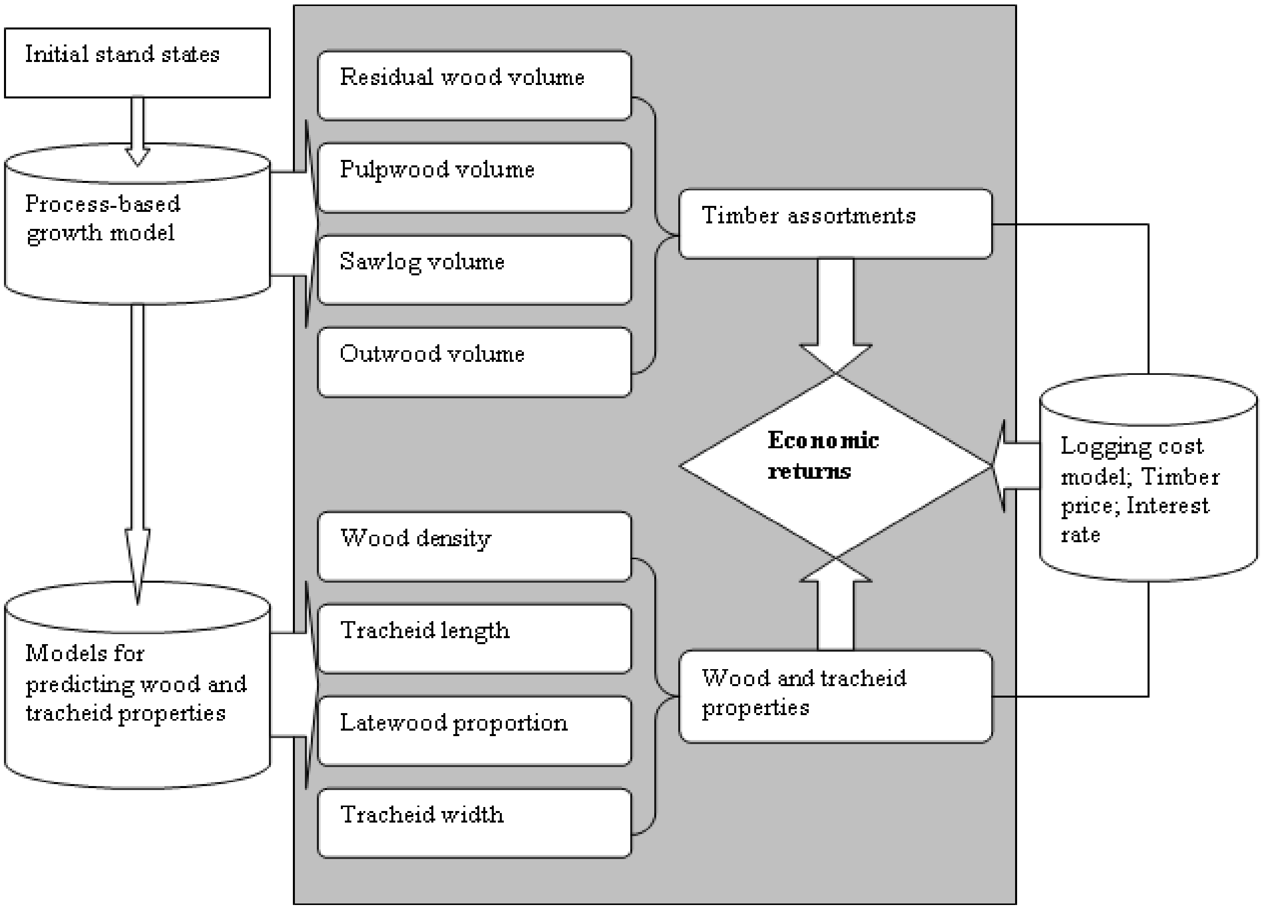
- 优化间伐 Optimal thinning (Cao et al., 2006)
- 木材质量 OPTIFOR Wood (Cao et al., 2008)
- 森林碳汇 OPTIFOR Carbon (Cao et al., 2010)
- 气候变化 OPTIFOR Climate (Nikinmaa et al. 2011)
- 生物能源 OPTIFOR Energy (Cao et al., 2015)

蓄积优化调控 （Cao et al., 2006）

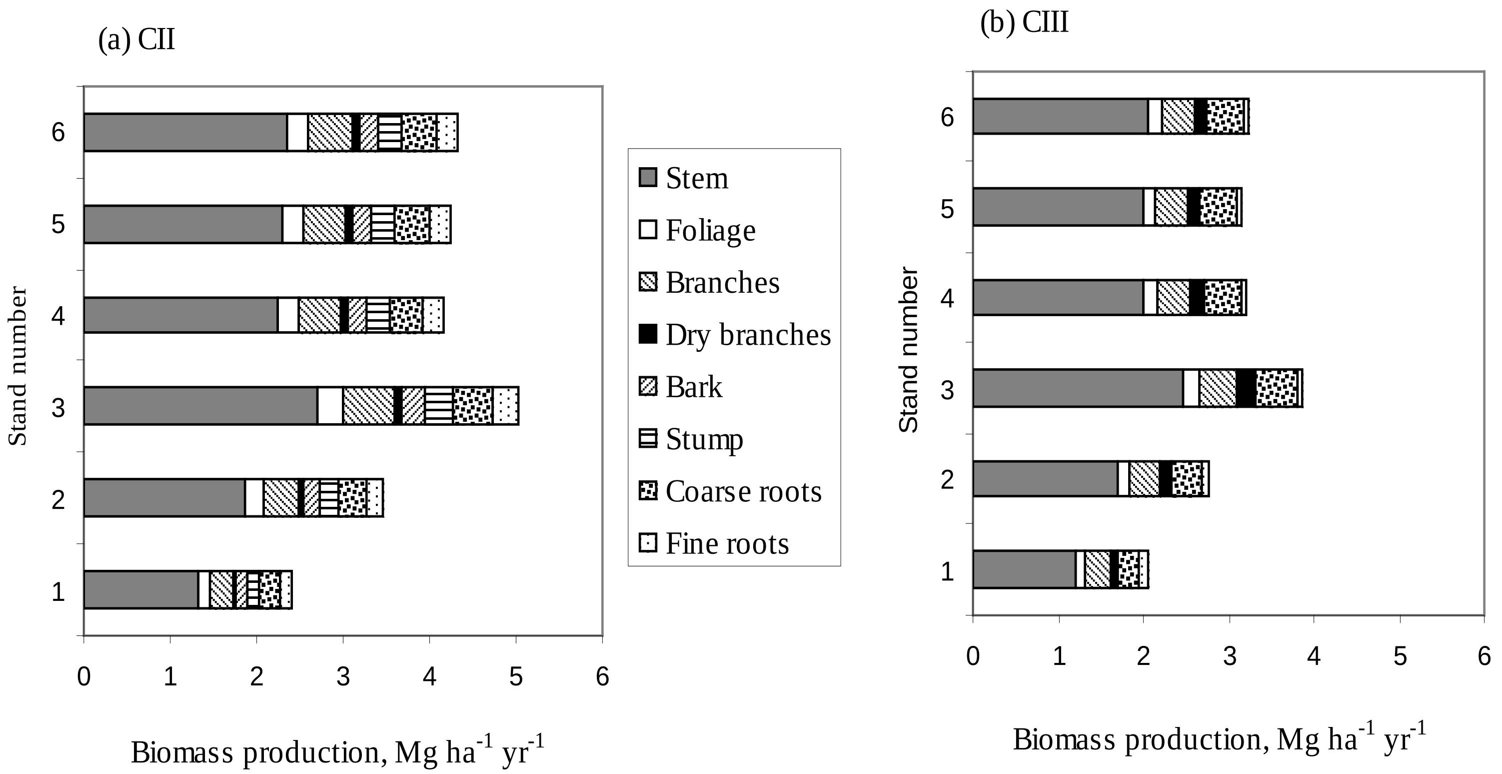
- Optimal stocking control



OPTIFOR Wood (Cao et al., 2008)



OPTIFOR Carbon (Cao et al. 2010)



应用 OptiFor 评估森林碳汇

- OptiFor 教学版http://www.optifor.cn/model/optifor-setup.rar
- 问题1：分别设计1-5次间伐方案，模拟计算木材价值和碳汇价值（默认木材价格，折现率，碳汇价格）
- 问题2：优化间伐方案（Hint: 间伐次数，间伐时间，间伐强度），计算优化后木材价值和碳汇价值（默认木材价格，折现率，碳汇价格）
- 问题3：以10%，30%，50% 递增碳汇价格，比较碳汇价格提升后的净现值和轮伐期。

OPTIFOR Energy（Cao et al. 2015）

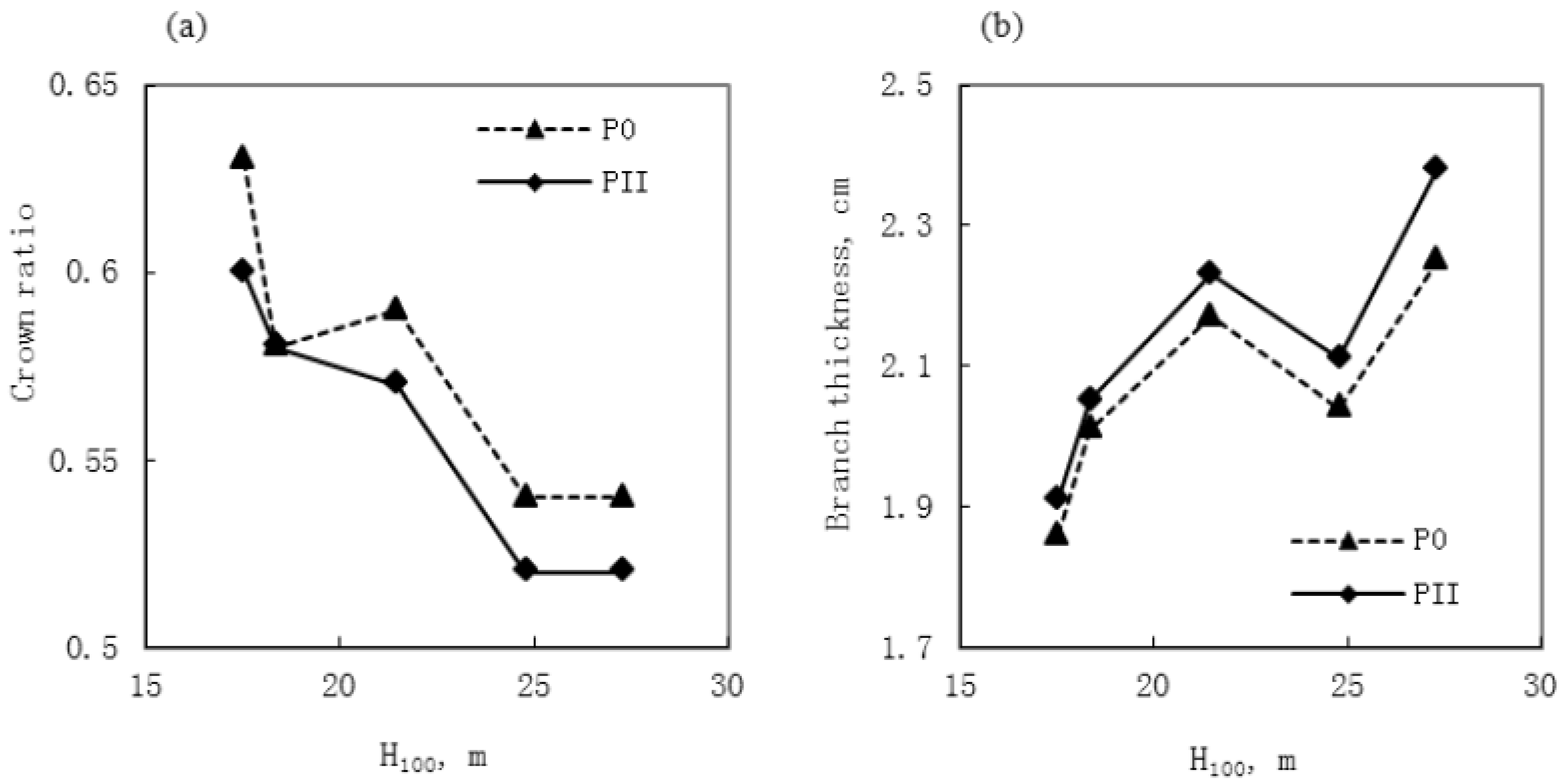


Figure 4. Crown ratio of dominant trees and branch thickness (cm) at the second thinning with Policy 0 and Policy II for five Scots pine stands (initial density 3000 trees ha^{-1}) by H_{100} (dominant height at 100 yrs, m), energy wood price 15 € m^{-3}, interest rate 3%.

Simulation models in OPTIFOR 2.0

- Yasso 07 (Tuomi et al. 2009)
- Wood quality (Mäkinen and Hynynen 2012)
- PreLES (Mäkelä et al. 2008, Peltoniemi et al. 2012)
- ROMUL (Chertov et al. 2001)
- QUASSI (Liao et al. 2017)

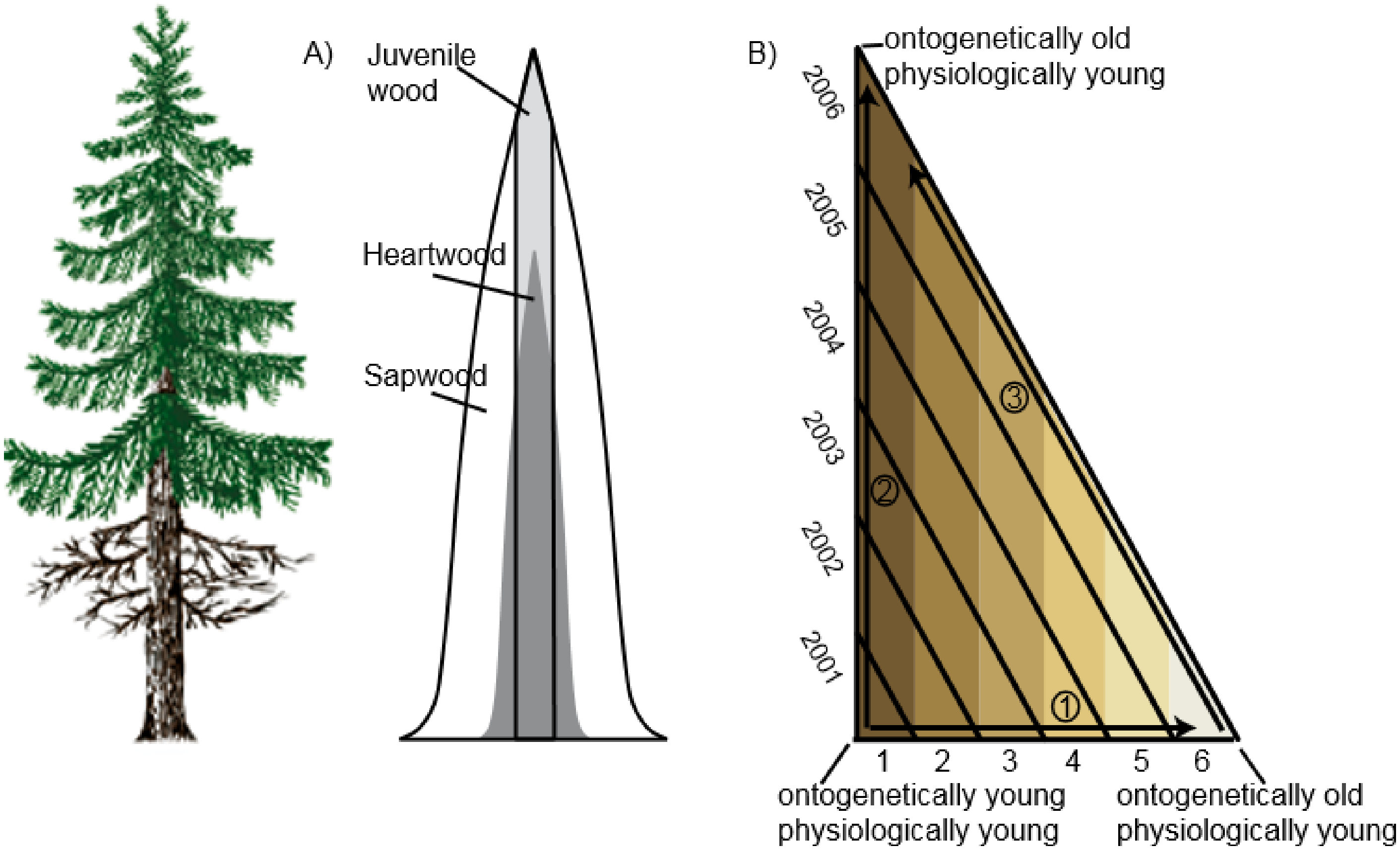


Figure 2. Juvenile wood, heartwood and sapwood in Norway spruce stem (A). Ageing of the xylem along the three major axes of the stem (B): radially from the pith to the bark (1), vertically from the stem base to the stem apex in a given annual ring from the pith (2), and concentrically around the given annual ring from the bark (3) (redrawn and modified from Duff and Nolan 1953, Schweingruber et al. 2006).

Calibration of PRELES

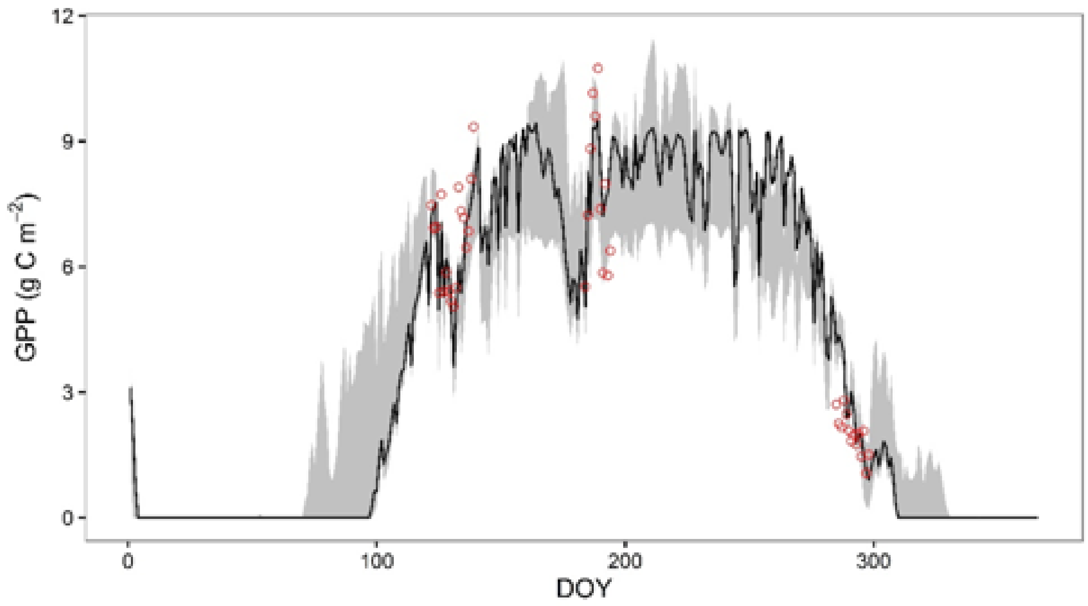
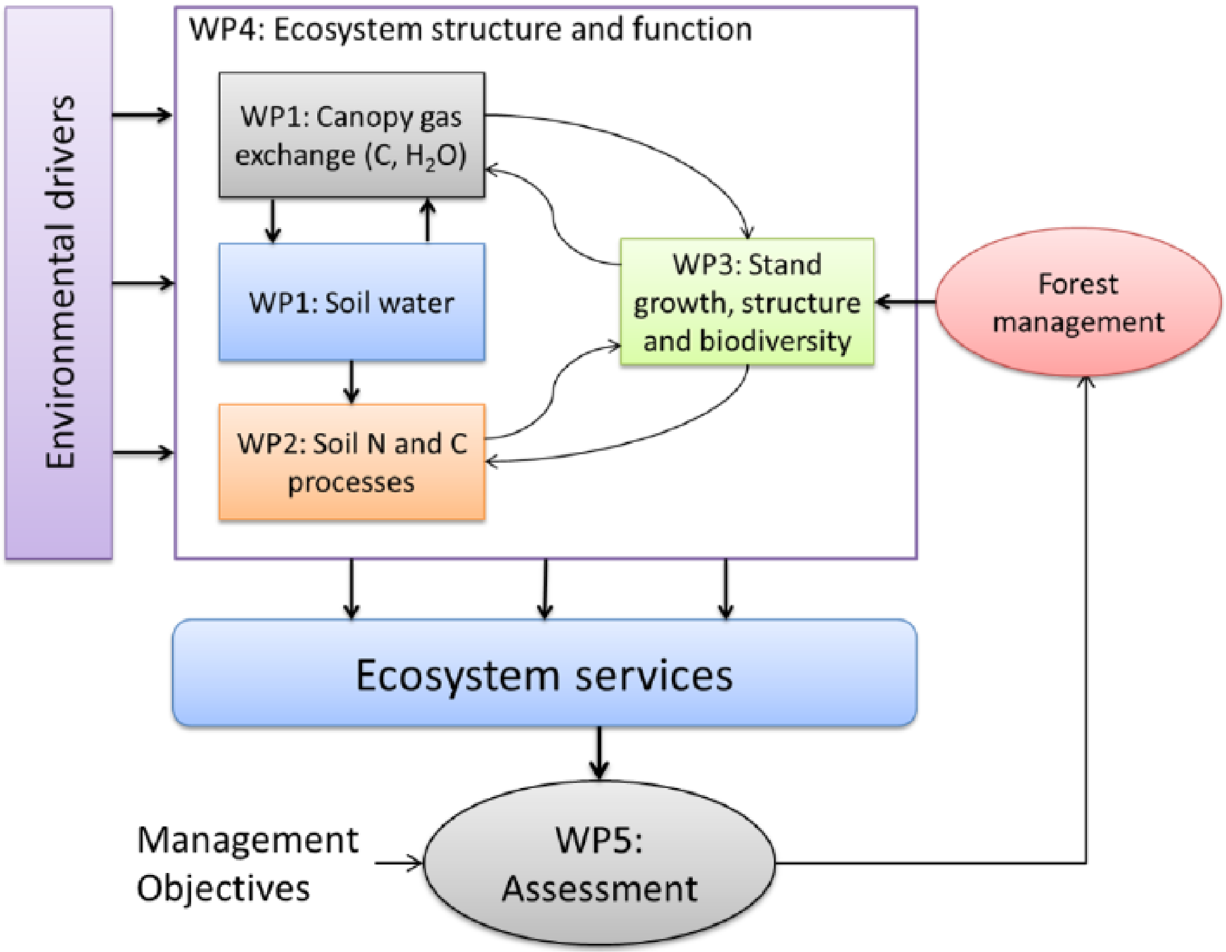


Fig. 6 Calibration of PRELES on Qinglin site. The predictive uncertainty is higher than any other site due to the limited amount of observations (43 days).

MultiFor



Environmental drivers
WP4: Ecosystem structure and function
WP1: Canopy gas exchange (C, H_2O)
WP1: Soil water
WP2: Soil N and C processes
WP3: Stand growth, structure and biodiversity
Forest management
Ecosystem services
Management Objectives
WP5: Assessment

Optimization algorithms in OPTIFOR 2.0

- Differential evolution (Storn and Price 1997)
- Particle swarm (Kennedy and Eberhart 1995)
- Evolution strategy (Bayer and Schwefel 2002)
- The method of Nelder and Mead (Nelder and Mead 1965)

Forest management objectives

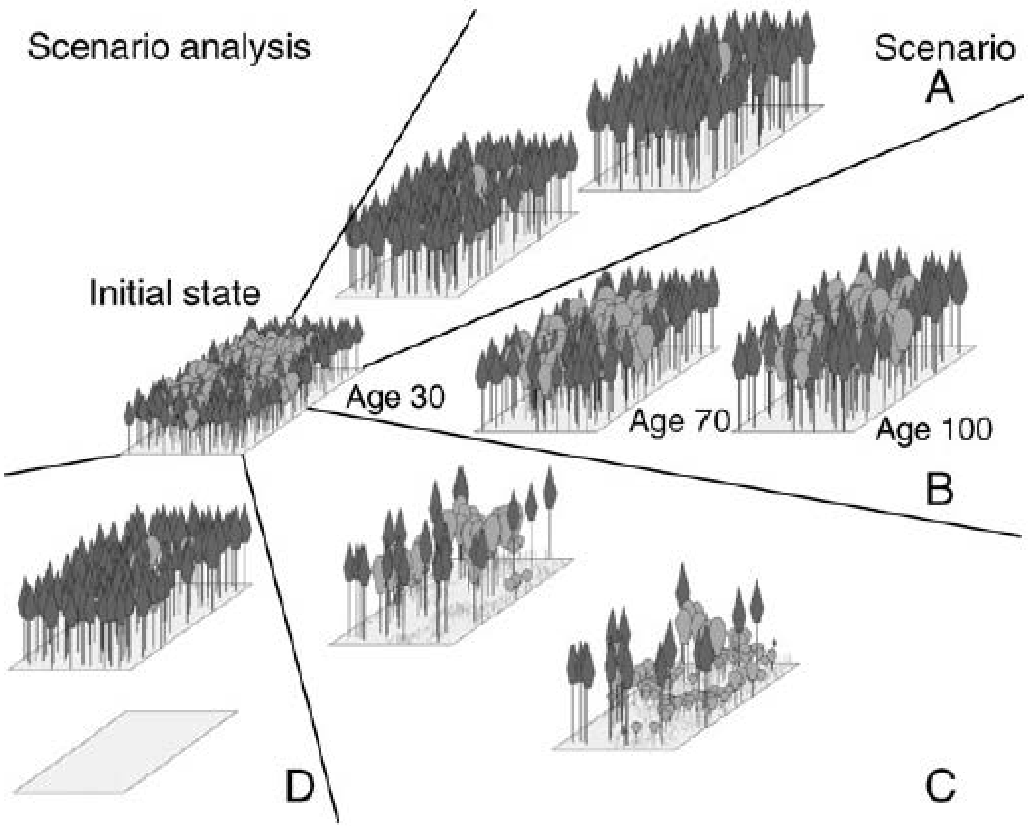


FIG. 2. Scenario analysis with forest stand models. Starting with an *initial state* of an ecosystem, models display the long-term consequences of the different management options A, B, C and D and the consideration of different *objective states*.

Definition

- What does sustainable forest management mean anyway?

- Sustainable timber yield?
- Sustainable forest biodiversity?
- Or sustainable forest ecosystem?

Group work

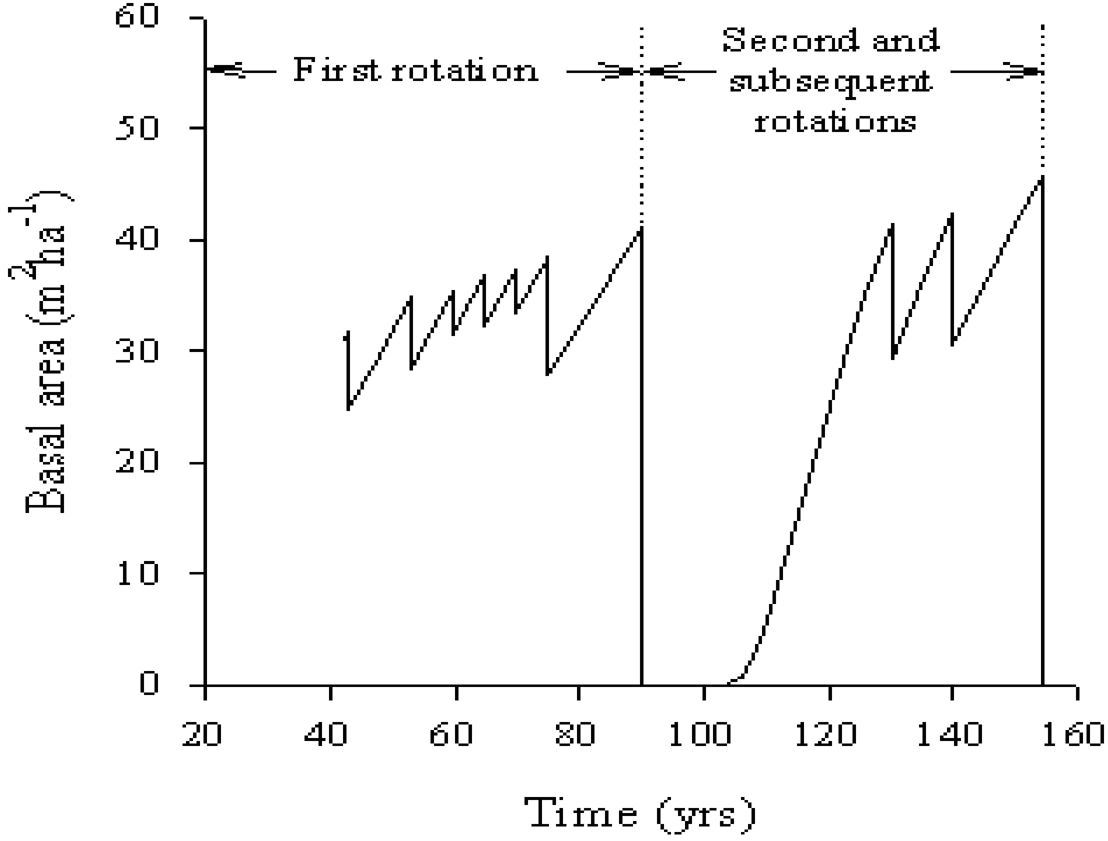
- Sustainable,
- close-to-nature,
- or adaptive forest management:

- doest it really matter?

Applications: even-aged stands

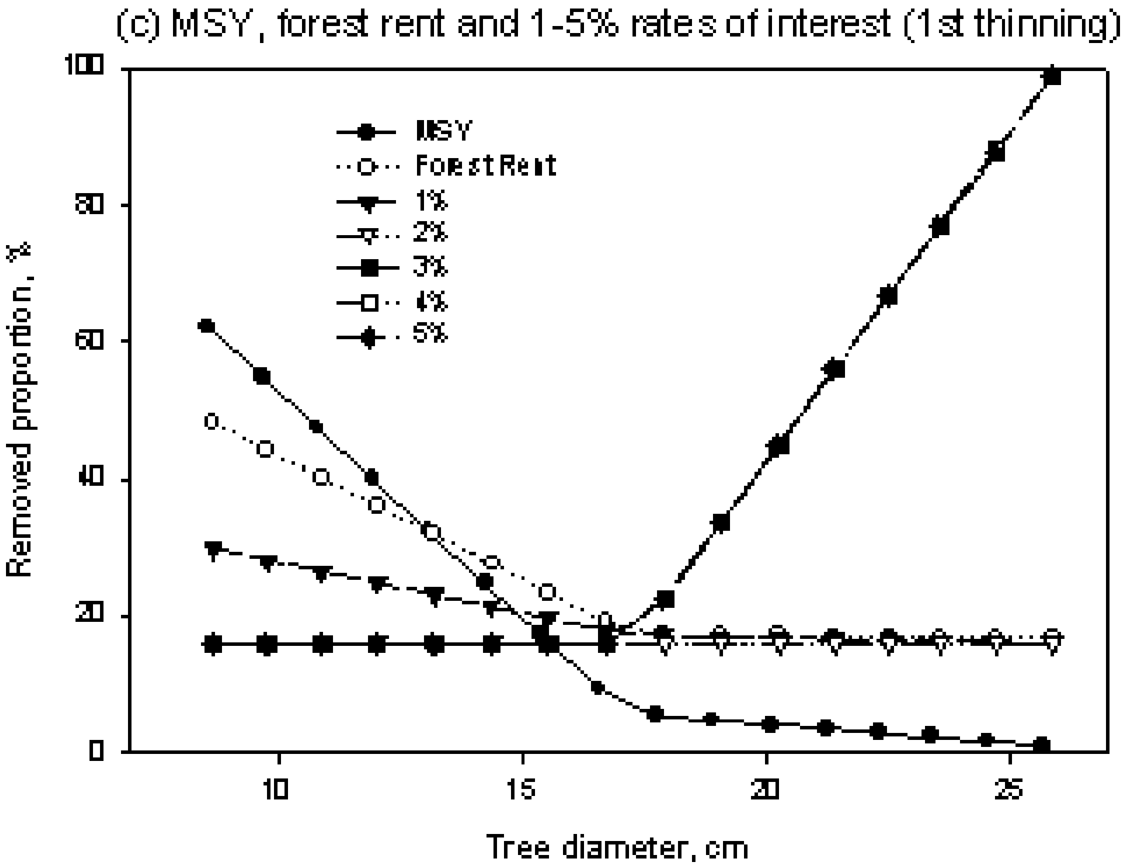
- Characteristics of even-aged stands
- Predicting growth and yield for even-aged
- Assessing forest resources for even-aged stands
- Assessing forested land for even-aged stands

Even-aged management



Source: Cao et al. (2006), Fig. 1

Type of thinning (Cao, 2003)



- Thinning from below was more profitable with interest rates less than 2%, whereas thinning from above was superior with interest rates of 3-5%.

Even-aged forest stand

- Regeneration
  - Natural vs. artificial regenerated
- Plantations
  - Sawlog or pulpwood
  - Energy wood
- Tree specises
  - Conifer vs. broadleaf
  - Ever-green vs. deciduous
- Stand structure
  - Diameter distribution
  - Spatial distribution

Predicting even-aged stand growth

- Empirical vs. process-based
- Whole stand vs. individual-tree
- Site quality evaluation
- Competition
- Tree height growth
- Diameter growth
- Basal area growth
- Mortality and self-thinning
- Ingrowth
- Thinning response

Pine-oak forests

- Forests dominated by *Pinus tabuliformis*, *Pinus armandii* and *Quercus aliena* occupy the major area of Qinling Mountains,

- Accurate prediction of the growth and yield for these species has been a problem for many years, due to the diversity in composition and structure of pine-oak forests.

- Generally, forest growth modeling needs a large number of continuous observed data, which is unavailable in Qinling.

A three-stage modeling approach

- The purpose is to develop and evaluate diameter increment models for pine-oak forests in Qinling Mountains with different approaches

- based on temporary plots,
- combining the analysis of increment cores
- and the exploration of diameter structure dynamics.

Diameter increment model

- Age-independent
  - Uneven-aged forest
  - Mixed forest
- Distance-independent
  - Practicability
  - Simplicity
  - Accuracy

Diameter increment model

Model form:

$$\Delta d_i = f\left(D_i, V_i, C_i, S_i\right) \qquad (1)$$

where Δd_i is the 5-year diameter increment of tree i; D_i, V_i, C_i, S_i represents tree size factor, historical vigor factor, competition factor and site productivity factor, respectively.

- Tree size — DBH, DBH^2, ln(DBH), 1/DBH, etc.
- Historical vigor — Crown ratio, canopy closure, LAI, etc.
- Competition — BA, BAL, CCF, etc.
- Site productivity — Site index, Forest type, Elevation, etc.

Stand diameter distribution

3-parameter Weibull distribution：

$$f(x)=\left(\frac{c}{b}\right)\left(\frac{x-a}{b}\right)^{c-1}\exp\left[-\left(\frac{x-a}{b}\right)^{c}\right];\quad x\geq a, b>0, c>0$$

where *x* is tree diameter; *a* is the location parameter; *b* is the scale parameter; *c* is the shape parameter.

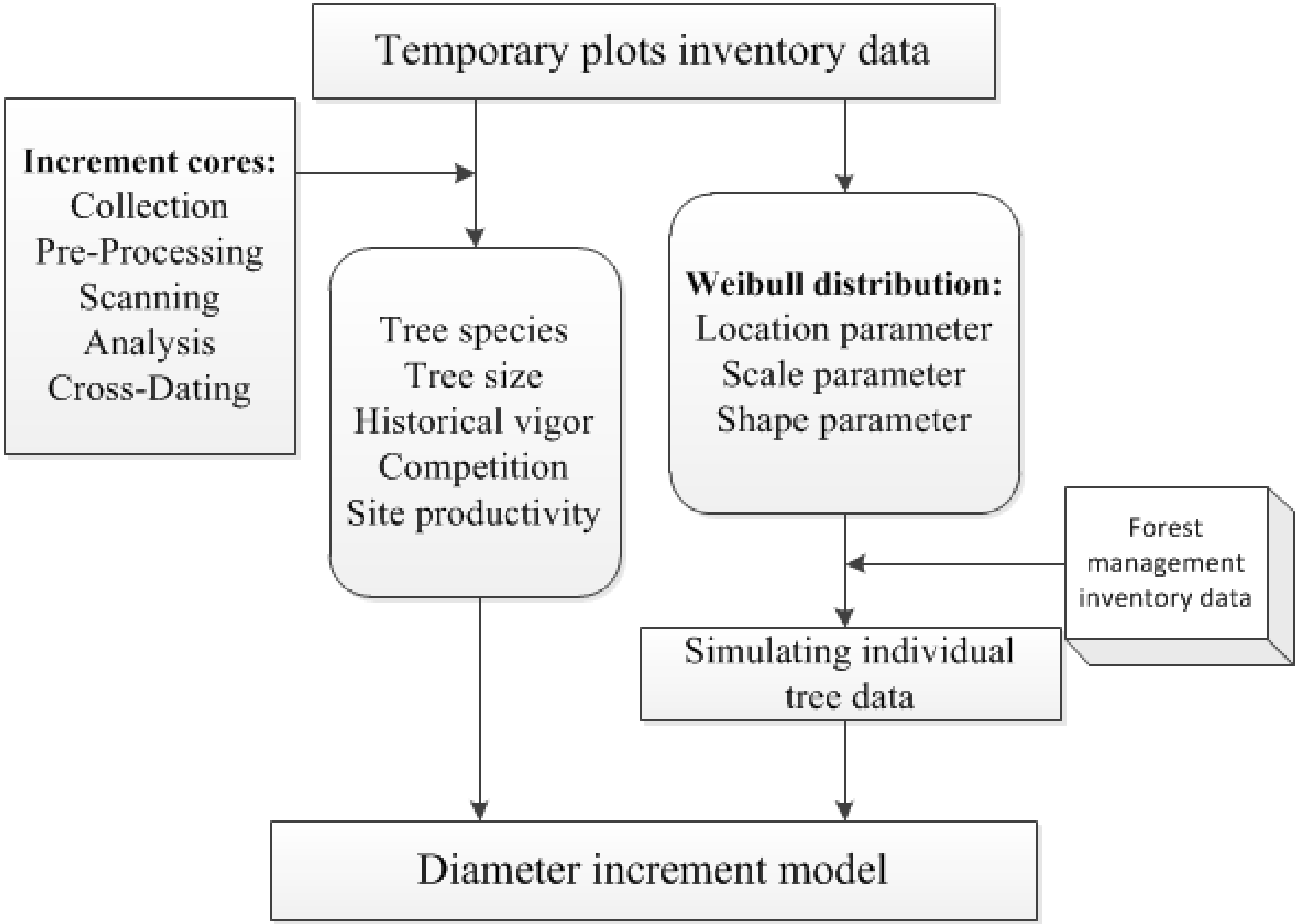
Optimizing diameter distribution

Objective function:

$$\min Z = \frac{\sum(D_i - \hat{D}_i)^2}{\hat{\sigma}_D^2} + \frac{\sum(B_i - \hat{B}_i)^2}{\hat{\sigma}_B^2} + \frac{\sum(N_i - \hat{N}_i)^2}{\hat{\sigma}_N^2} \quad (3)$$

where D is diameter, B is basal area, N is density, $\hat{\sigma}$ is estimated value of the standard deviation.

计算实验 Computational experiments



Even-aged stand management

- Alternative tree specises
- Planting density
- Silvicultural treatments
- Thinning and rotation
- Timber production
- Biodiversity
- Carbon sequestration
- Landscape
- Risk management

Using Bayesian Calibration

1. Data requirements: small amount of data is acceptable, bridging the gap between models and data.

2. Previous investigation data is good prior information for next experiment, considering that forest inventory is continuous.

3. Bayesian calibration provides a likelihood framework for different types of measurement error.

Tools for Bayesian Calibration

To estimate the posterior distributions, we use a Markov Chain Monte Carlo (MCMC) algorithm.

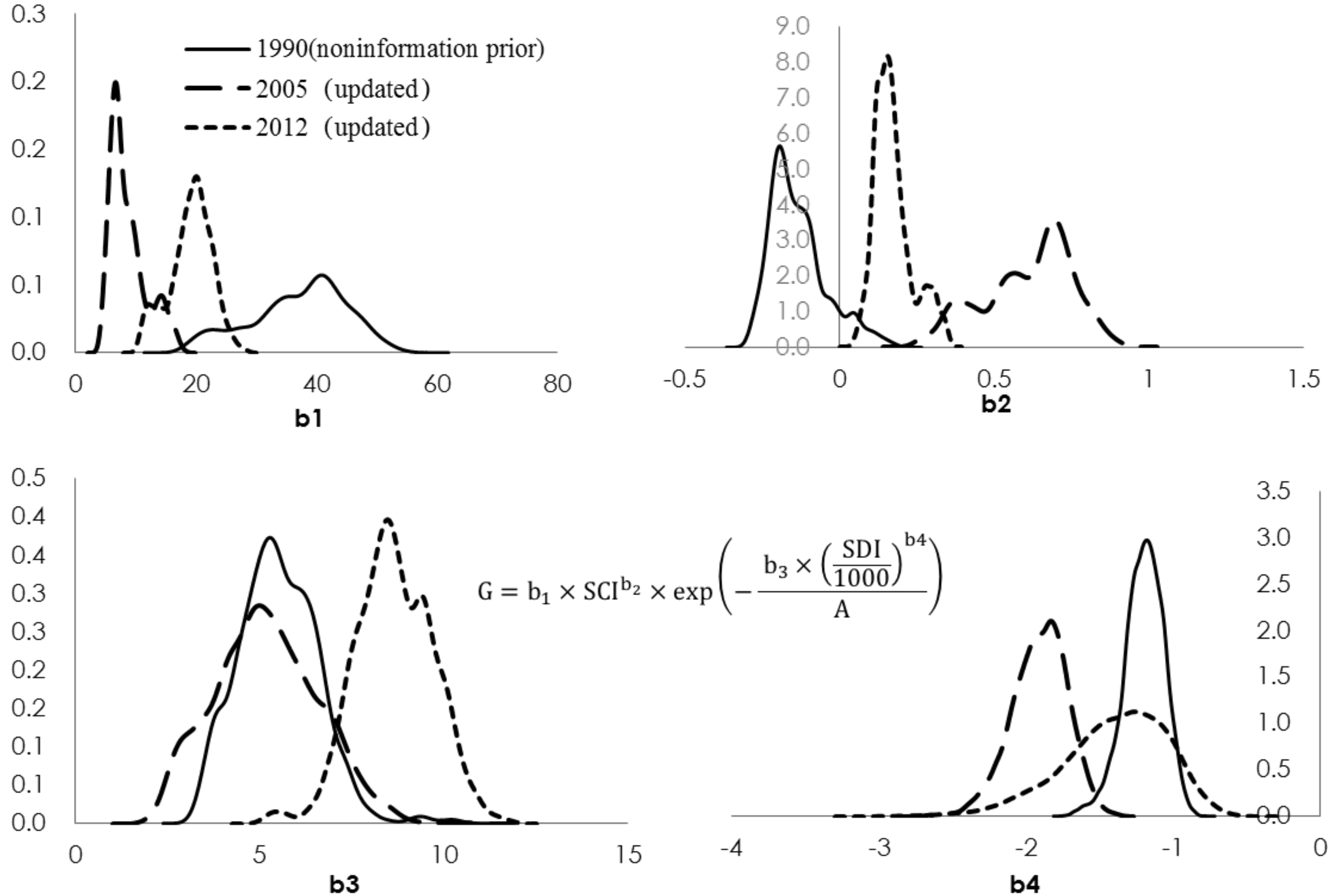
1. WinBUGS
   (Bayesian inference Using Gibbs Sampling)

2. R2WinBUGS
   Package linking R with WinBUGS

3. R programming
   （For example, Gibbs within Metropolis）

More R packages see CRAN Task View: Bayesian inference (https://cran.r-project.org/web/views/Bayesian.html)

New inventory data updated



$$G = b_1 \times SCI^{b_2} \times \exp\left(-\frac{b_3 \times \left(\frac{SDI}{1000}\right)^{b4}}{A}\right)$$

The default is a bandwidth computed from the variance of x, specifically the ‘oversmoothed bandwidth selector’ of Wand and Jones (1995, page 61)

Model linkages

- Biomass equations
- Taper curve equations
- Timber grading module
- Tracheid properties
- Wind throw
- Forest fire
- Forest biotic damages

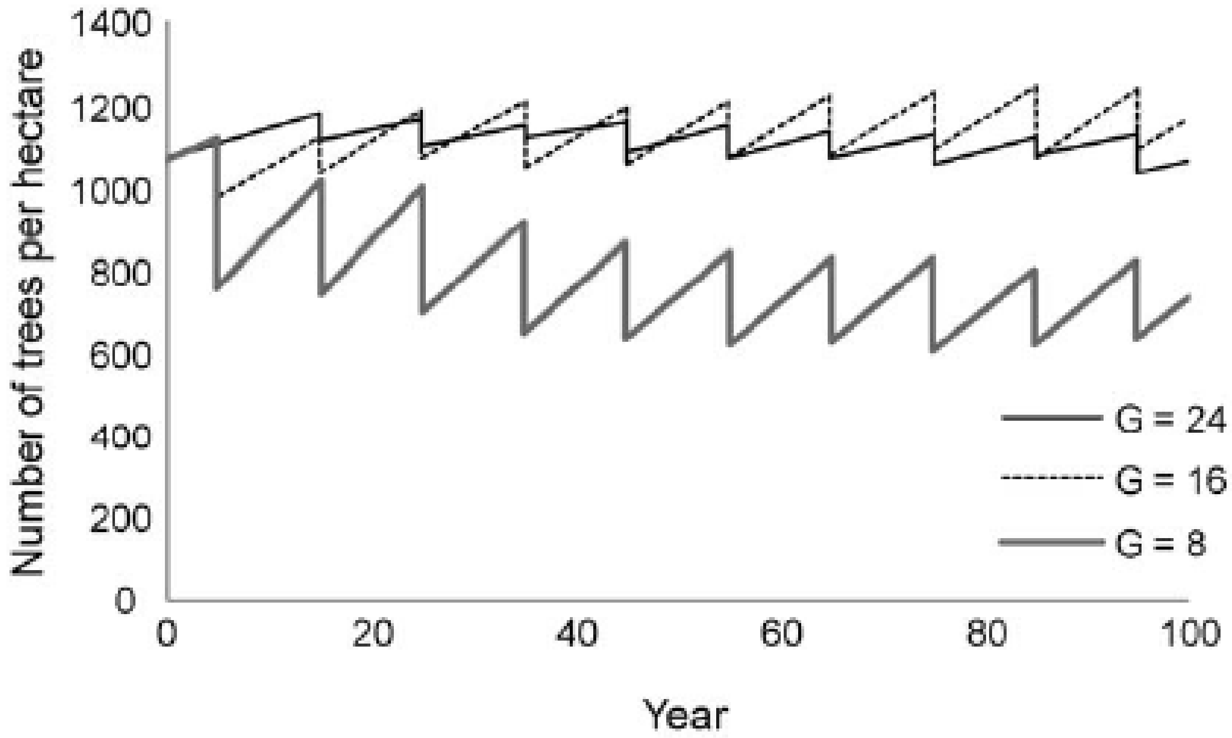
Applications: uneven-aged stands

- Characteristics of uneven-aged stands
- Predicting growth and yield for uneven-aged stands
- Assessing forest resources for uneven-aged stands
- Assessing forested land for even-aged stands

Uneven-aged management

- Uneven-aged
- Mixed forest
  - Boreal forest (conifer dominant)
  - Temperate forest (conifer & broadleaf)
  - Tropical forest (broadleaf dominant)
- Diameter distributiion: reverse "J" sharp
- Regeneration: natural vs. artificial
- Succession: shade tolerant vs. light-demanding

Uneven-aged management



Source: Pukkala et al. (2009), Fig. 8

Predicting uneven-aged stand growth

- Whole stand models: few
- Transition matrix models: e.g., Buongiorno & Michie (1980)
- Tree list models: e.g., Prognosis (Stage, 1972)
- Individual-tree growth models
  - Spatial models (e.g., Ek and Monserud, 1974)
  - Non-spatial models
    - Stochastic, e.g. JABOWA (Botkin et al., 1972)
    - Pukkala et al. (2009)

Simulation and uncertainty analysis

■ Methods:

Prior distribution of parameter can be guessed which come from others research. The data which come from sample plots investigation will be used to update the prior information by the computation of the posterior distribution.

$$P(A_i|B) = \frac{P(A_i)P(B|A_i)}{\sum_{j=1}^{k} P(A_j)P(B|A_j)} \quad i = 1, 2, \cdots, k$$

$P(A_i)$: Prior distribution

$P(B|A_i)$: likelihood function

$P(A_i|B)$: Posterior distribution

Environment and competition factors

- Environment factors
  - elevation ,
  - slope ,
  - aspect ,
  - the interaction of slope and aspect

- Competition factors
  - stand density ,
  - stand basal area ,
  - stand average diameter (DBH),
  - stand canopy closure

Height growth of juvenile trees

- Explanatory variables:

Tree size: height

Competition factors: stand density , stand basal area , stand average diameter (DBH), larger trees basal area (BAL)

Site factors: site index , slope, the interaction of slope and aspect

- The height growth model of juvenile trees:

$$HTG = \beta_0 + \beta_1 \times SL \times COS(ASP) - \beta_2 \times SL \times SIN(ASP) - \beta_3 \times SL + \beta_4 \times LN(HT) + \beta_5 \times CCF + \beta_6 \times (\frac{BAL}{100}) + \varepsilon_2$$

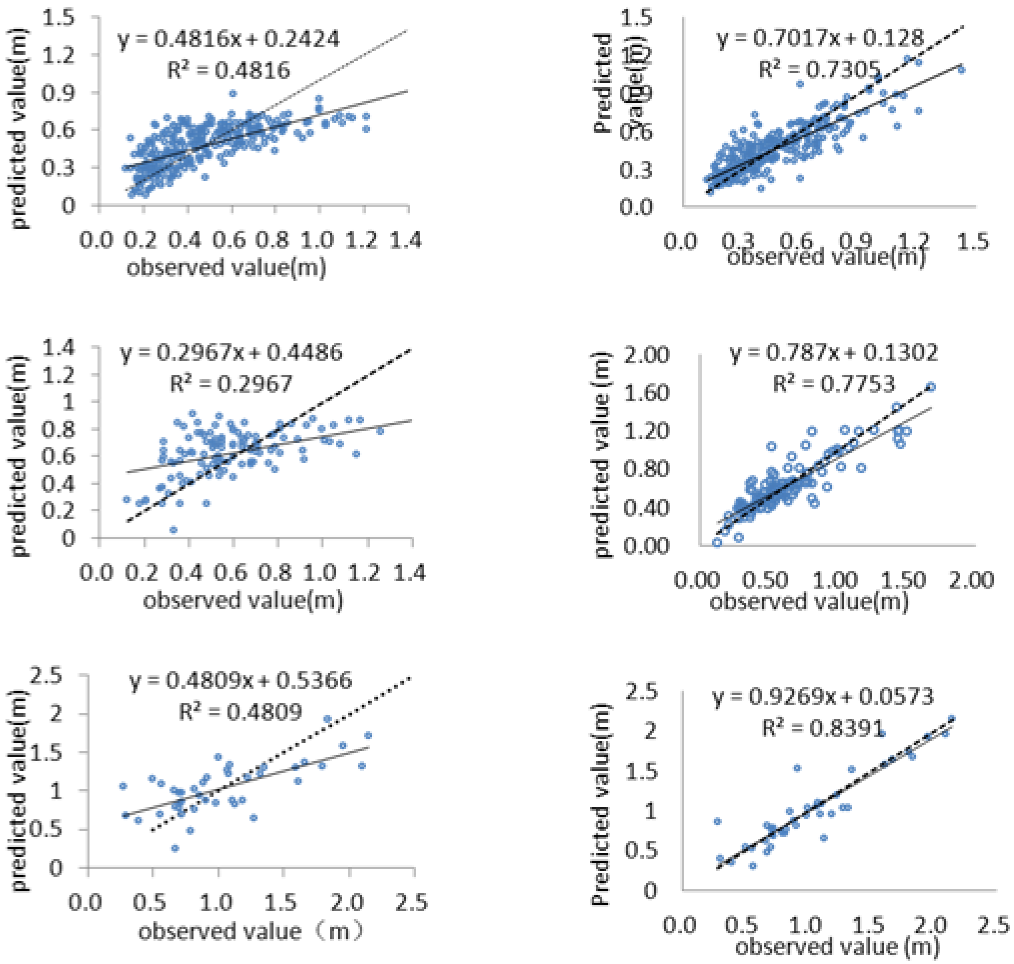
Recruitment models

- Recruitment models predict tree reaching a specified threshold size , usually based on height (breast height) or diameter (5, 7, 9, or 10 cm), a threshold diameter of 5 cm was selected in this study.
- Forest stand recruitment is a complicated stochastic process influenced by several stand characteristics, climatic, geographical factors at a range of spatial and temporal scales.

Recruitment models, con't

- Likelihood function
  - Estimating number of recruitment trees by 5-year juvenile tree height model and 5-year diameter increment model.
- Posterior distribution
  - To update the prior information by the likelihood function, and to obtain Posterior distribution of recruitment model parameter.

ANN vs. Bayesian, 5-yr height growth



Pinus armandii

Pinus tabulaeformis

Pinus tabulaeformis

Bayesian method

ANN

Forest management objectives

- Timber production
- Forest biodiversity
- Carbon sinks
- Forest bioenergy
- Climate mitigation
- Multi-functional services

Model linkages and applications

- Growth model + dynamic carbon model
- Growth model + wood quality module
- Growth model + climate-sensitive module
- Growth model + energy wood module
- Growth model + biodiversity index

Optimization modeling techniques

- Linear programming
- Goal programming
- Integer programming
- Dynamic programming
- Nonlinear programming
- Artificial intelligence

Forest management planning

- Even-aged management
- Uneven-aged management
- Regeneration methods
- Silvicultural operations
- Logging methods

Model linkages

- Forest growth and yield models
- Wood quality models
- Dynamic carbon models
- Nutrient cycling models
- Water balance models
- Logging models

Forest growth models

- Tree level vs. size class level
- stand level vs. forest level
- Even-aged vs. uneven-aged
- Empirical vs. mechanistic
- Deterministic vs. stochastic

Forest ecosystem functions

- IUFRO Division 8.01
- 8.01.00 – Forest ecosystem functions

- 8.01.01 – Old growth forests and forest reserves
- 8.01.02 – Landscape ecology
- 8.01.03 – Forest soils and nutrient cycles
- 8.01.04 – Water supply and quality
- 8.01.05 – Riparian and coastal ecosystems
- 8.01.06 – Boreal forest ecosystems
- 8.01.07 – Hydrologic processes and watershed management

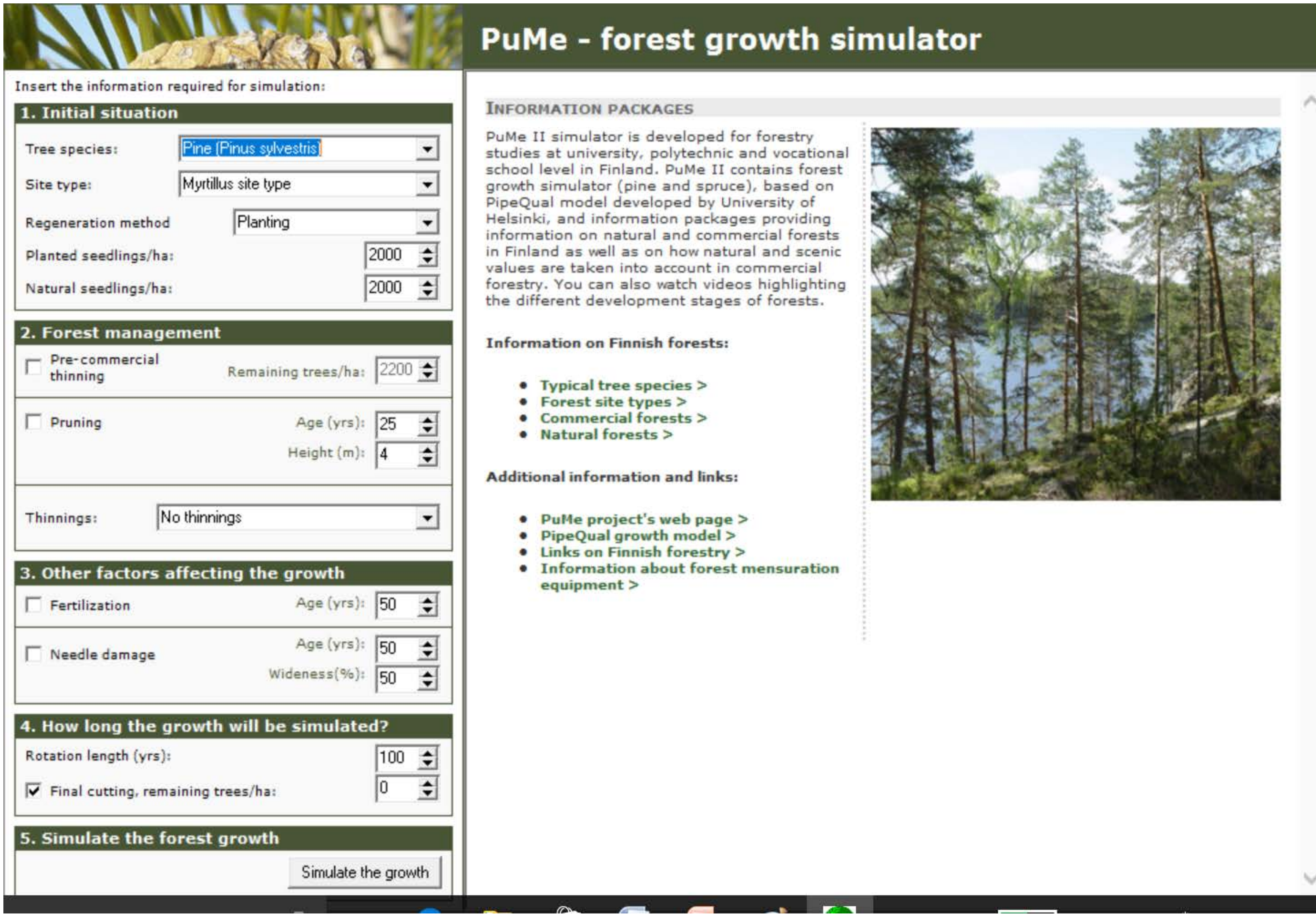
Forest biodiversity

- 8.02.01 – Key factors and ecological functions for forest biodiversity
- 8.02.02 – Forest biodiversity and resilience
- 8.02.03 – Humus and soil biodiversity
- 8.02.04 – Ecology of alien invasives
- 8.02.05 – Wildlife conservation and management
- 8.02.06 – Aquatic biodiversity in forests
- 8.02.07 – Bioenergy productions systems and forest biodiversity
- 8.02.08 – African wildlife conservation and management (AWCM)

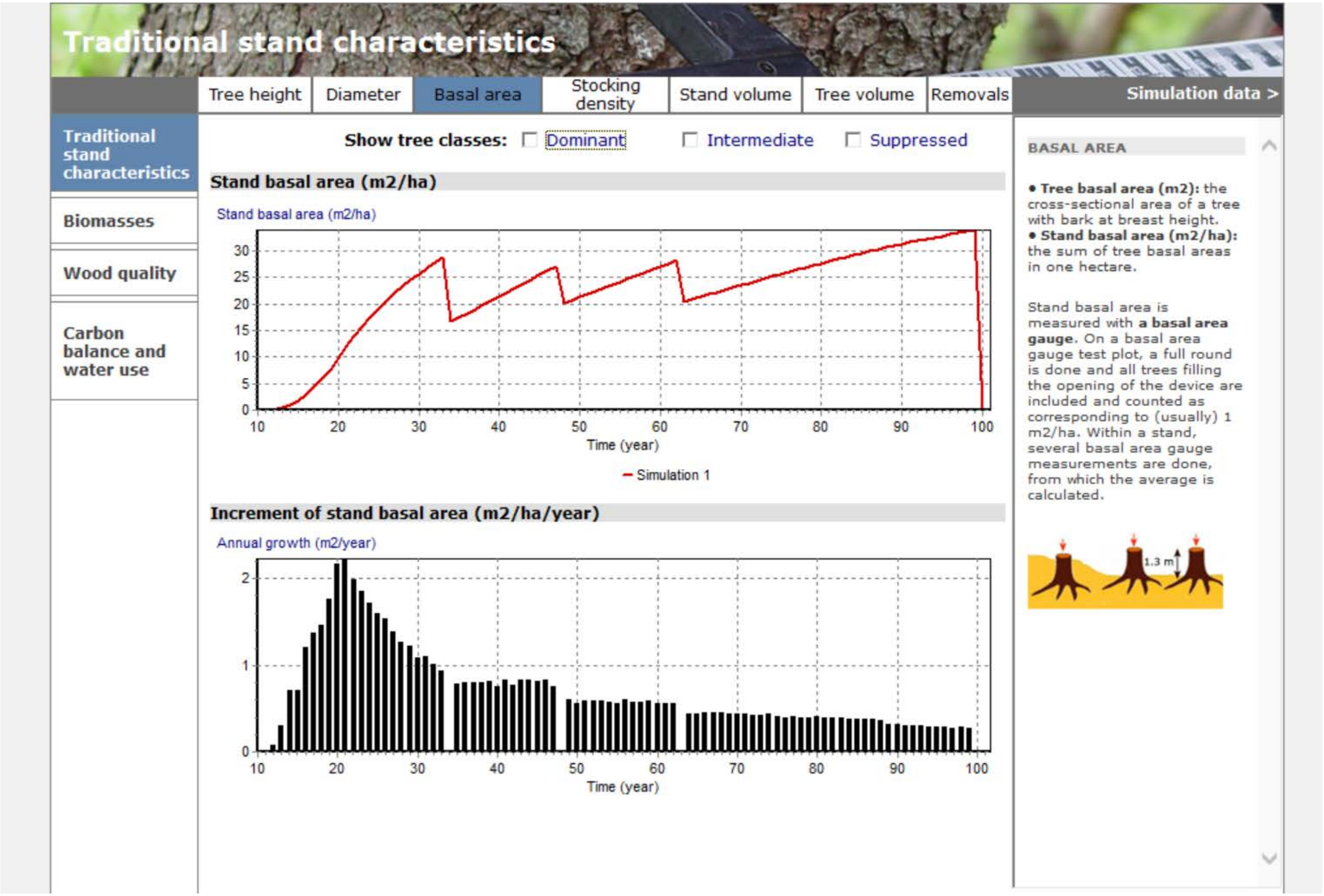
PuMe II for Forestry Education

- Student version
- Process-based
- Wood quality
- Soil carbon
- Water use

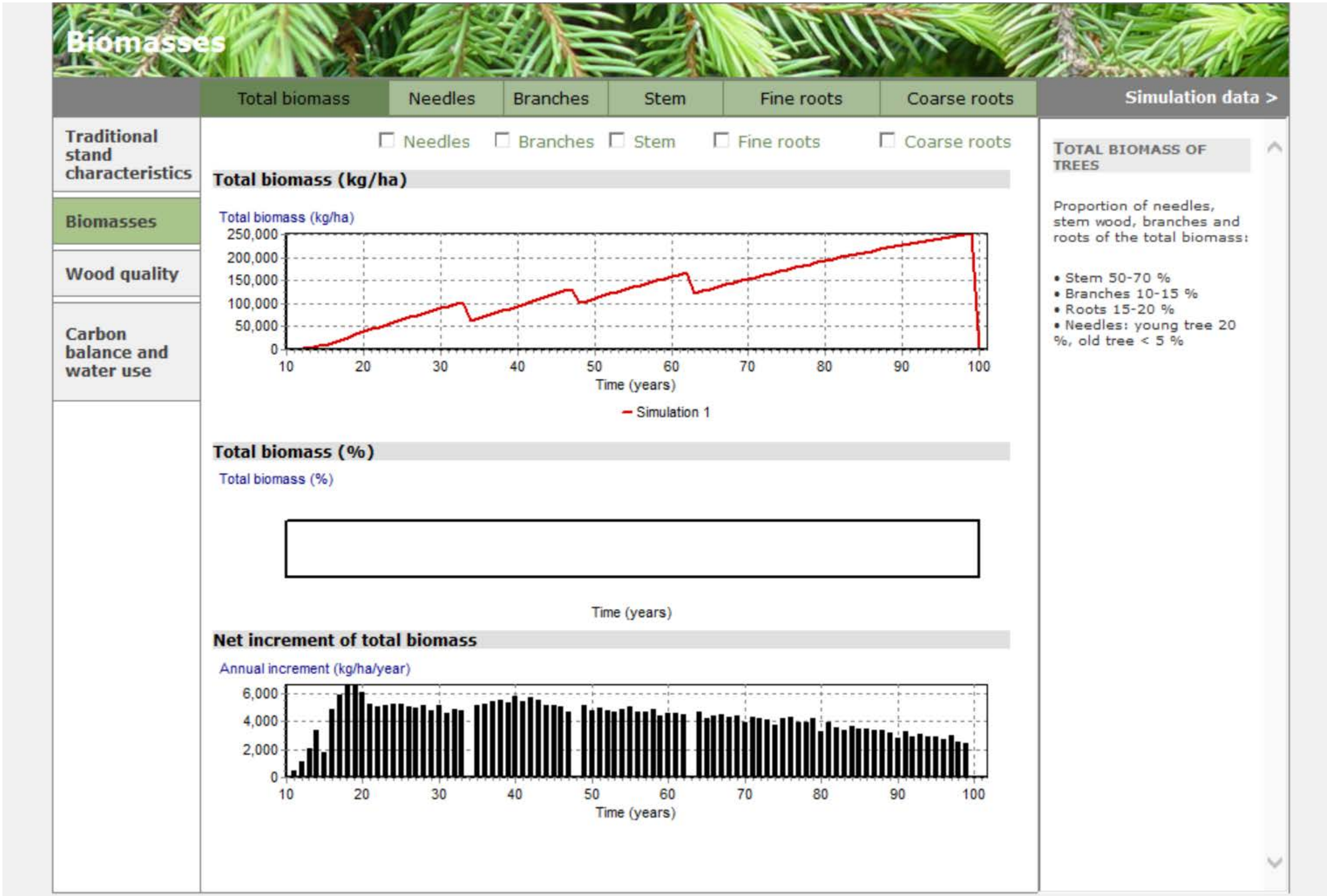
PuMe II


PuMe - forest growth simulator
Insert the information required for simulation:
1. Initial situation
Tree species:
Pine (Pinus sylvestris)
Site type:
Myrtillus site type
Regeneration method
Planting
Planted seedlings/ha:
2000
Natural seedlings/ha:
2000
2. Forest management
Pre-commercial thinning
Remaining trees/ha:
2200
Pruning
Age (yrs):
25
Height (m):
4
Thinnings:
No thinnings
3. Other factors affecting the growth
Fertilization
Age (yrs):
50
Needle damage
Age (yrs):
50
Wideness(%):
50
4. How long the growth will be simulated?
Rotation length (yrs):
100
Final cutting, remaining trees/ha:
0
5. Simulate the forest growth
Simulate the growth
INFORMATION PACKAGES
PuMe II simulator is developed for forestry studies at university, polytechnic and vocational school level in Finland. PuMe II contains forest growth simulator (pine and spruce), based on PipeQual model developed by University of Helsinki, and information packages providing information on natural and commercial forests in Finland as well as on how natural and scenic values are taken into account in commercial forestry. You can also watch videos highlighting the different development stages of forests.
Information on Finnish forests:
Typical tree species >
Forest site types >
Commercial forests >
Natural forests >
Additional information and links:
PuMe project's web page >
PipeQual growth model >
Links on Finnish forestry >
Information about forest mensuration equipment >

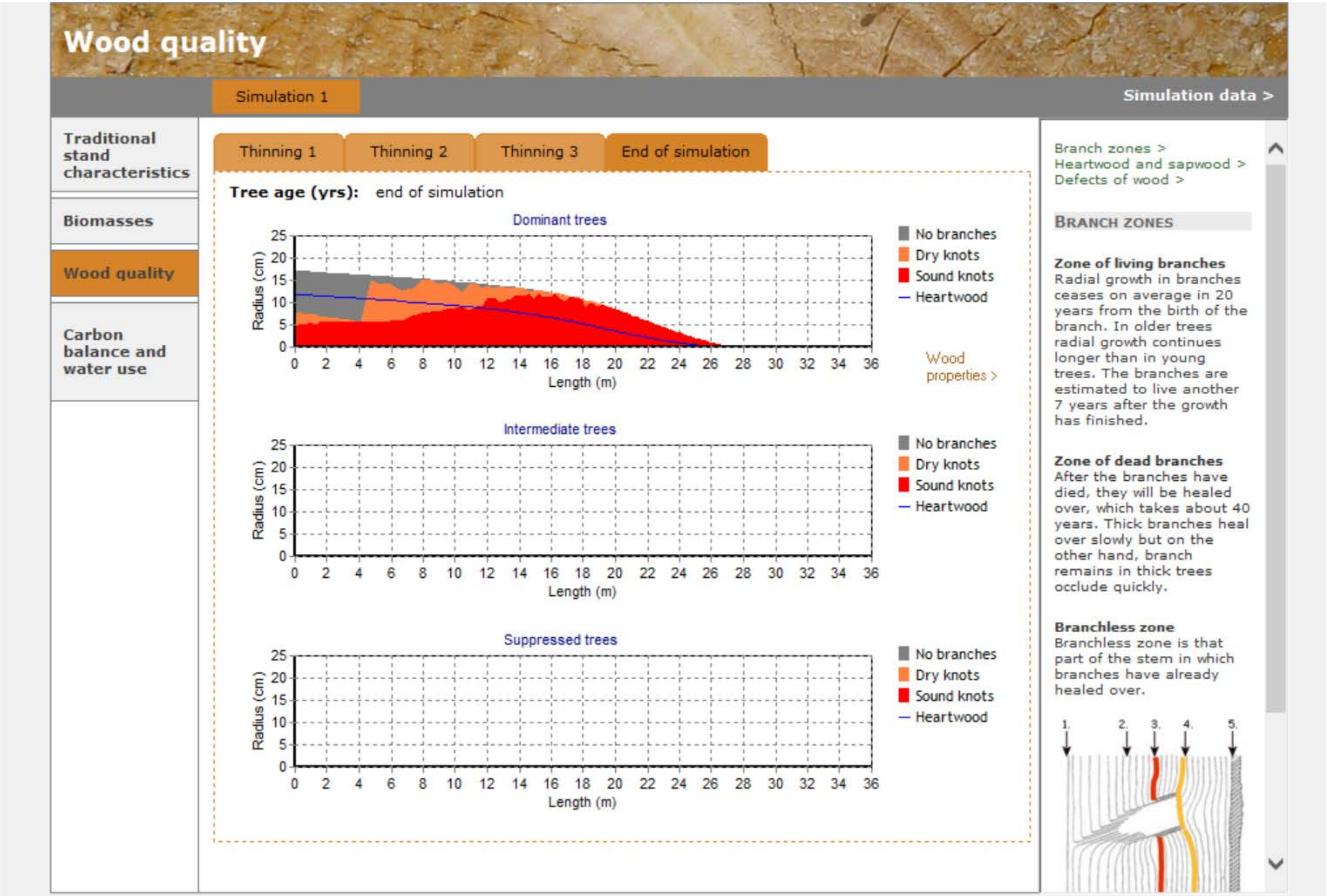
Silvicultural recommendations



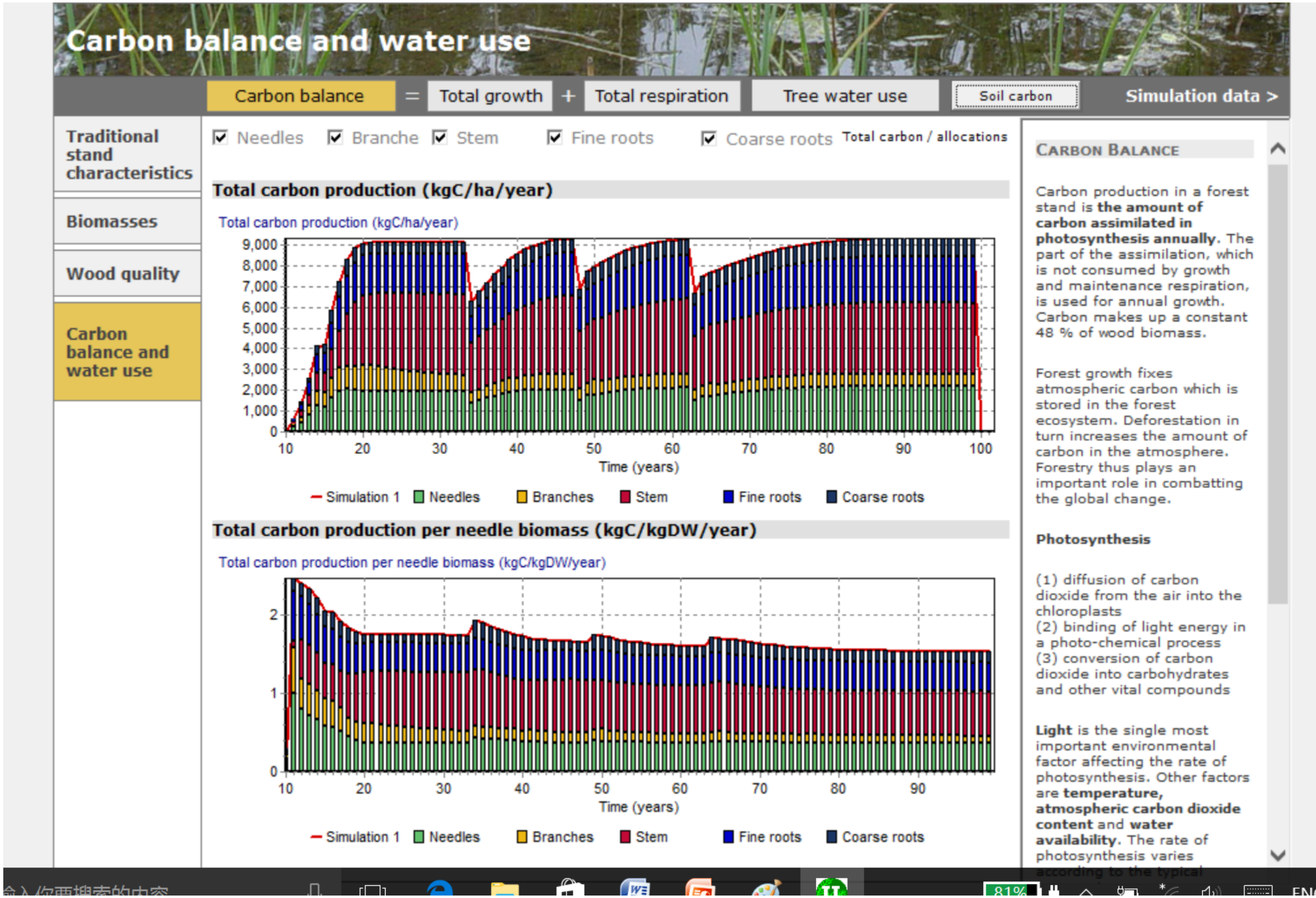
Biomass production



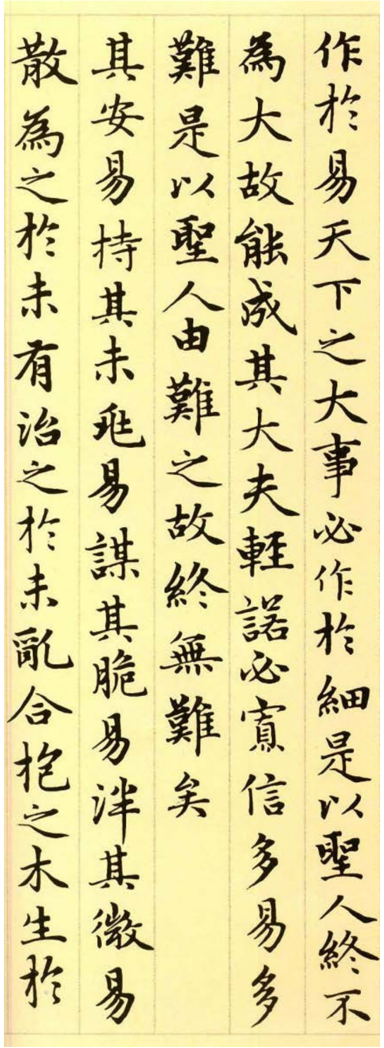
Wood quality



Carbon balance and water use



Forest management planning



Therefore deal with things before they happen; Create order before there is confusion.

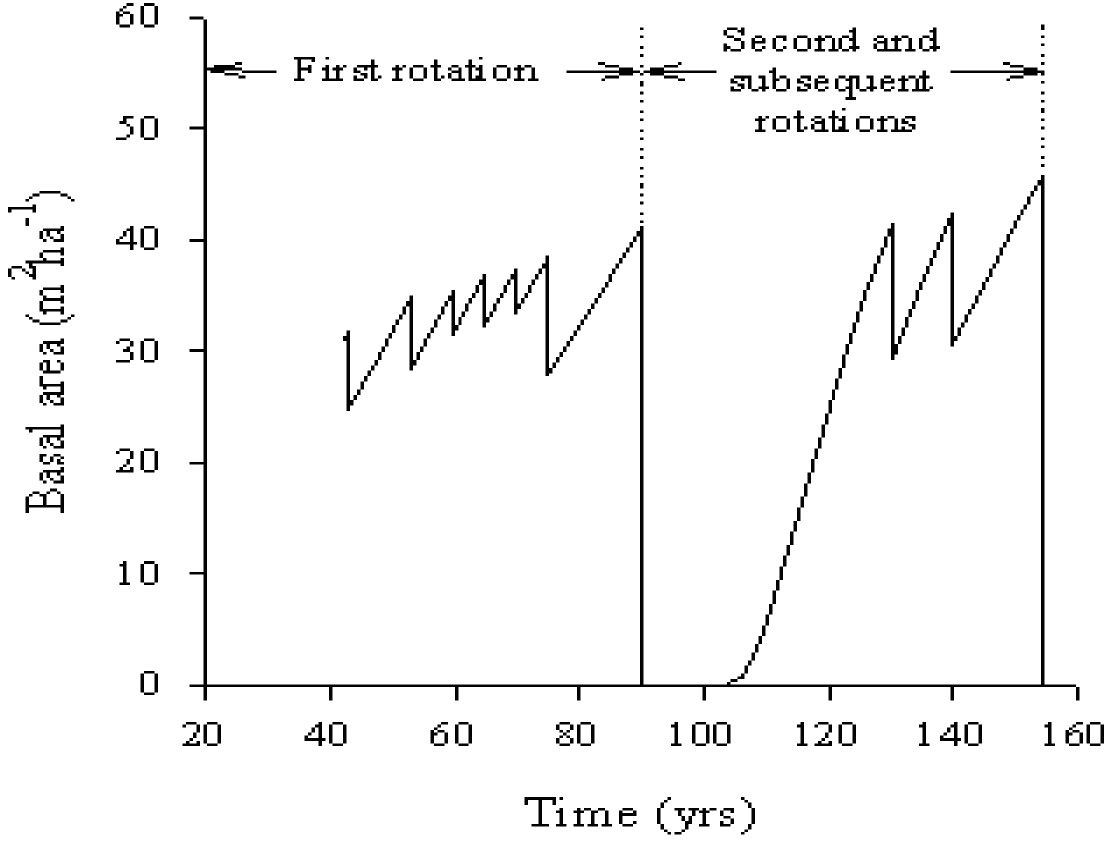
4.04.00 – Forest management planning

- 4.04.02 – Planning and economics of fast-growing plantation forests
- 4.04.03 – SilvaPlan: Forest management planning terminology
- 4.04.04 – Sustainable forest management scheduling
- 4.04.06 – Nature conservation planning
- 4.04.07 – Risk analysis
- 4.04.08 – Adaptation to climate change

Even-aged management

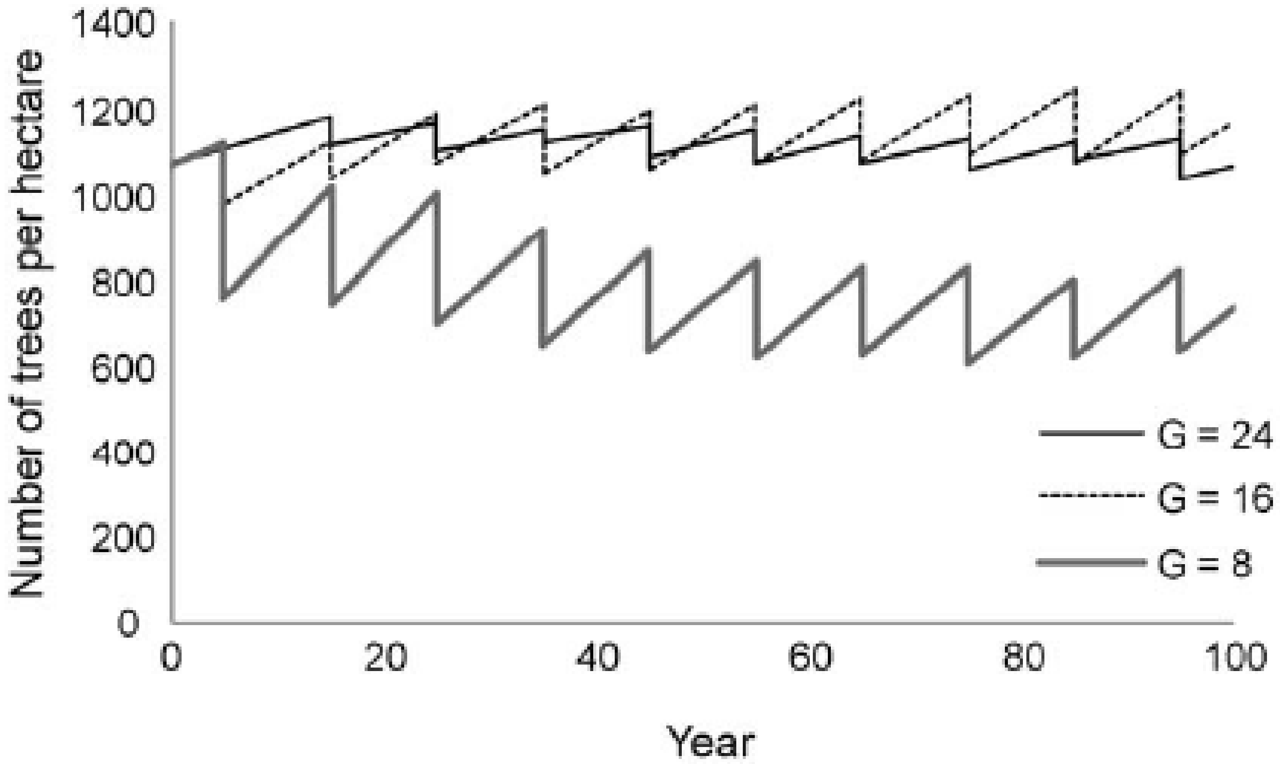
- Even-aged management deals with forests composed of even-aged stands.
- In such stands, individual trees originate at about the same time, either naturally or artificially.
- In addition, stands have a specific termination date at which time all remaining trees are cut.
- This complete harvest is called a *clear-cut*.

同龄林经营 Even-aged management



Source: Cao et al. (2006), Fig. 1

异龄林经营 Uneven-aged management



Source: Pukkala et al. (2009), Fig. 8

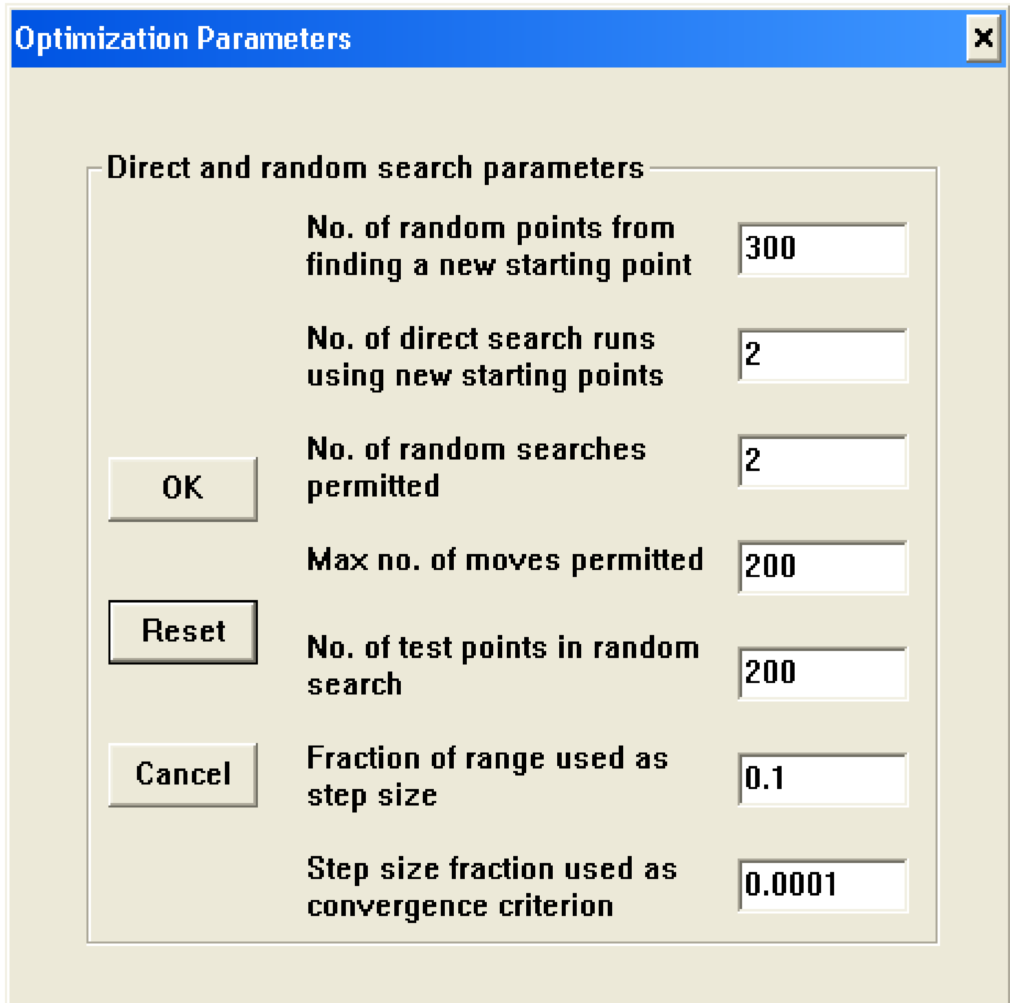
Regeneration methods

- Regeneration of even-aged stands may be done by planting or seeding. The latter may be natural. For example, in a *shelterwood* system a few old trees are left during the period of regeneration to provide seed and protect the young seedlings.
- Natural regeneration may continue for a few years after initial planting or seeding.
- Nevertheless, the basic management remains the same, it leads to a total harvest and a main crop when the stand has reached rotation age.
- Light cuts called “thinnings” are sometimes done in even-aged stands before the final harvest.

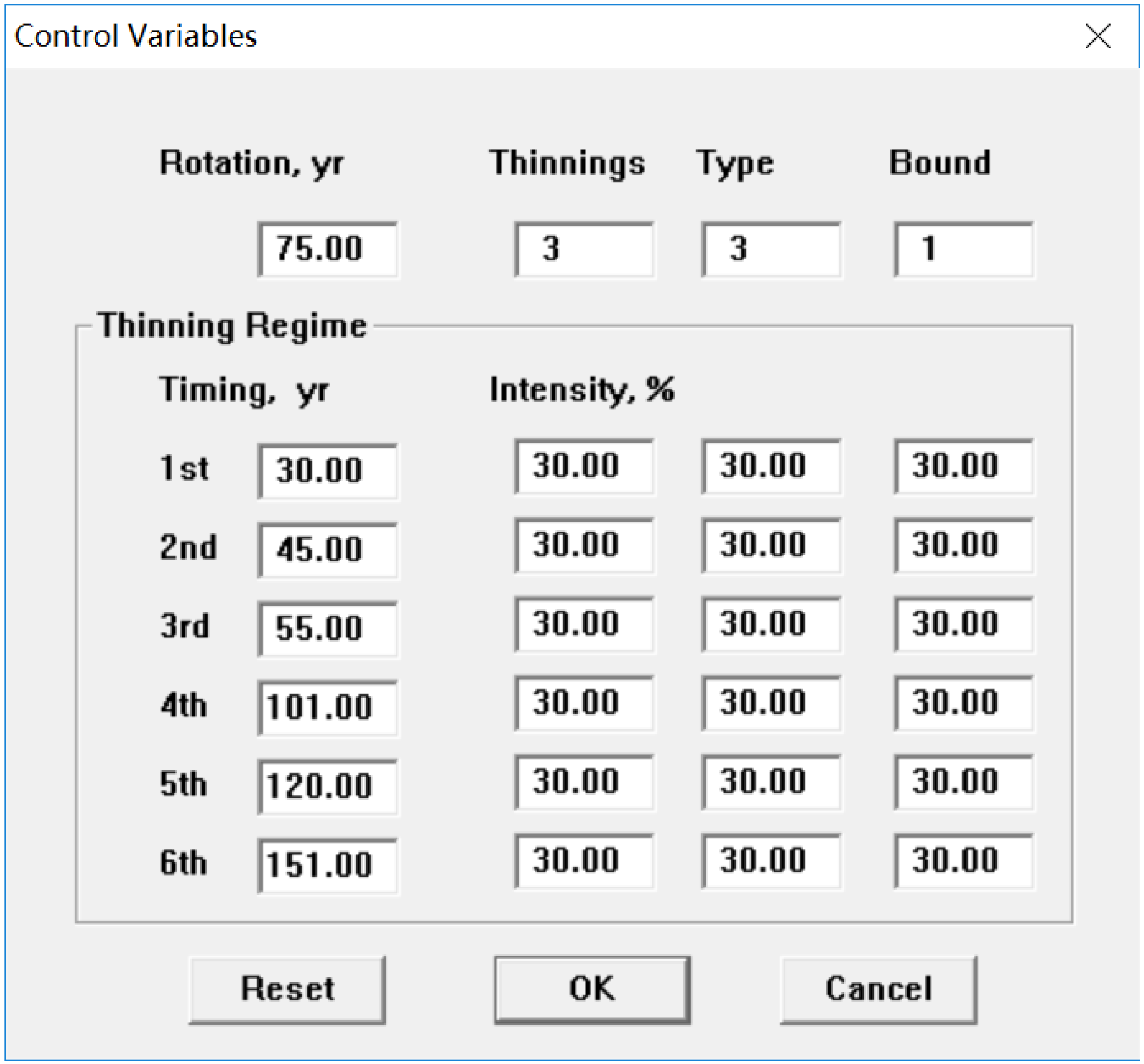
OptiFor demo

- A simulation-optimization tool for forest resources management
- Website: www.optifor.cn
- Documentation
- Student version
- Scientific version

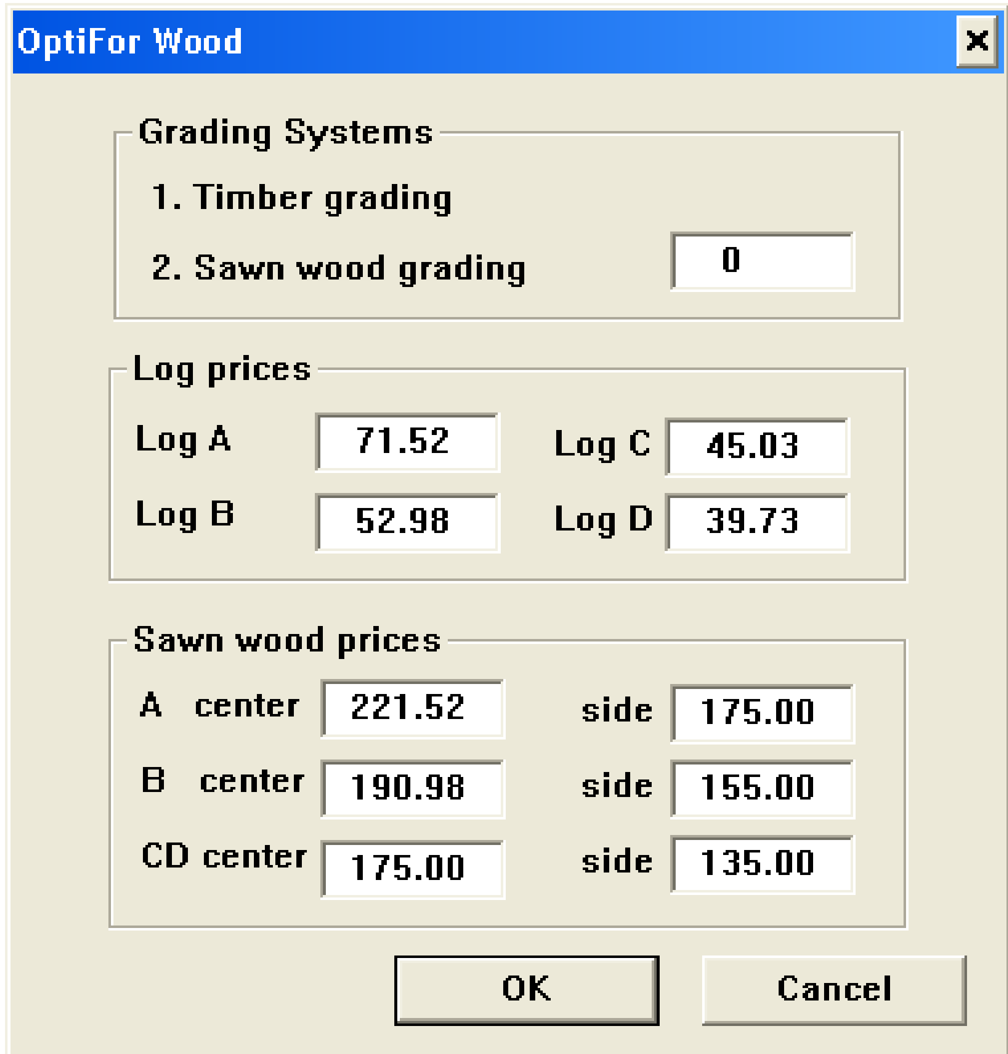
HJ algorithm parameters



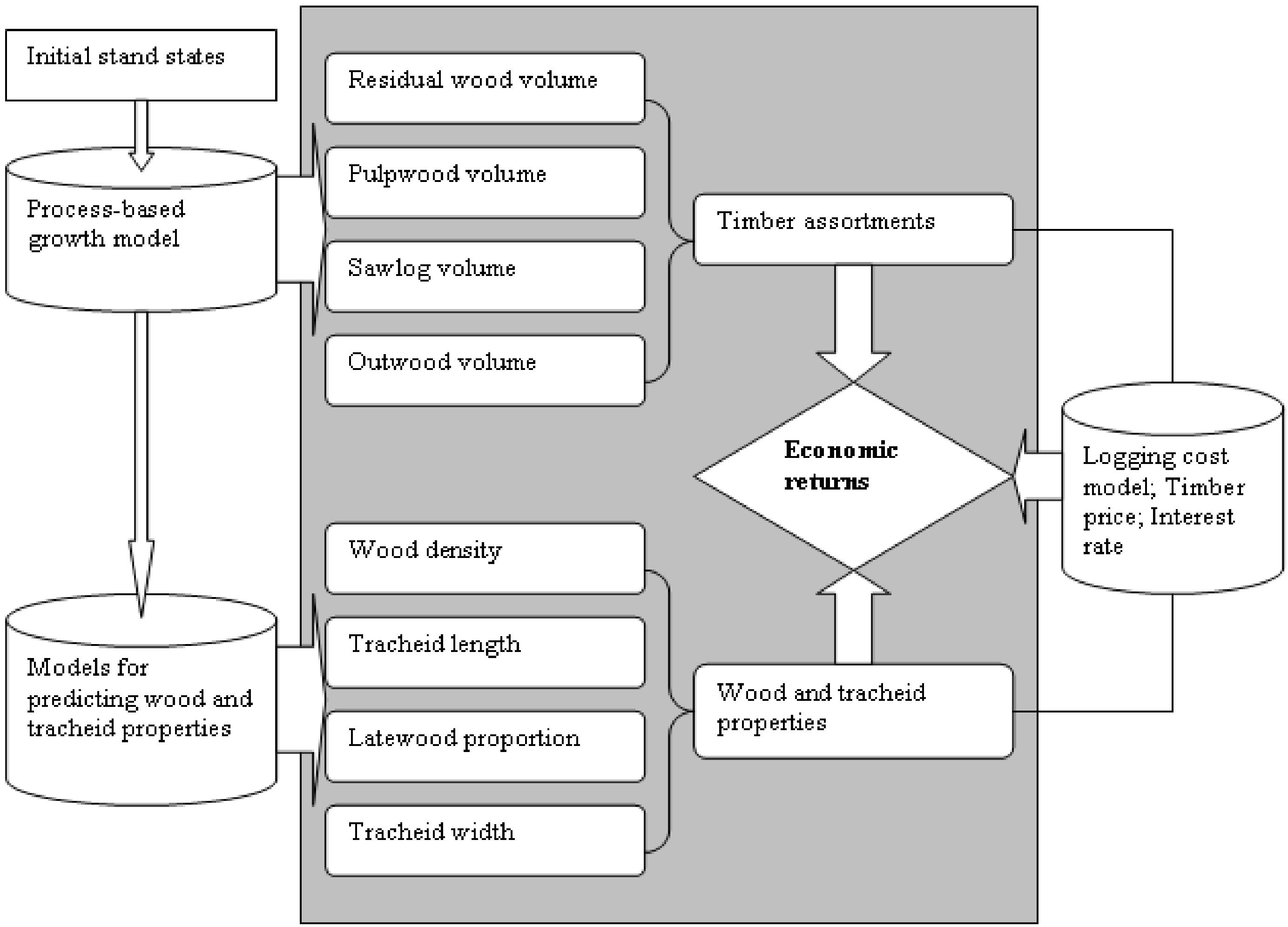
Harvest scheduling



OptiFor Wood



Cao et al. (2008)



Hurttala et al. (2017)

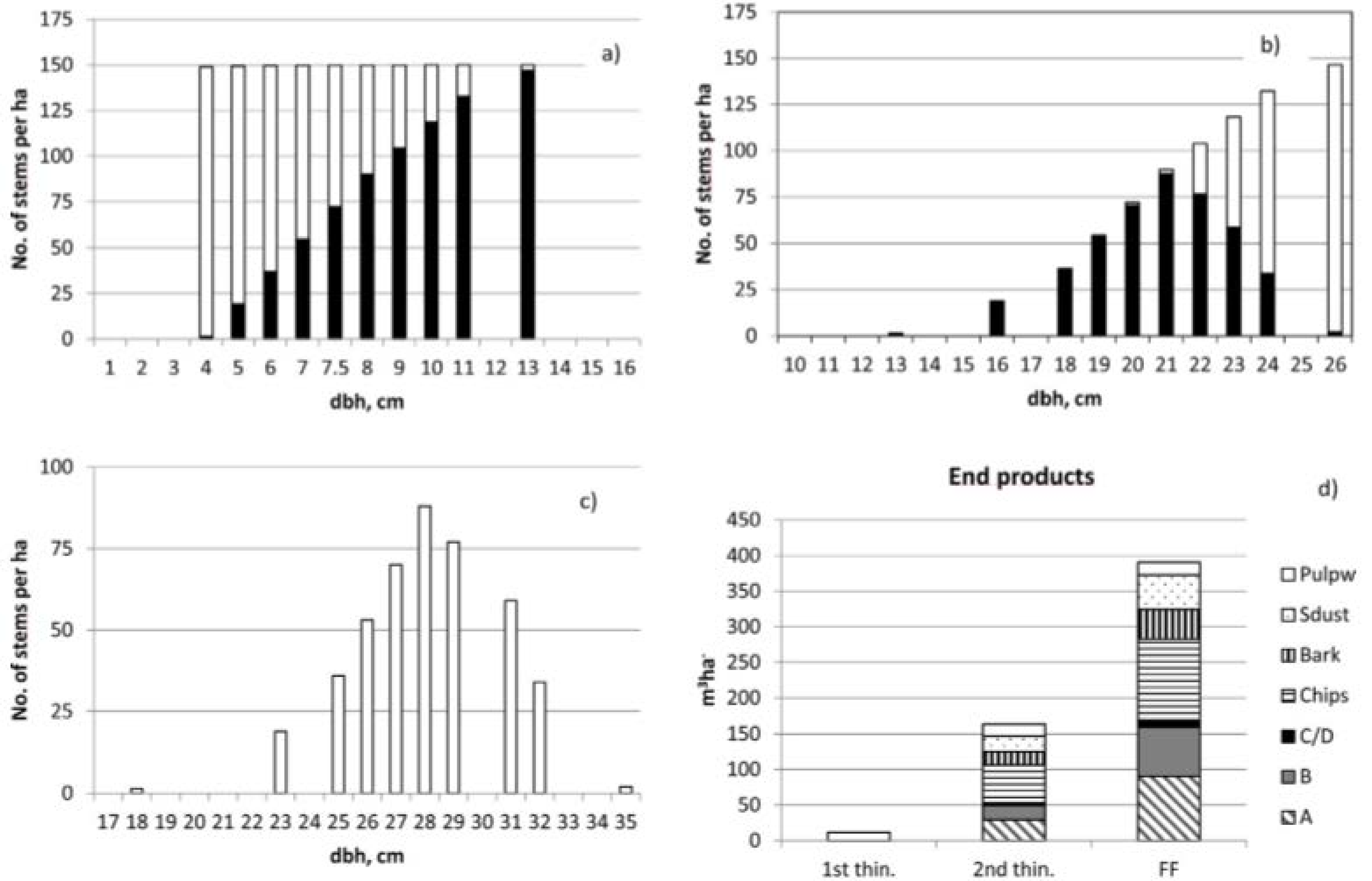
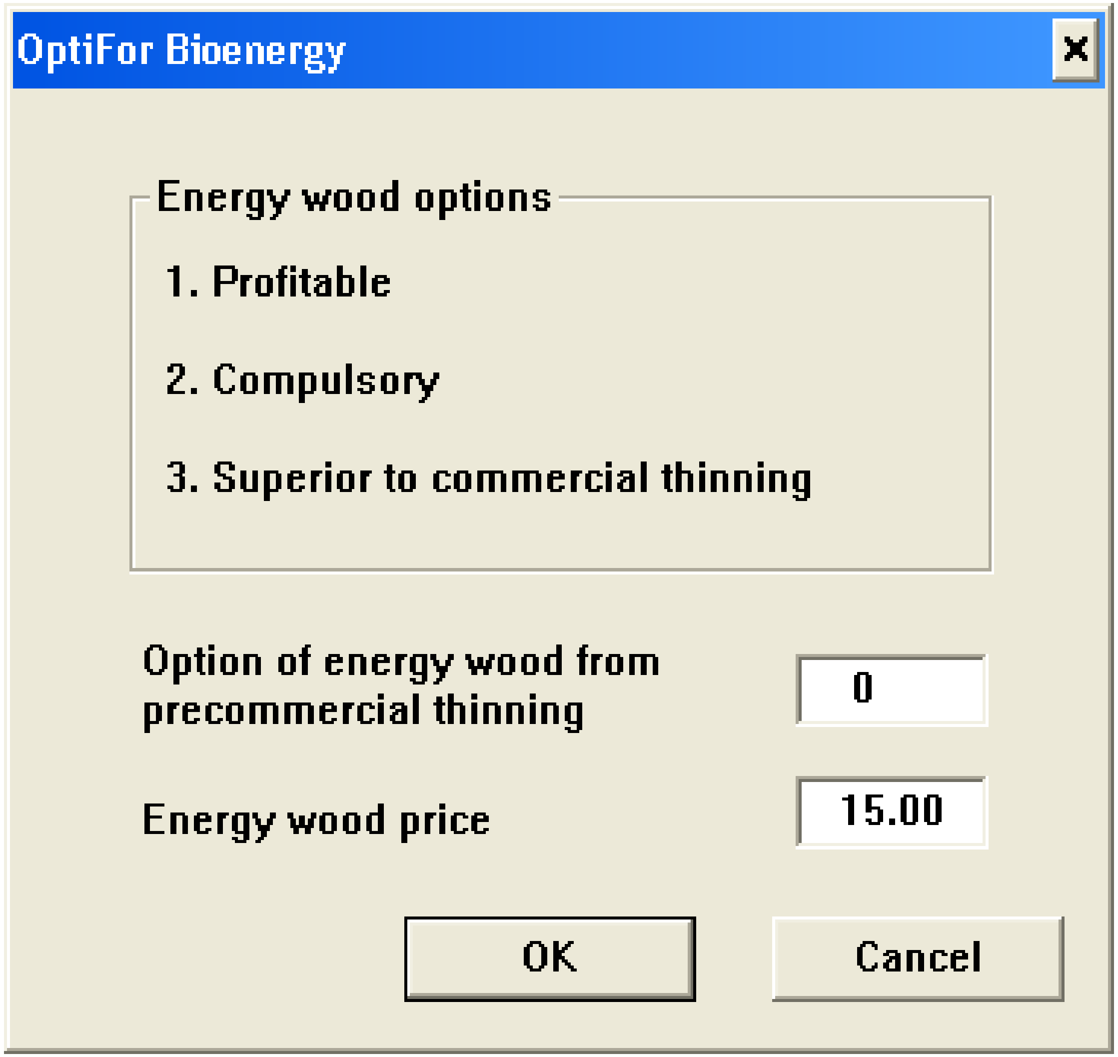


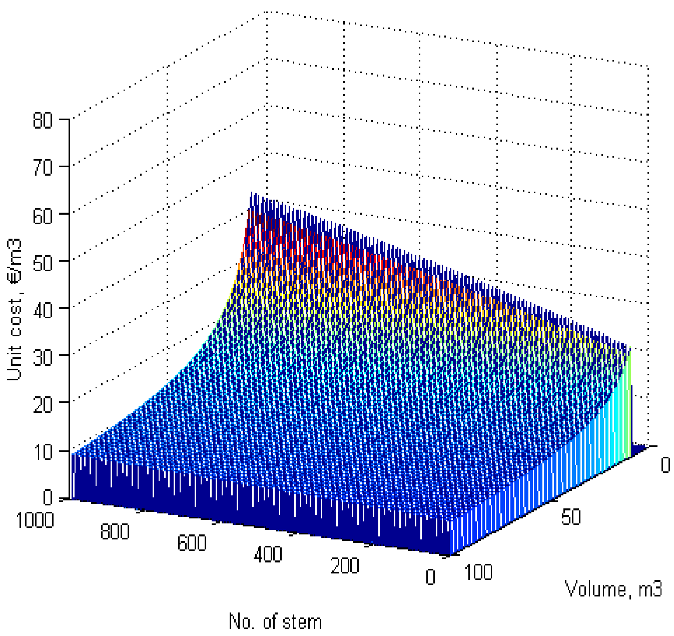
Fig. 4. Removals (open bars) in size classes (a–c) and yields of end products in thinnings and final felling in the QPC on MTS$_{1500}$ (d).

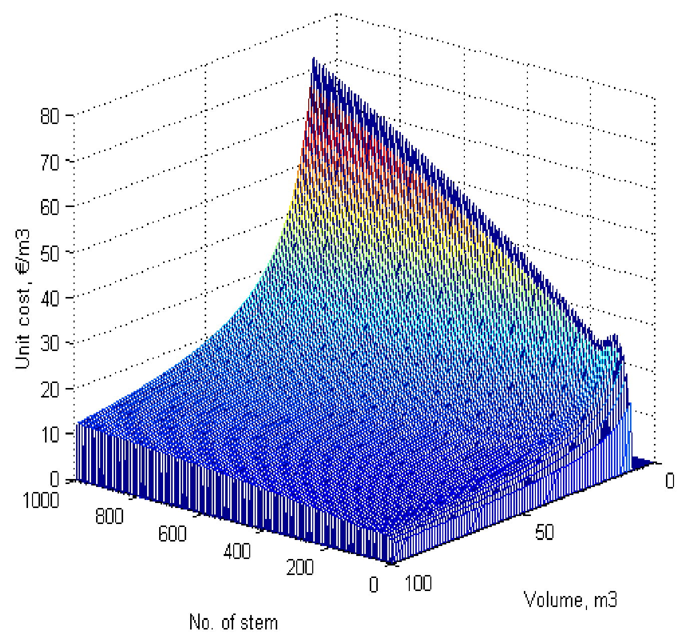
OptiFor Bioenergy



Cao et al. (2015)

- (a) Energy wood harvesting (b) Conventional thinning





森林风险管理 risk management

- Predicting biotic forest damages 森林病虫害的预测
- Predicting abiotic forest damages 森林火灾、旱灾、风灾和雪灾的预测
- Impacts of Climate Change 气候变化冲击
- Decision-making under risk 风险决策评价
- Decision-making under uncertainty 不确定性决策评价

Risk and Uncertainty in Forest Dynamics

Risk and uncertainty in forestry

- Economic risk and uncertainty
  - Timber prices and Interest rate
- Management risk and uncertainty
  - Human interventions
  - Natural disasters
  - Forest health

(Kangas and Kangas 2004, Lohmander 2007)

- Ecological stochastic processes
  - Competition and succession
  - Climate change impacts

Forest decision-support systems

- http://fp0804.emu.ee/wiki/index.php/Category:DSS
- EFISCEN
http://www.efi.int/portal/completed_projects/efiscen/
- FVS http://www.fs.fed.us/fmsc/fvs/
- MOTTI, SIMO, MONSU , SMA
http://www.metla.fi/metinfo/motti/index-en.htm
www.simo-project.org
http://fp0804.emu.ee/wiki/index.php/Monsu
http://www.helsinki.fi/forestsciences/research/projects/sma/programme/index.htm
- OptiFor
http://www.optifor.cn

Climate Change Impacts

- Long term impacts
  - Self-thinning
  - Forest dynamics
  - Tree specise migration

- Short term impacts
  - Forest wildfire
  - Insect outbreaks
  - Extreme wheather events

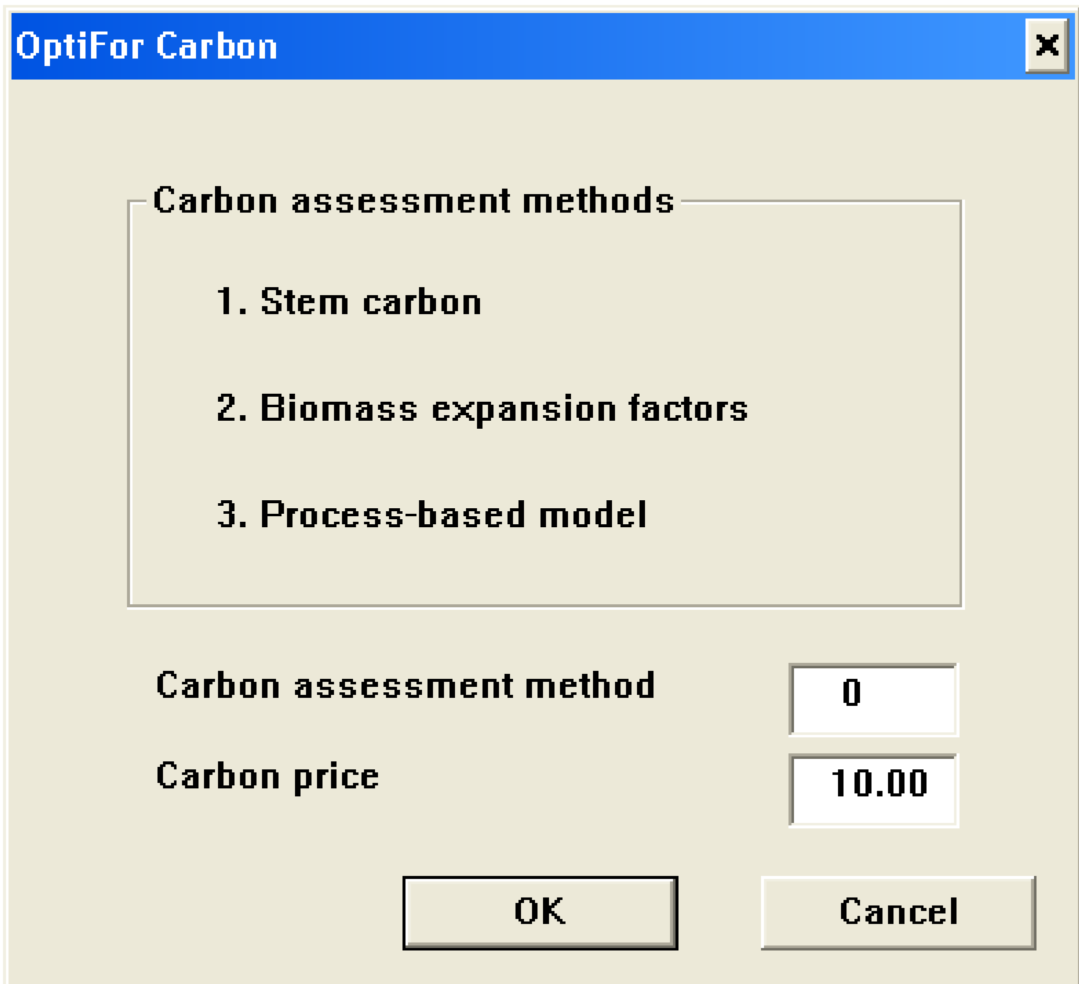
Climate-sensitive growth models

- The empirical approach
  - Climate variables (e.g. preci., temp.)

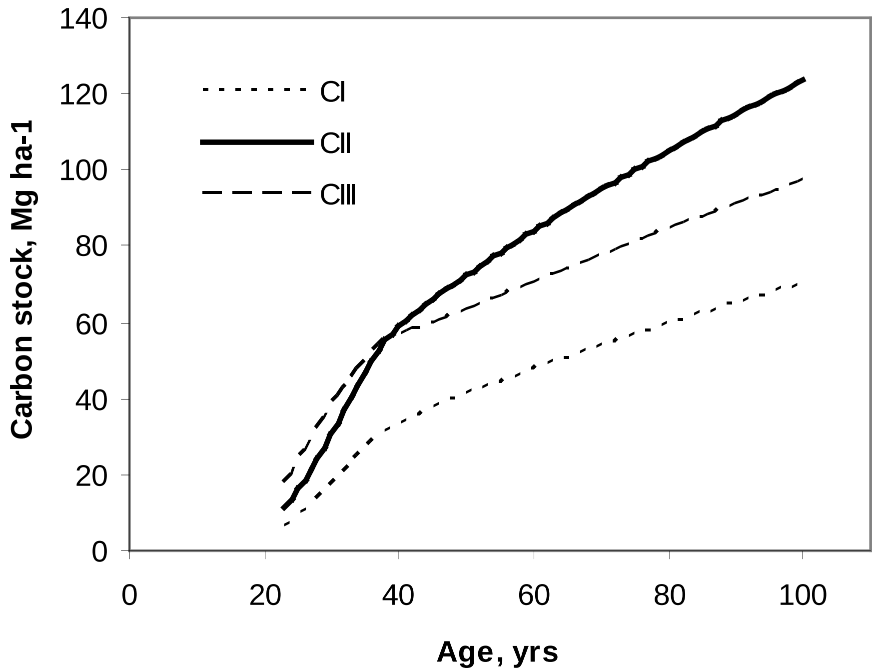
- The process-based approach
  - C, N, H_2O
  - LUE, NUE, WUE
  - GPP, NPP
  - Carbon allocation

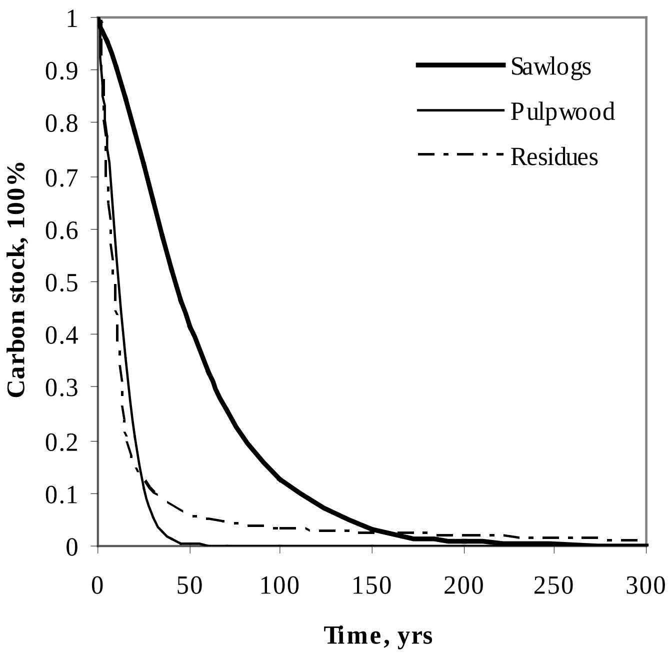
- The hybrid approach
  - semi-emprical
  - semi-process

OptiFor Carbon

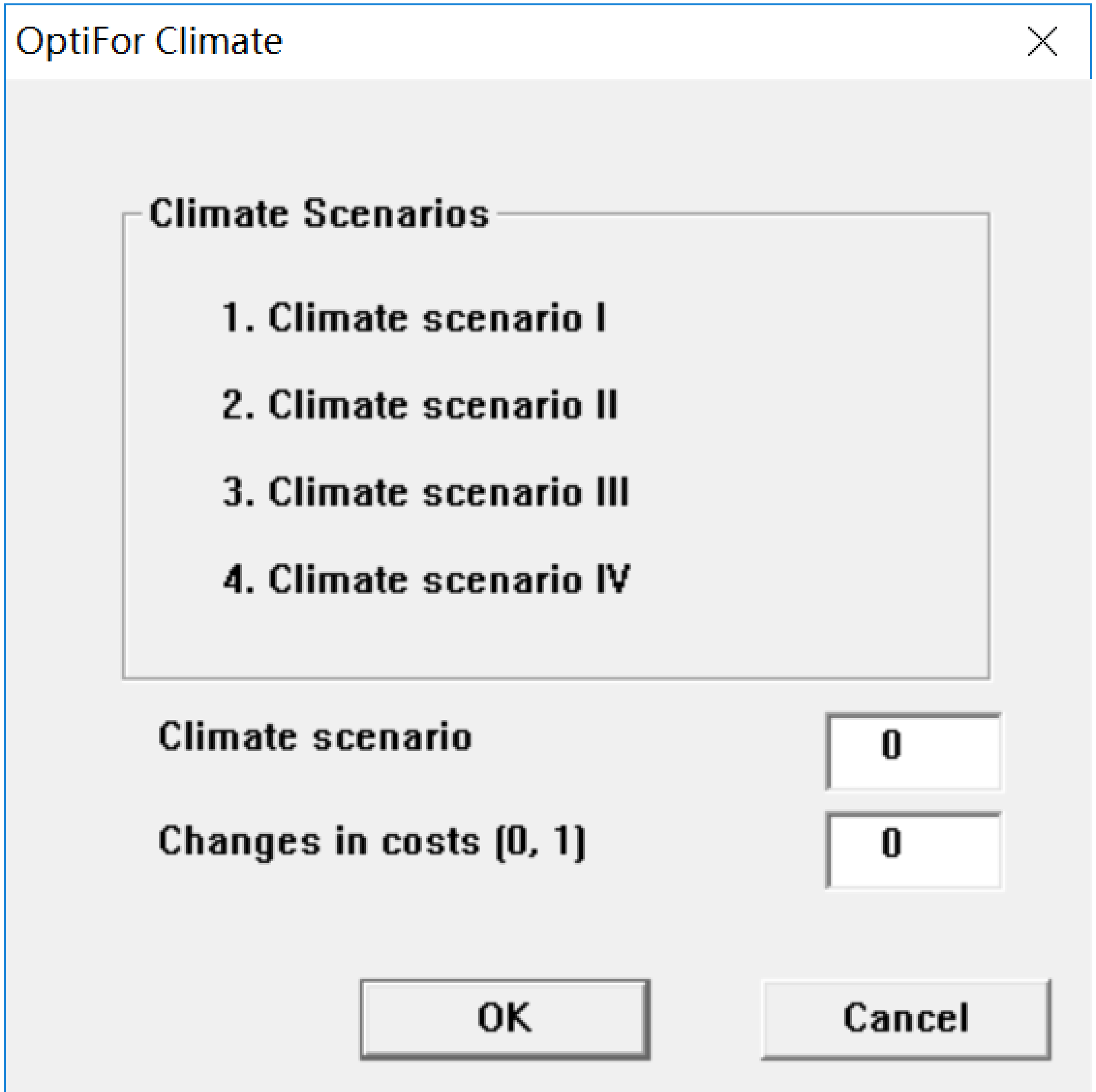


Cao et al. (2010)





OptiFor Climate



Climate-sensitive model 气候敏感性模型

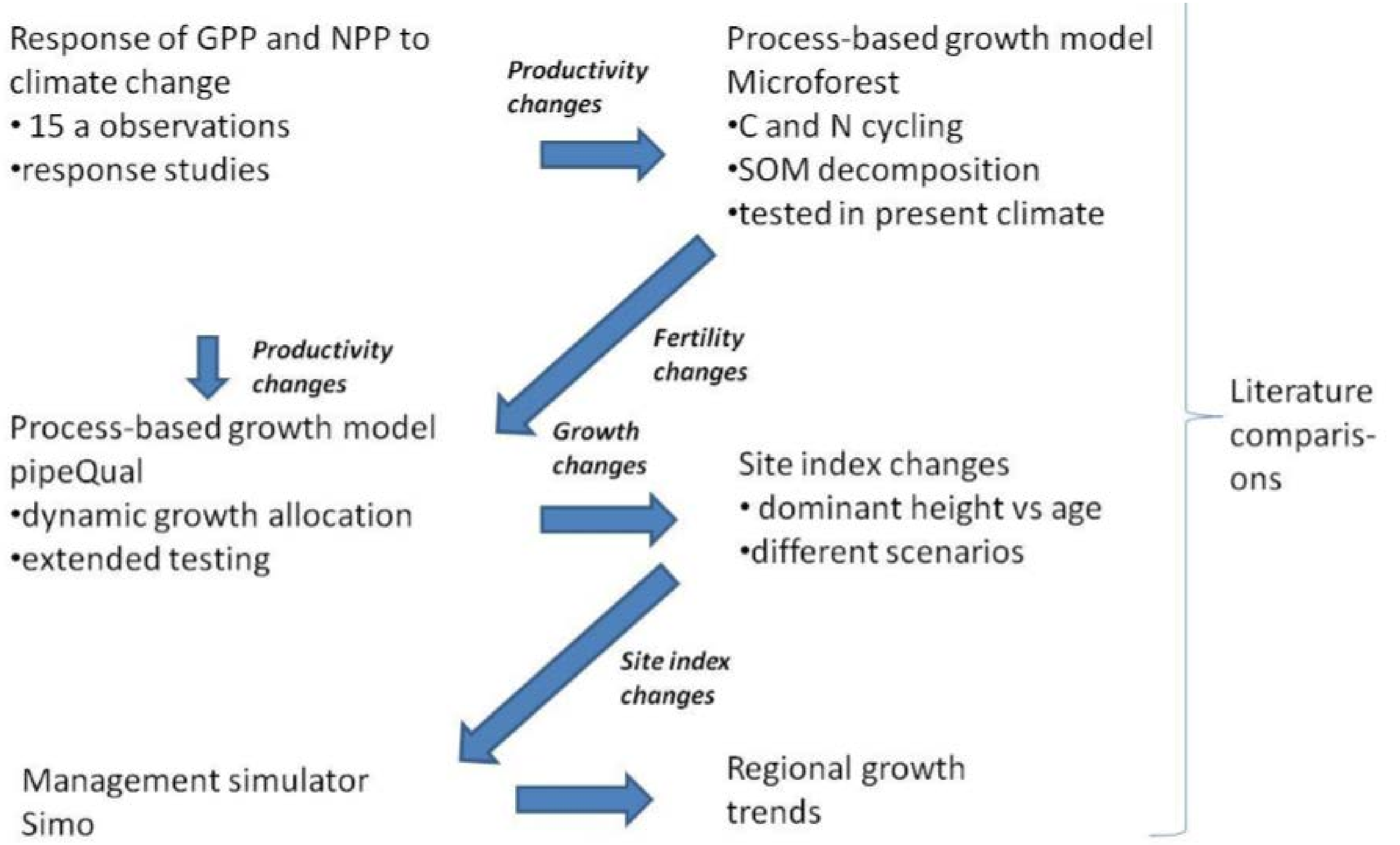
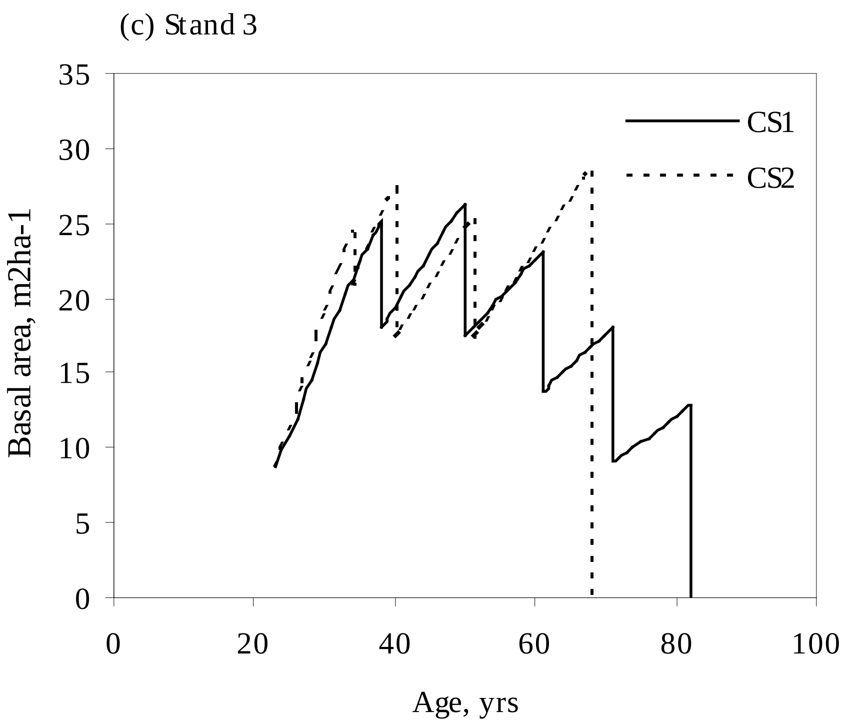
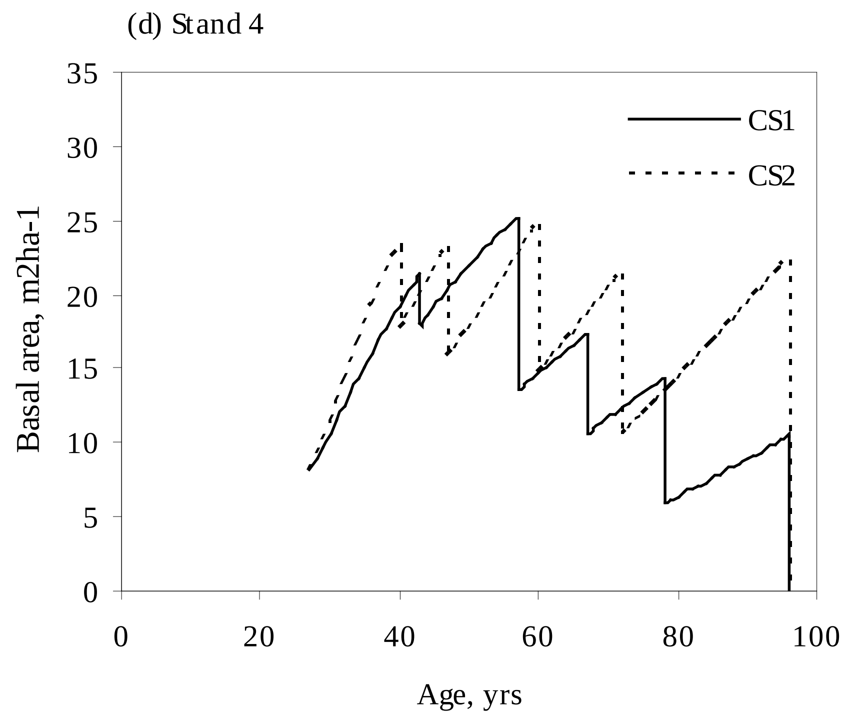


Figure 1. Schematic presentation of the used approach to analyze climate change impacts on forest productivity

Nikinmaa et al. (2011)





Insect outbreaks, the empirical approach

	D	H	A		Mortality of bettle effects						
	0.487	0.61598	0.56334		P_bettle (%) = 0.487*D+0.61598*H+0.56334*A						
SCI：	11		SDI：	400							
年龄(yr)	平均树高（m）	平均胸径（cm）	林分断面积（m^3/ha）	林分密度（株/ha）	平均单株材积（m^3/株）	林分蓄积量（m^3/ha）	平均生长量（m^3/ha）	连年生长量(m^3/ha)	蓄积生长率(%)	密度指数的不相容性	P_bettle (%)
20	8.6	12.8	9.70	754	0.0641	48.4	2.4			**322.06**	22.79455984
25	10.0	15.7	11.66	605	0.1074	65.0	2.6	3.3	5.9	**379.81**	27.85126212
30	11.0	17.9	13.18	522	0.1519	79.4	2.6	2.9	4.0	**423.95**	32.40449411
35	11.8	19.7	14.39	470	0.1947	91.6	2.6	2.4	2.9	**458.58**	36.59746694
40	12.4	21.2	15.37	435	0.2347	102.0	2.6	2.1	2.2	**486.4**	40.52790863
45	13.0	22.4	16.17	409	0.2714	111.0	2.5	1.8	1.7	**509.2**	44.26261708
50	13.4	23.5	16.85	389	0.3050	118.8	2.4	1.6	1.4	**528.21**	47.84811986
55	13.8	24.3	17.42	374	0.3356	125.5	2.3	1.4	1.1	**544.28**	51.31756712
60	14.1	25.1	17.91	362	0.3634	131.5	2.2	1.2	0.9	**558.06**	54.69510977
65	14.3	25.8	18.34	352	0.3888	136.7	2.1	1.1	0.8	**569.98**	57.99870946
70	14.6	26.3	18.71	343	0.4120	141.4	2.0	0.9	0.7	**580.4**	61.24197712
75	14.8	26.9	19.04	336	0.4332	145.6	1.9	0.8	0.6	**589.59**	64.43540194
80	15.0	27.3	19.34	330	0.4526	149.4	1.9	0.8	0.5	**597.75**	67.5871906

The Lotka-Volterra system (Pielou, 1969)

- Let x1 denote the population level of the prey, and let x2 denote the population level of the predator.

  $$dx_1/dt = (b_1 - c_1 x_2) x_1$$

  $$dx_2/dt = (-b_2 + c_2 x_1) x_2$$

- The parameter b1 denotes the normalized growth rate of the prey when the predator is not present (x2=0).
- b2 denotes the rate at which the predator population decreases in the absence of prey (x1=0)
- The term -c1x1x2 represents the decrease in the prey population as a resulte of the actions by the predator,
- the term c2x1x2 represents the increase in the predator population as a result of the availability of prey.
- The period of the cycle is: T = 2pi/b1b2

Modelling the spread of butt rot

- Möykkynen, T., Miina, J. & Pukkala, T., Von Weissennerg, K., 1998. Modelling the spread of butt rot in a *Picea abies* stand in Finland to evaluate the profitability of stump protection against *Heterobasidion annosum*. For. Ecol. Manage. 106, 247–257.

- Möykkynen, T., Miina, J. & Pukkala, T. 2000. Opimizing the Management of a *Picea abies* Stand Under Risk of Butt Rot. Forest Pathology 30: 65-76.

Predicting biotic forest damages

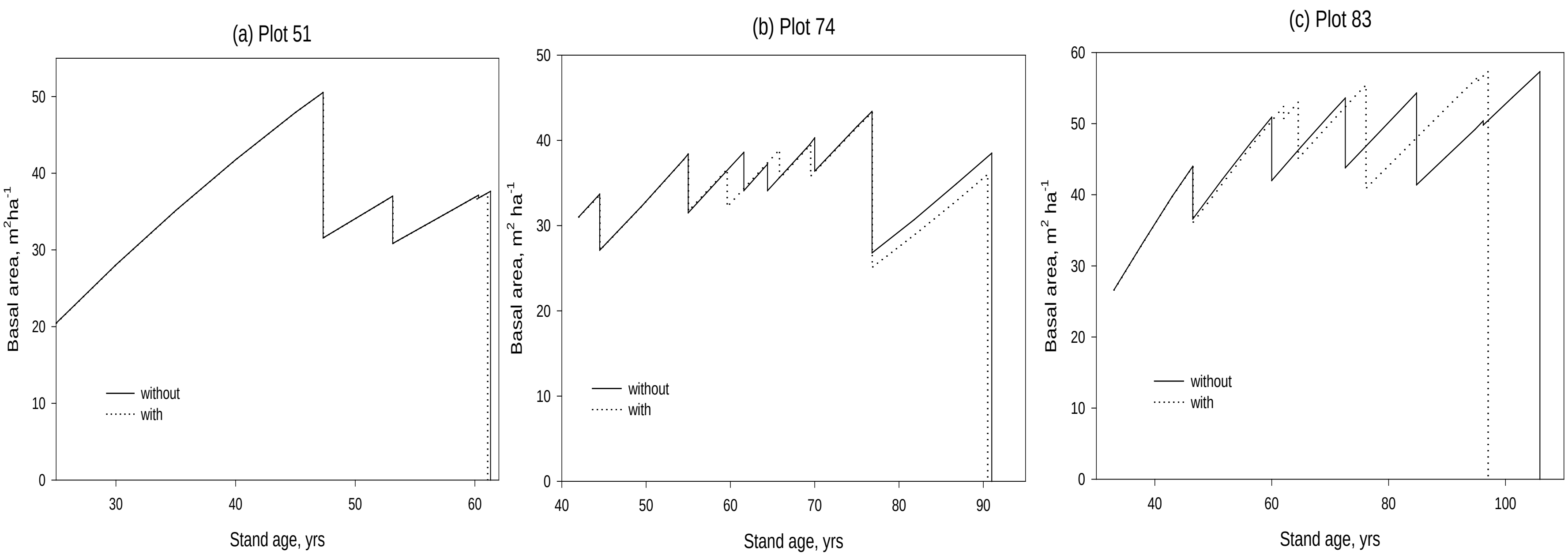
- mycelium originating from old-growth stumps may be viable for up to 60-120 yrs, and spread after felling of butt-rotted trees (Stenlid & Redfern 1998).
- Frequent summer thinnings without stump treatment are the most important operation increasing the proportion of trees with butt rot at the end of rotation (Swedjemark & Stenlid 1993, Venn & Solheim 1994, Vollbrecht & Agestam 1995).
- Cao, T., 2003. Optimal harvesting for even-aged Norway spruce using an individual-tree model. Finnish Forest Research Institute, Research Papers 897. 44 pp. ISBN 951-40-1886-9, ISSN 0358-4283.

Stand Management Under Risk of Butt Rot

- A simulation model was developed to predict the growth of a Norway spruce stand under risk of butt rot caused by *Heterobasidion annosum* stump infection and logging injuries.

- The simulation model was distance-dependent.
- The spread of butt rot through root contacts depended on tree location. Infection of stumps and injured trees,
- The spread of butt rot in the stand were stochastic processes whereas tree growth and mortality were treated as deterministic processes.

With and without butt rot effects (Cao 2003)



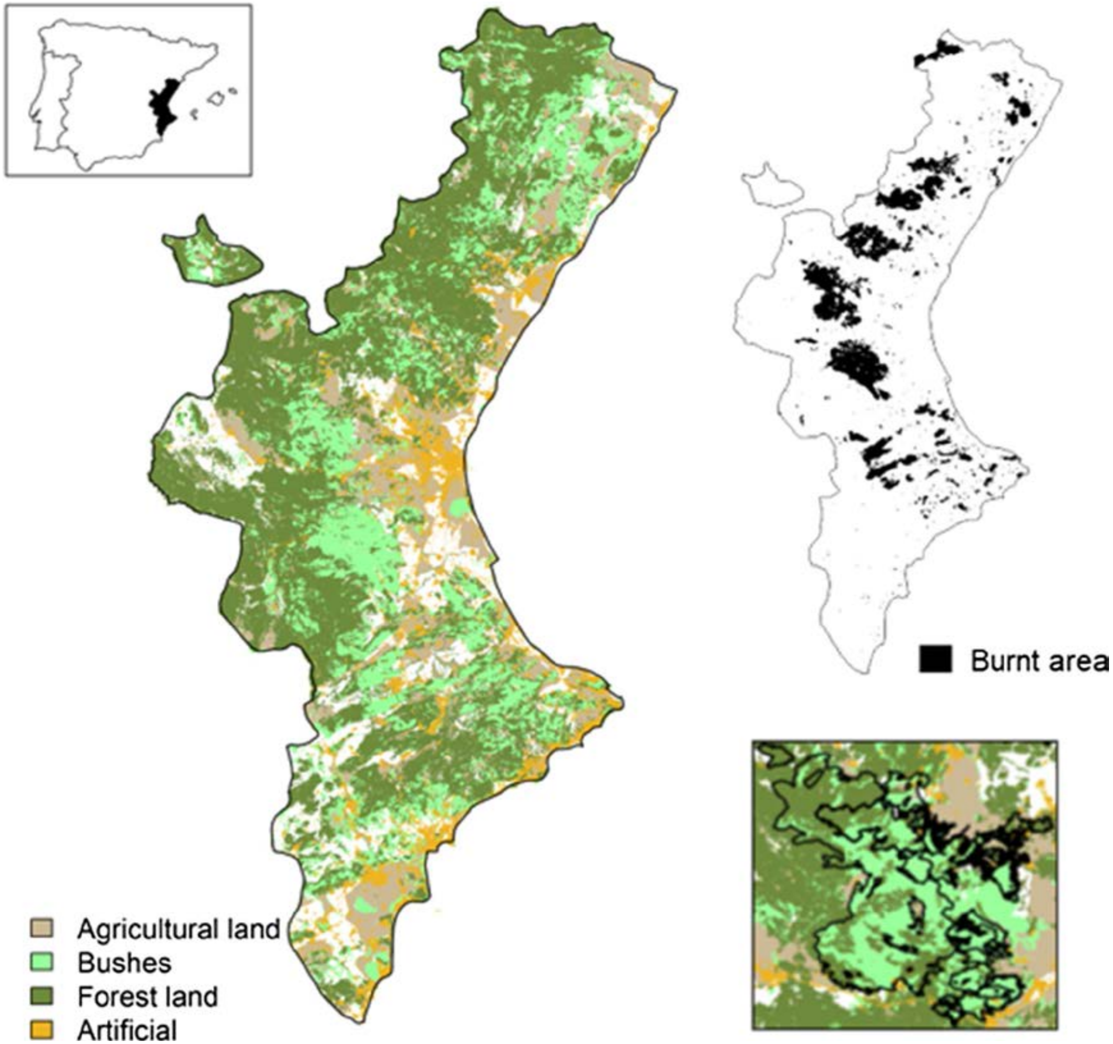
Simulation of spread of butt rot

- The progress of decay in the root system was 30 cm per year (ISOMÄKI and KALLIO 1974; STENLID 1987; SWEDJEMARK and STENLID 1993).

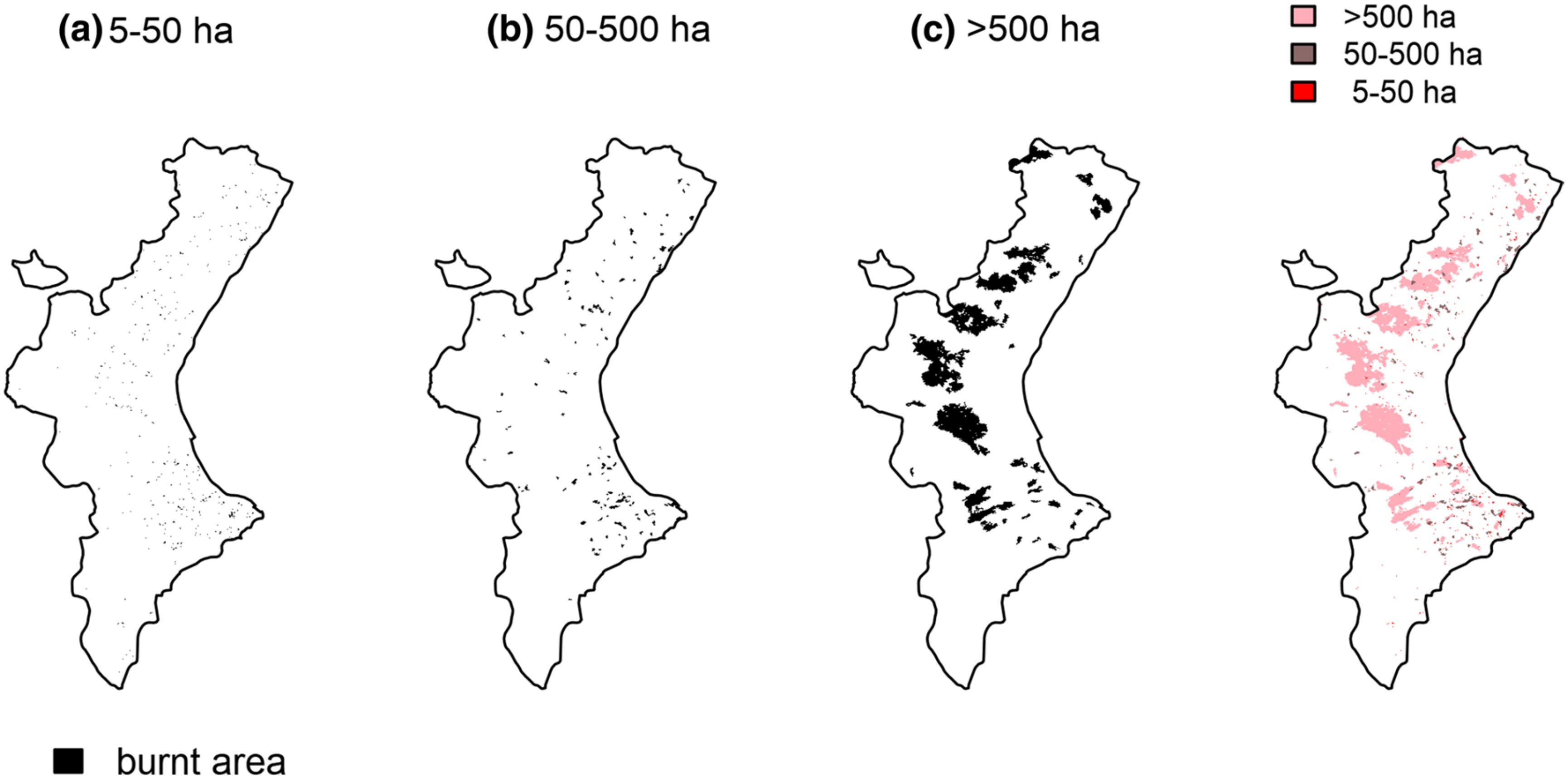
- $h_{rot} = 4.78 * t_d^{0.5} + 1.59 * t_d^{0.5} * d_d$
- $d_{rot} = 0.05 * h_{rot}$

- For example, a tree infected 10 years ago with d.b.h. of 2 dm has a decay cone which is 25.2dm high with a diameter of 1.26dm at the stump level.

Fire occurrence in Mediterranean forests

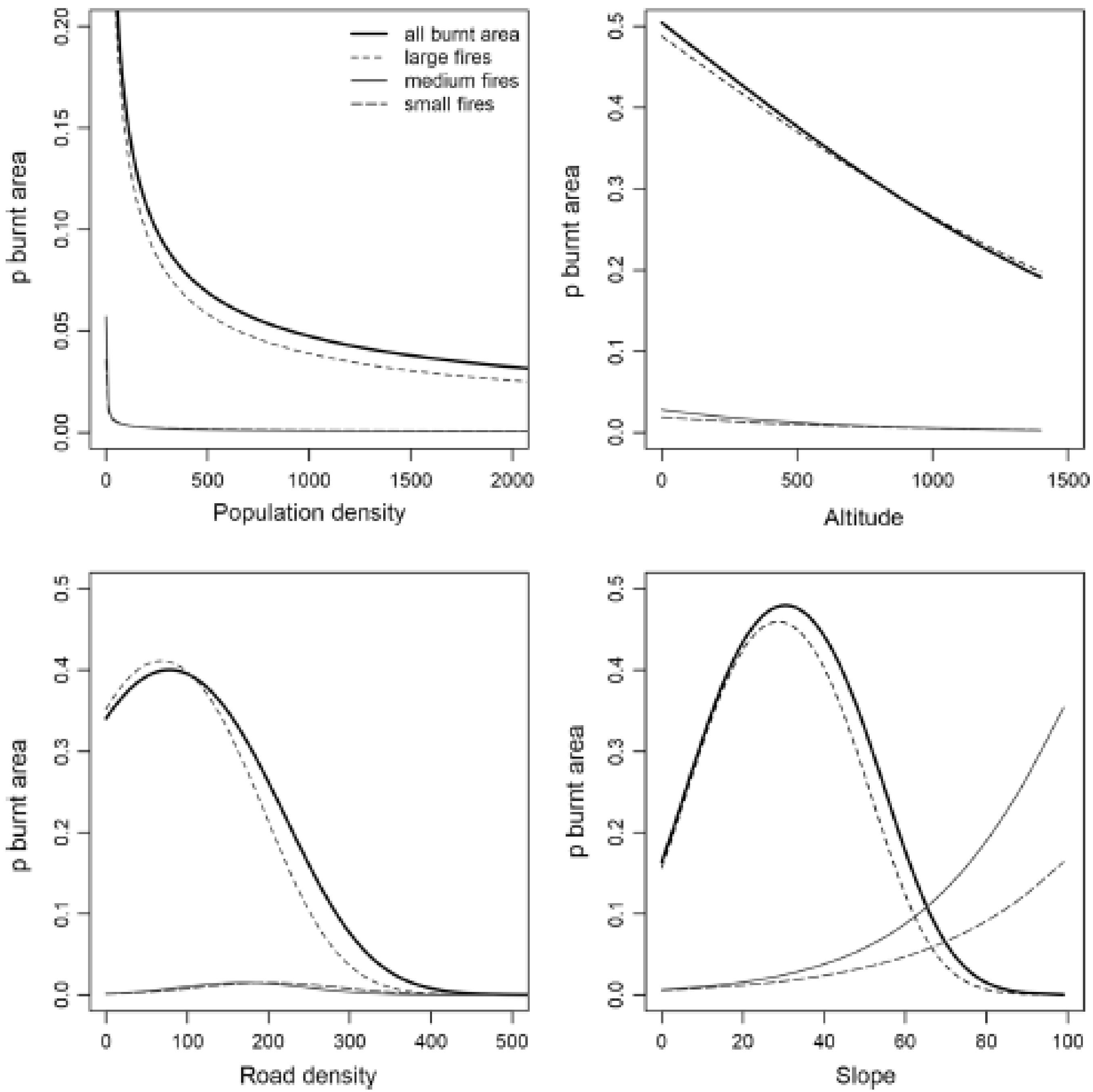


Burnt areas in Eastern Spain (1993-2015)



Variables of fire events

Fire size (ha)	5–50	50–500	> 500
N	585	146	59
	5.45%[a]	1.36%[a]	0.55%[a]
Burnt forest surface (ha)	7968.08	23,247.46	248,653.9
	2.7%[b]	8.1%[b]	87.2%[b]
Mean burnt surface (ha)	13.62 (0.42)	159.22 (8.64)	4214.47 (835.09)
Forest formation	*P. halepensis*	*P. halepensis*	*P. halepensis*
	22.26%[b]	21.53%[b]	24.25%[b]
Fuel type	Low vegetation cover	Bushes/small trees	Bushes/small trees
	44.9%[c]	41.01%[c]	48.74%[c]
Fire type	Surface	Surface	Surface, surface and crowns
Mean relative humidity (%)	41.17 (1.05)	40.12 (1.95)	33.98 (2.92)
Mean max temperature (°C)	15.21 (0.40)	16.53 (0.86)	21.03 (1.49)
Altitude (m)	414.67 (12.31)	471.14 (22.21)	617 (32.25)
Slope (%)	16.93 (0.51)	20.38 (1.2)	16.84 (1.38)
Population density (hab km^{-2})	37.44 (13.21)	20.75 (11.03)	9.2 (5.55)

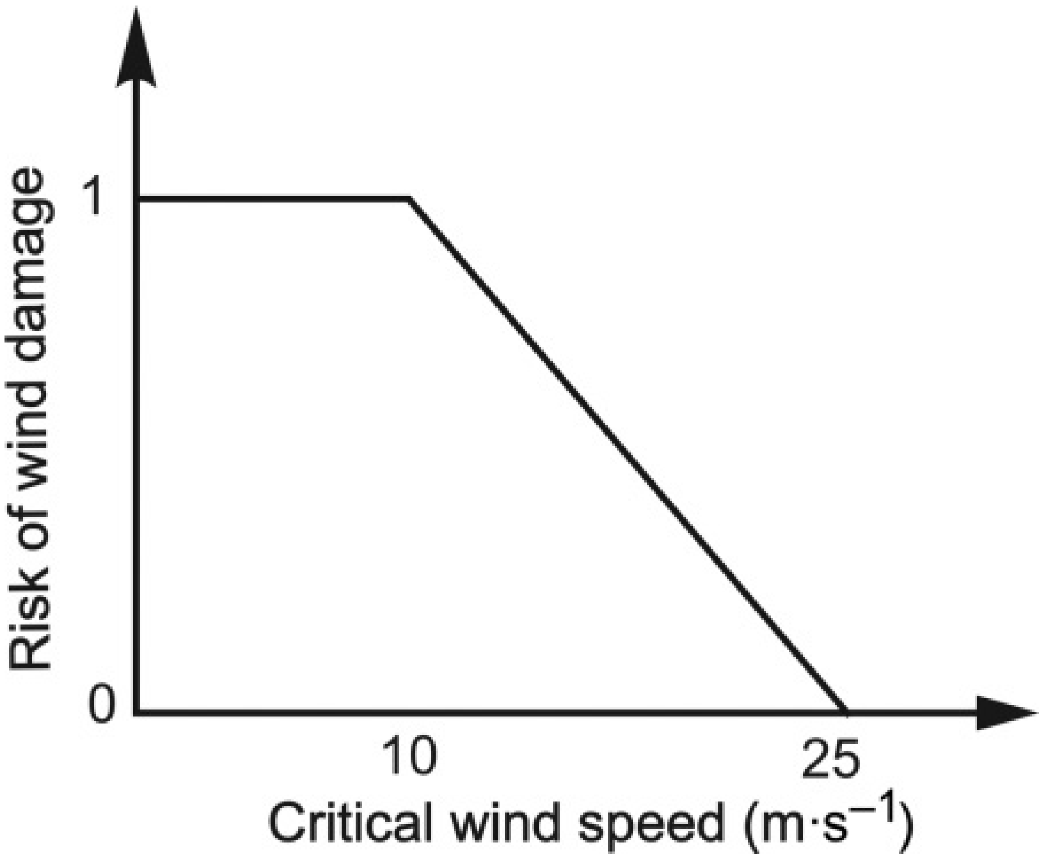


all burnt area
large fires
medium fires
small fires
p burnt area
Population density
Altitude
Road density
Slope
0.00
0.05
0.10
0.15
0.20
0.0
0.1
0.2
0.3
0.4
0.5
0
500
1000
1500
2000
100
200
300
400
20
40
60
80

The mechanistic wind damage model HWIND

- The threshold wind speed (critical wind speeds at canopy top) lasting 10 min at which trees will be uprooted and/or broken at upwind stand edge. (Peltola et al., 1999)
- In the model, the mean wind profile at upwind stand edge is represented by a logarithmic function.
- A tree is asssumed to be uprooted if the maximum bending moment (due to forces by wind and gravity) exceeds the resistance of the root–soil plate.
- The stem is assumed to be broken if the breaking stress exceeds the critical value of the modulus of rupture (Petty and Swain, 1985; Peltola et al., 1999).

Risk utility function (Zeng et al. 2010)



Risk management

- This is one of the most important topics on investment analysis - and perhaps one of the most frustrating, because the guidelines are so fuzzy.
- The essence or risk and uncertainty is that we don't know some things for sure.
- So while we yearn for precise decision guides, equations, and computer programs to tell us to the nearest penny the value of forestry alternatives, that's not the nature of the world,especially with forestry's long payoff periods.

Decision makers

- Decision makers categories
  - risk averse,
  - risk neutral
  - risk preferring.
- Maximizing expected value
  - risk neutraler
- Maximizing the maximum value (Maxmax)
  - extreme risk lover
- Maximizing the minimum value (Maxmin)
  - extreme risk averter

Decision-making under risks

- Production risk
  - Silvicultural operations
  - Biotic and Abiotic risks
- Price risk
  - Timber market
  - Financial market
  - Long-term investment
- Institutional risk
  - Common forestry policy
- Risk and insurance
  - Forest fire insurance

Risk analysis

- The degree of risk in a revenue is the amount of variation in its possible outcomes. A risk-free return has no variation.
- The expected value of any risky variable is the sum of the possible values multiplied by their probabilities of occurrence.
- Most people are risk-averse: they prefer less variation in revenues.
- The certainty-equivalent of a risky revenue is a sure dollar amount giving the investor the same satisfaction as the risky revenue.

Risk analysis, con't

- For a risk-averse person, the certainty-equivalent of a risky revenue will be less than its expected value.
- Risk-free revenues and certainty-equivalents should be discounted with a risk-free interest rate to arrive at the correct present value.
- The correct present value of a risky revenue is its expected value discounted with a risk-adjusted discount rate (RADR). For a risk-averse investor, this RADR exceeds the risk-free discount rate.
- Make sure you're discounting expected values, not optimistic values.

Trends in Forest modelling

- Model development

  Static: 树高-胸径公式、削度方程、一元/二元材积表、生物量公式

  H-D, taper curve, volume, biomass equations

  Dynamic: 生长模型、林窗模型、结构功能模型、过程模型

  growth and yield, succession, structure-function, process models,

  可视化 visulization，决策系统 decision-making systems

- Model applications

  APPs: 优化间伐、木材质量、生物质能源、森林火灾、气候变化

  thinnings, wood quality, bioenergy, forest fire, climate change

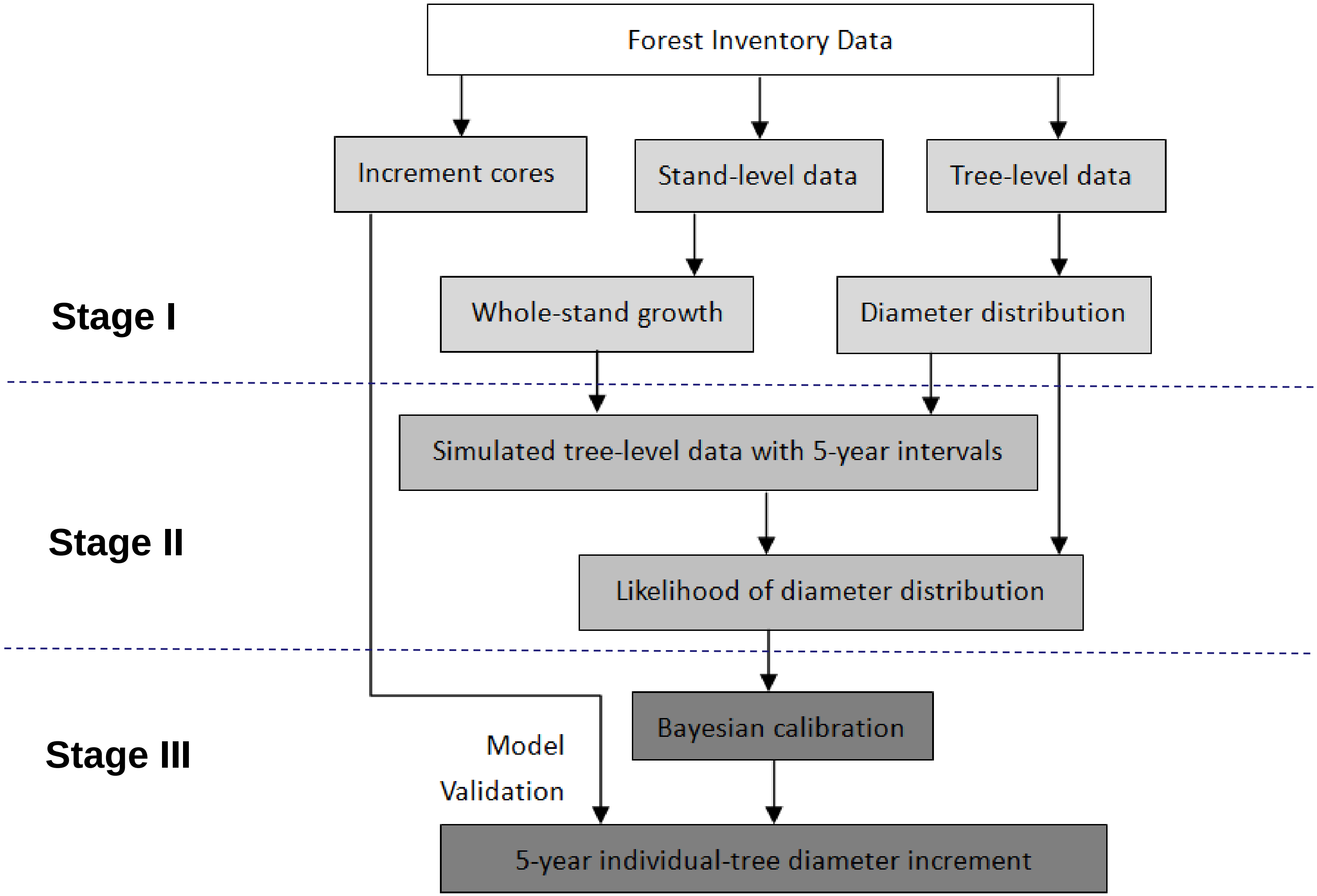
  DSSs: 单木水平、径阶水平、林分水平、森林水平、区域水平

  single-tree, size-class, stand, forest, regional, and global level

方法创新 Methodolgoy development

- 传统统计学 Fitting to curve
- 非参数方法 ANN, RF, SVM
- 贝叶斯统计 Bayesian networks
- 运筹学技术 Reliability optimization
- 人工智能技术 Artificial intelligence

方法创新：三阶段建模法


Forest Inventory Data
Increment cores
Stand-level data
Tree-level data
Stage I
Whole-stand growth
Diameter distribution
Simulated tree-level data with 5-year intervals
Stage II
Likelihood of diameter distribution
Bayesian calibration
Stage III
Model
Validation
5-year individual-tree diameter increment

理论创新 Theory development

- 自动控制论 Automation control theory
  - Open-loop control => Closed-loop control
- 工程控制论 Engineering cybernetics
  - Simulation system => Parallel system
- 复杂系统理论 Complex system theory
  - Dynamics system => Complex system

理论创新：复杂森林系统理论

Forests as complex systems

- Complexity of tree physiology
- Complexity of stand structure
- Complexity of forest models

The theory of complex forest systems

- The theory of complexity
- The theory of importance
- The theory of reliability

Methodologies

- A three-stage modeling approach
- Parallel simulation and optimization

Complex systems 复杂系统理论

Examples (Mitchell 2009)

- Biological systems
- Social systems
- Physical systems

Properties (Boccara 2004, Mitchell 2009)

- Heterogeneity, hierarchy, self-organization, openness, adaptation, memory, non-linearity, and uncertainty

Features (Wang and Kang 2012)

- Global behavior can not be deduced from that of their components;
- Global behavior can not be predicted in long term

复杂性科学体系 Science of complexity

- 系统工程 =〉 系统科学 =〉 复杂系统
- 从定量到定性的综合集成法 Meta synthesis
- Complexity: variables => structure/layers => flow

- Santa Fe Institute, SFI. 1984. Science of complexity.
- 钱学森, 于景元, 戴汝为 1990. 一个科学新领域--开放的复杂巨系统及其方法论. 自然杂志 13(1): 3-10.
- Filotas, E. Parrott, L., Burton, P.J. et al. 2014. Viewing forests through the lens of complex systems science. Ecosphere. Volume 5(1):1-23.

Social-Economic-Natural Ecosystems

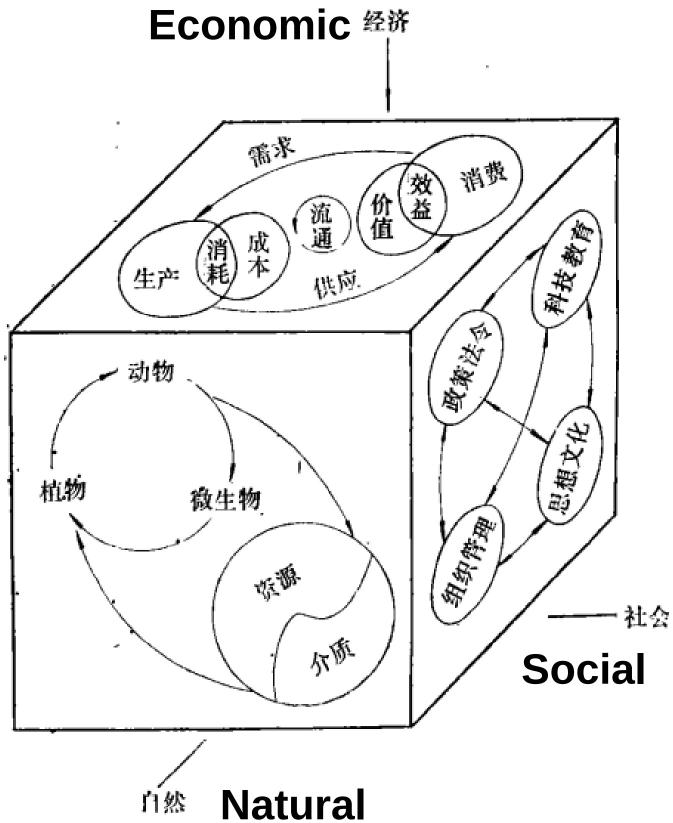
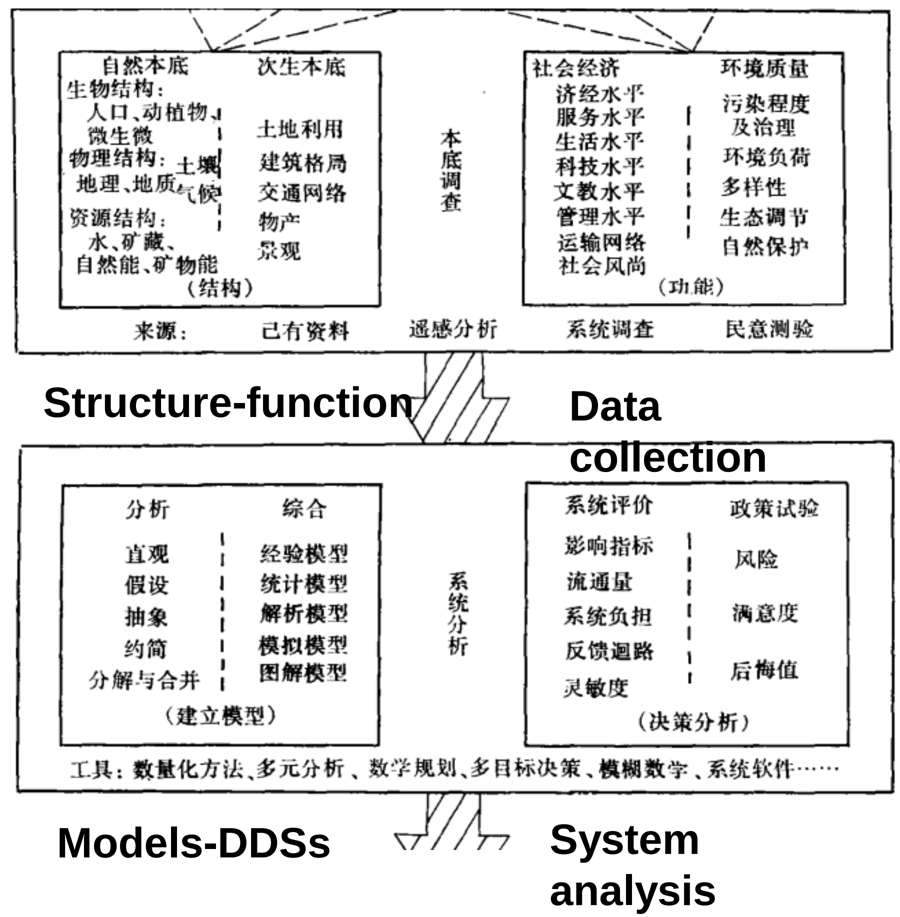
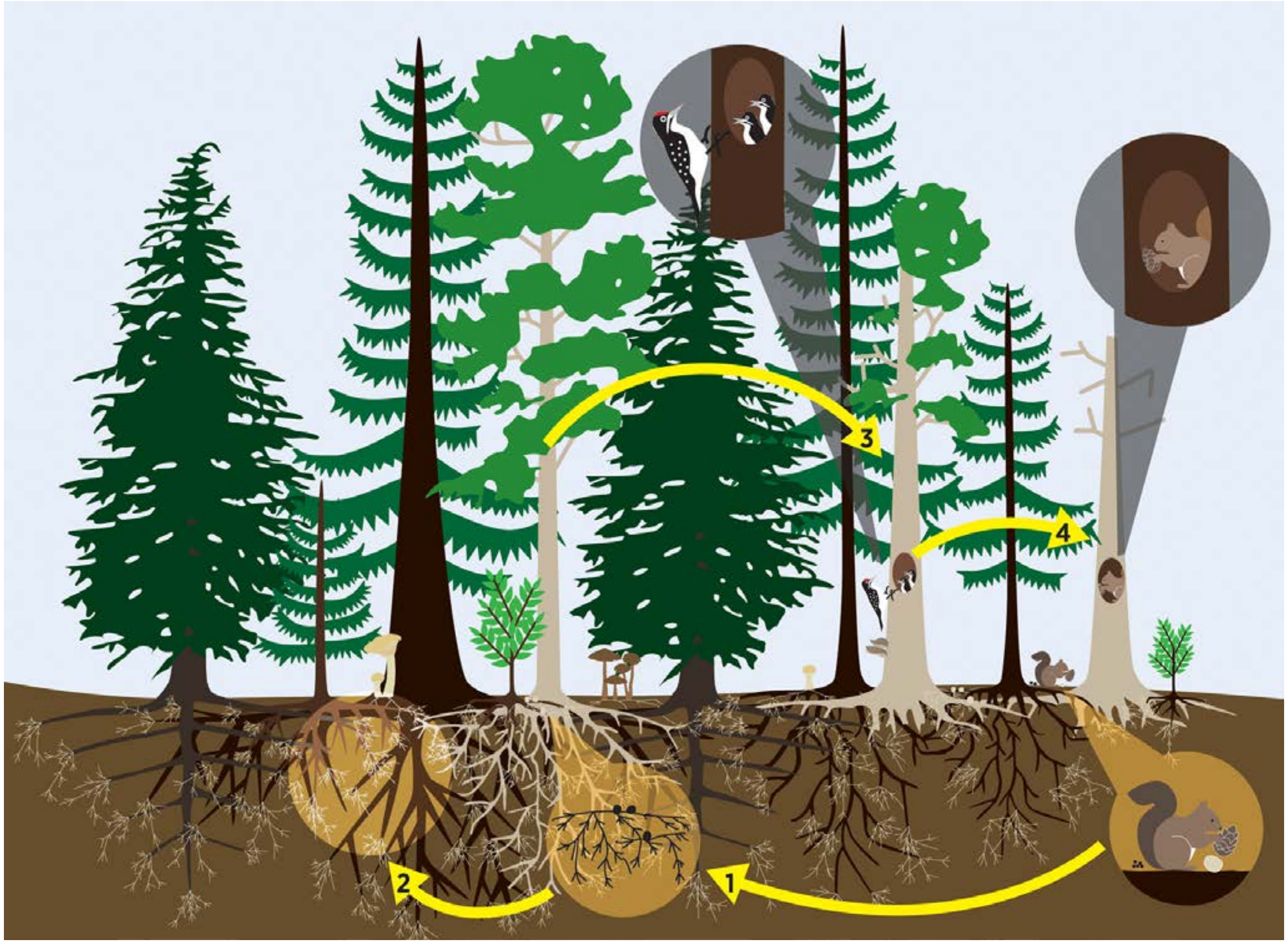


图 1　社会-经济-自然复合生态系统示意图



Source: 马世俊, 王如松 1984. 社会-经济-自然复合生态系统. 生态学报. 第4卷, 第1期. 1-9页.

A self-organizing meta-network



Source: Filotas et al. (2014)

Structure-functional complexity

Forrester (2017)

- Changes in stand structure and APAR
- Changes in LUE and C partitioning
- The influence of stand density on WUE

Seidel et al. (2019)

- Tree-level vs. Stand-level structural complexity
- Tree architecture and forest structure
- Large-crowned, highly-complex tree individuals as key elements of stand structural complexity

森林复杂系统 Complex forest systems

Complex forest systems are characterized by

- (1) heterogeneity,
- (2) self-organization,
- (3) adaptation,
- (4) hierarchy,
- (5) non-linearity
- (6) openness,
- (7) memory,
- (8) uncertainty.

(1) Complexity

(2) Importance

(3) Reliability

Complexity scales and methodologies

Low complex 小系统

e.g. whole-stand models, 3-5 variables

- Dynamic programming
- Model linkages

Medium complex 大系统

e.g. process models, 30-50 variables

- Non-linear programming
- Bayesian networks

High complex 巨系统

e.g. transportation systems, 1000-10000+ variables

- ACP methodology
- Complex ecological networks

Applications of Bayesian networks

Aspen regeneration

- Hass TC, 1991. A Bayesian belief network advisory system for aspen regeneration. Forest Science, 37(2):627-654.
- Hass TC, Mowrer HT, Shepped WD,1994. Modeling aspen stand growth with a temporal Bayes network. AI Applications, 8(1):15-28.

District ranger decision making

- Hass TC, 1992. A Bayesian network of district ranger decision making. AI Applications, 6(3):72-88.

Regeneration with a Bayes network

Nontemporal variables (unaffected by time)

- Temperature Range,
- Soil Moisture, Soil Type, SMT Index,
- Management Activity,
- Undergrowth Type, and Year-2 Stem Density.

Temporal variables (time dependent)

- Crown cover, CCC, light availability, and ungulate density at time t, 0-12 yrs.
- Snow, wind damage, insect attacks, and disease at t, 2-12 yrs.
- The fraction of stem survives the time period for t, 4-12 yrs.

Empirical parameters 经验模型参数校正

Hynynen et al. (2002)

- Routine inventory data
- Updating empirical growth models

模型校正步骤如下：

(1) 计算Bias=ln(H)-ln(H*),

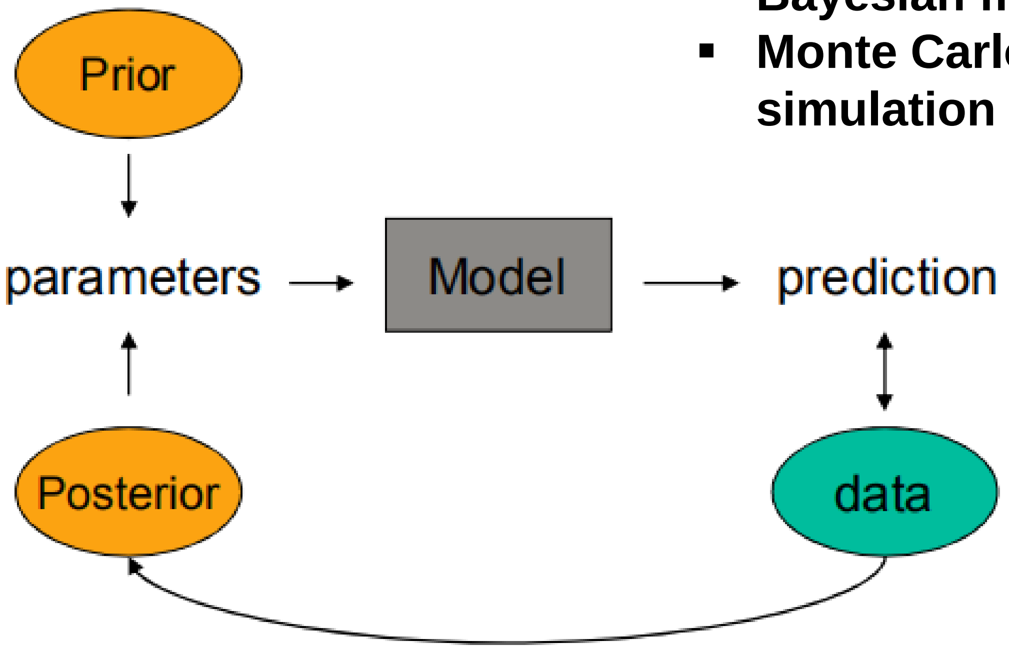
(2) 计算H*(cal)=exp(ln(H*)+Bias*)，

(3) 计算校正后树高H(cal)=Cratio*H^exp(Bias*)，

where Cratio=H(obs)_mean/H(cal)

过程模型参数校正 (Mäkelä 2011)

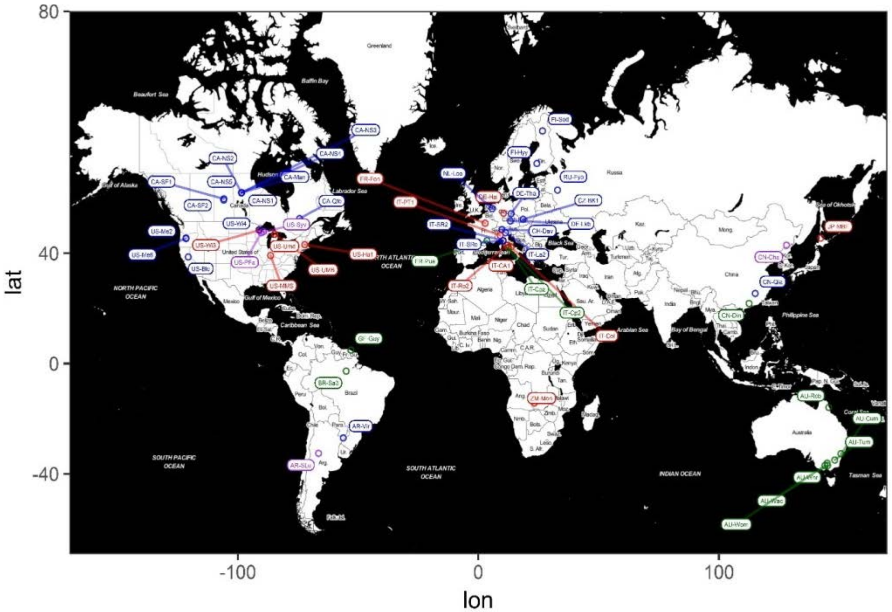
- Calibration
- Bayesian method
- Monte Carlo simulation



Data for calibrating the PRELES model

Eddy covariance data (55 sites)

- DBF(13)
- EBF(12)
- ENF(26)
- MF(4)

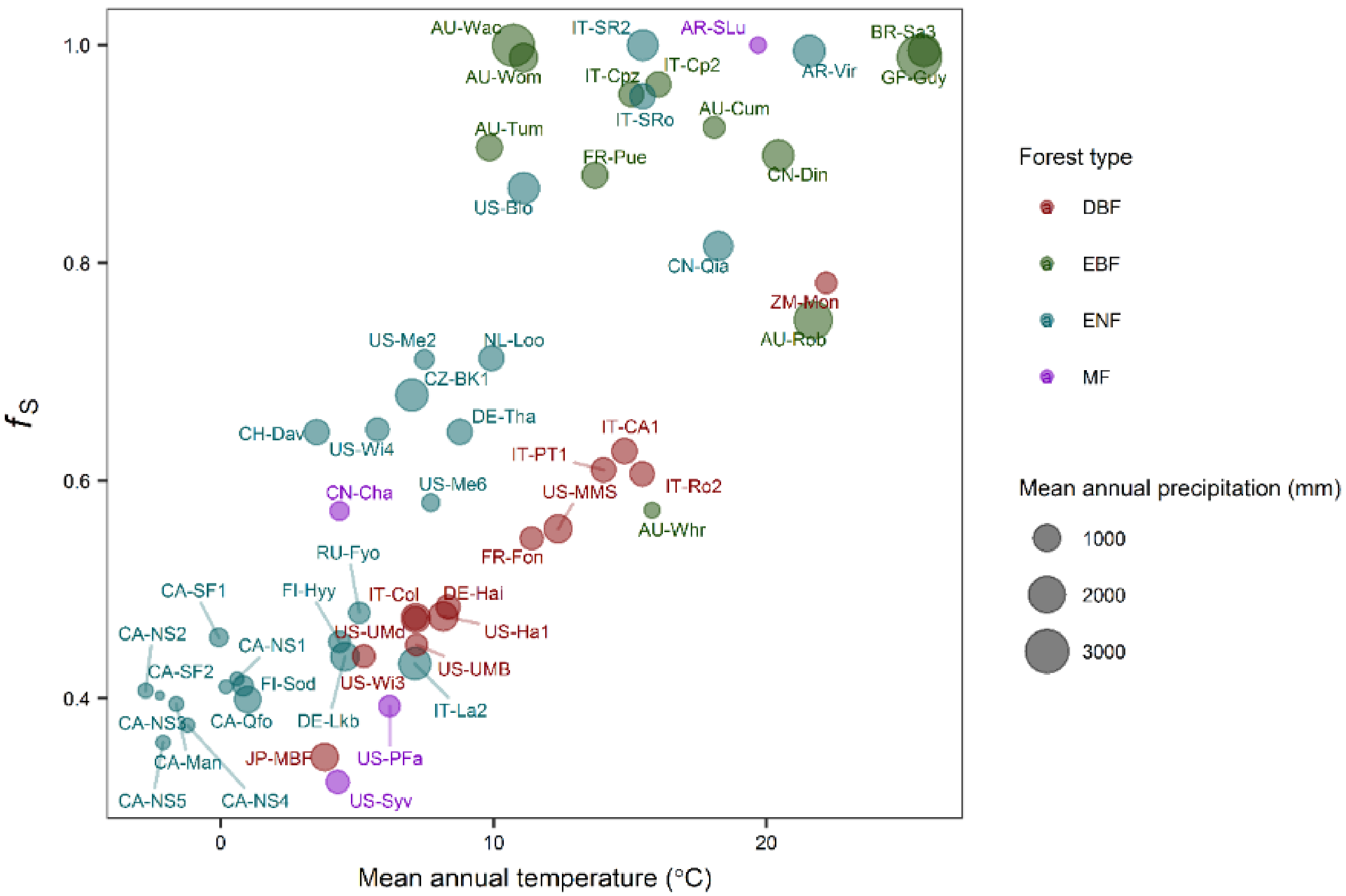


MODIS fAPAR data

MODIS Collection 6
Official Name: MOD15A2H
Platform: Terra
Spatial Resolution: 500m
Temporal Granularity: 8 Day

MODIS Collection 5
Official Name: MOD15A2
Platform: Terra
Spatial Resolution: 1000m
Temporal Granularity: 8 Day

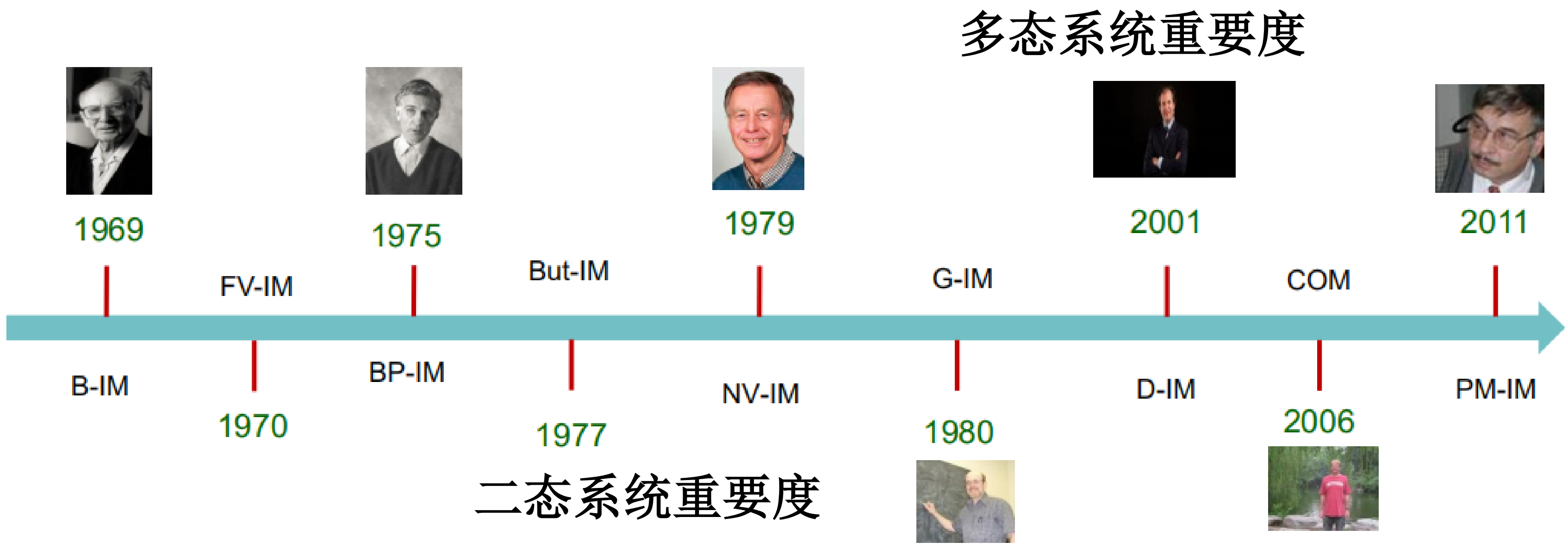
Temp. accli. modifier (Tian et al. 2020a)



The theory of importance (Si 2015)

$$I_i^{IIM}(t) = -\frac{\partial R_S \;\; t}{\partial R_i \;\; t} * \frac{dR_i \;\; t}{dt}, \quad I_{i\to k}^{IIM}(t) = \sum_{i=1}^{k} -\frac{\partial R_S \;\; t}{\partial R_i \;\; t} * \frac{dR_i \;\; t}{dt}$$

$$I_m^{IIM}(i) = P_{im} * \lambda_{m,0}^{i} \sum_{j=1}^{M} a_j \left[P(\Phi(m_i, X) = j) - P(\Phi(0_i, X) = j) \right]$$



The theory of importance 重要度理论

- 重要度研究的数学基础：偏微分
- 重要度研究是系统优化，灵敏度分析，可靠性设计，风险分析，及资源配置的主要数学工具
- 重要度：
  - 结构重要度，
  - 概率重要度，
  - 周期重要度
- 综合重要度：(Si et al. 2014. SAS软件研究所采用)
  - 系统单元对时间的导数=>时间对系统可靠性的影响
  - 随机过程与重要度结合=>时间累积和过程变化对系统可靠性的影响

Sensitivity analysis 敏感性分析

- *p* input parameter
- *Y* output

How do small changes in input propagate to results?

- Sensitivity S = $\partial Y/\partial p$

What is the relative importance of different components?

- Relative sensity S_R = $\partial Y/\partial p * p/Y$

敏感性计算

- p, input parameter
- Y, output
- Δp , a very small change
- S(t), sensitivity function

$$S(t) = \partial Y(t,p)/\partial p \approx (Y(t,p+\Delta p) - Y(t,p)) / \Delta p$$

Uncertainty analysis 不确定性分析

- p, input parameter
- Y, output
- Δp , error/uncertainty in p

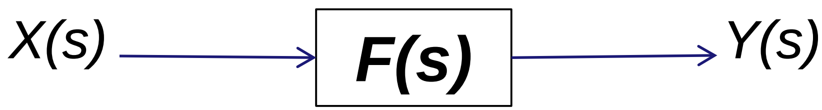
Uncertainty $U = \partial Y/\partial p * \Delta p$

- Total uncertainty is additive
- How does uncertainty/error in input information propagate to results?
- What is the significance of different sources of error/uncertainty?

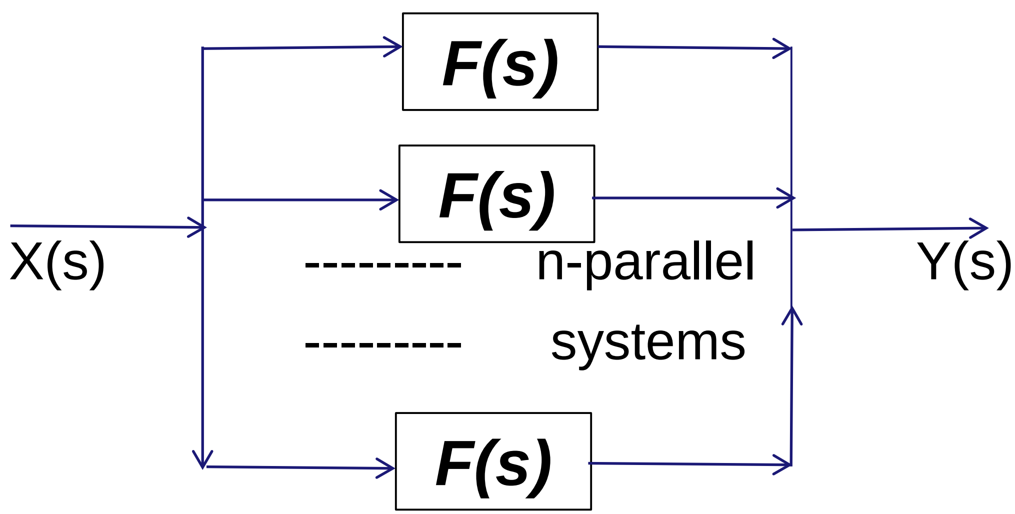
Stochastic processes 随机过程

- 泊松过程
  - 单一变量 λ 决定了某一时间内事件的发生率
- 更新过程
  - 事件间隔是独立的且为同分布随机变量
- 交替更新过程
  - 事件时间在两分布中不断交替变换
- 非齐次泊松过程
  - 事件发生时间为非稳态序列
- 连续时间马尔科夫链
  - 通过时间区间 (0,S] 上的转置，生成服从指数分布的事件时间 T 以及为离散值的过程状态X(t)

The theory of reliability 可靠性理论



- a simple system 开环串联系统



- n-parallel systems 闭环并联系统

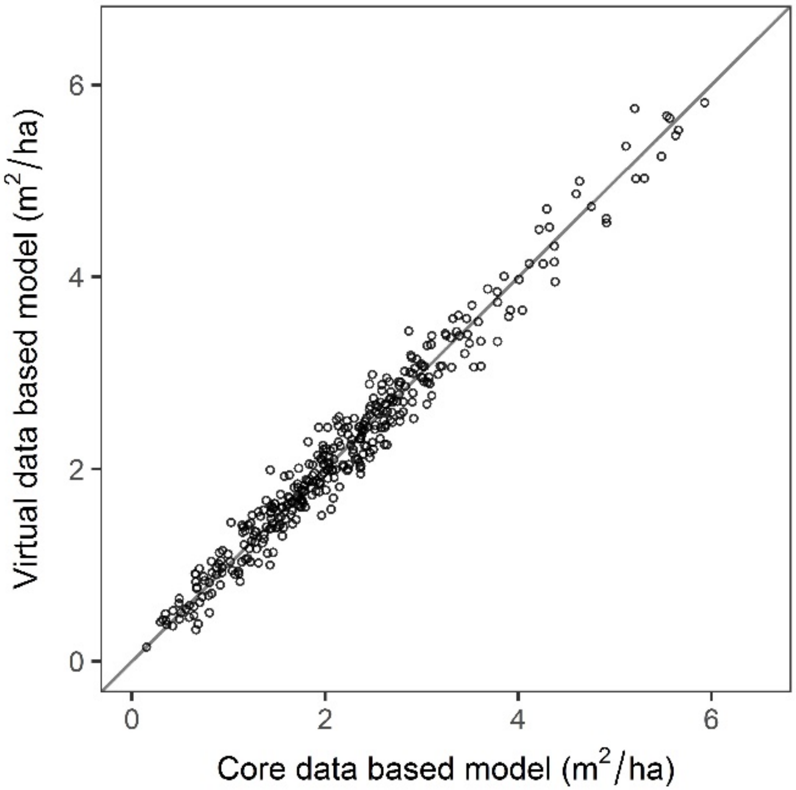
Control of error 冗余控制

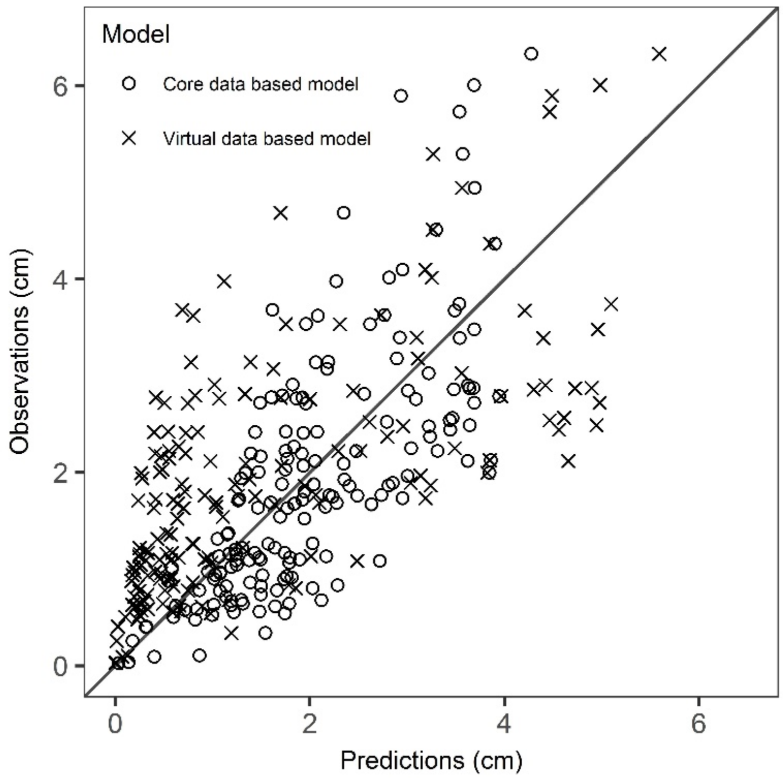
- 钱学森 1954. 工程控制论. 麦格劳希尔出版公司. USA

- Reliability by duplication
- Method of multiplexing
- Error in executive component
- Error of multiplexing systems

“This particular method of synthesizing a reliable system out of unreliable elements is called the method of multiplexing by von Neumann.” -- 钱学森 Hsue-shen Tsien

三阶段建模法：单木模型 (Tian et al. 2020b)



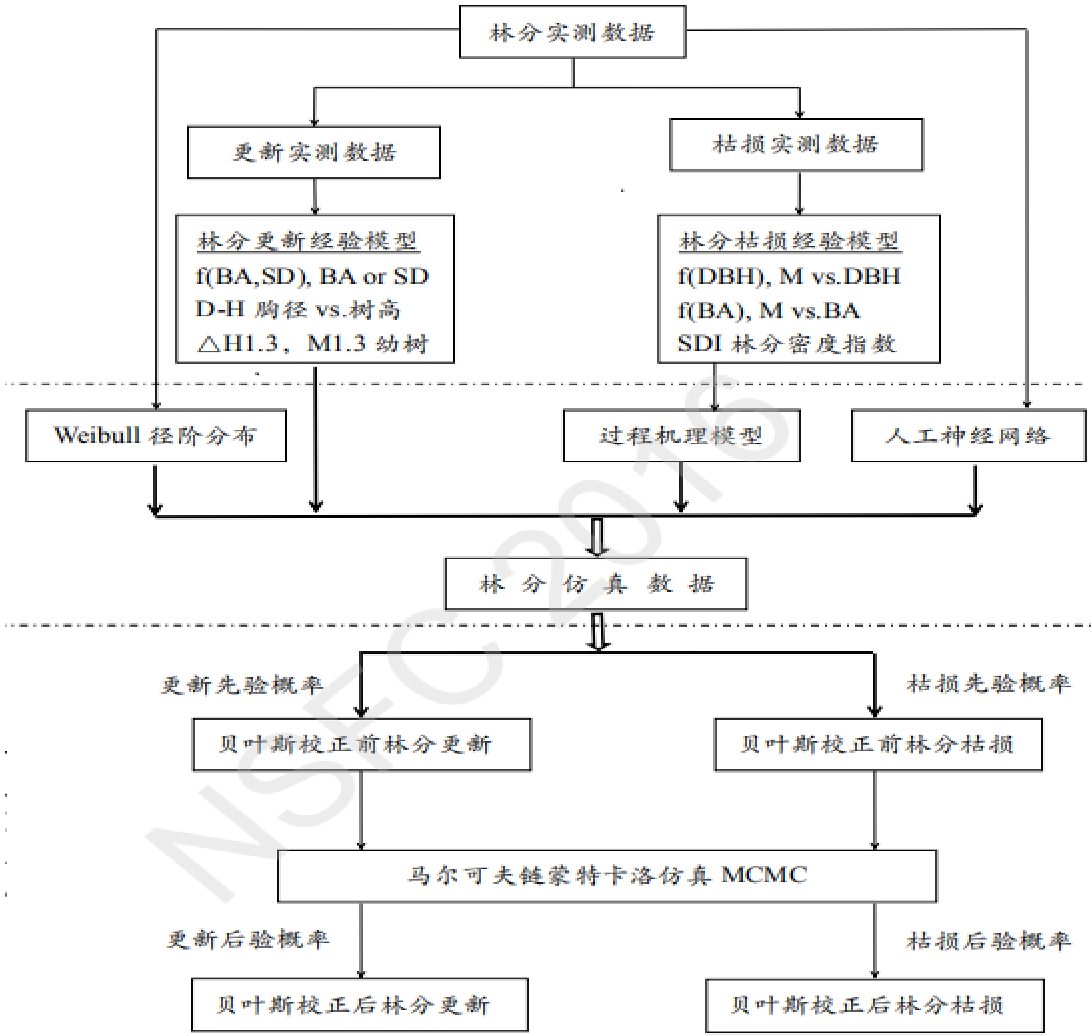


三阶段建模法：更新与枯损

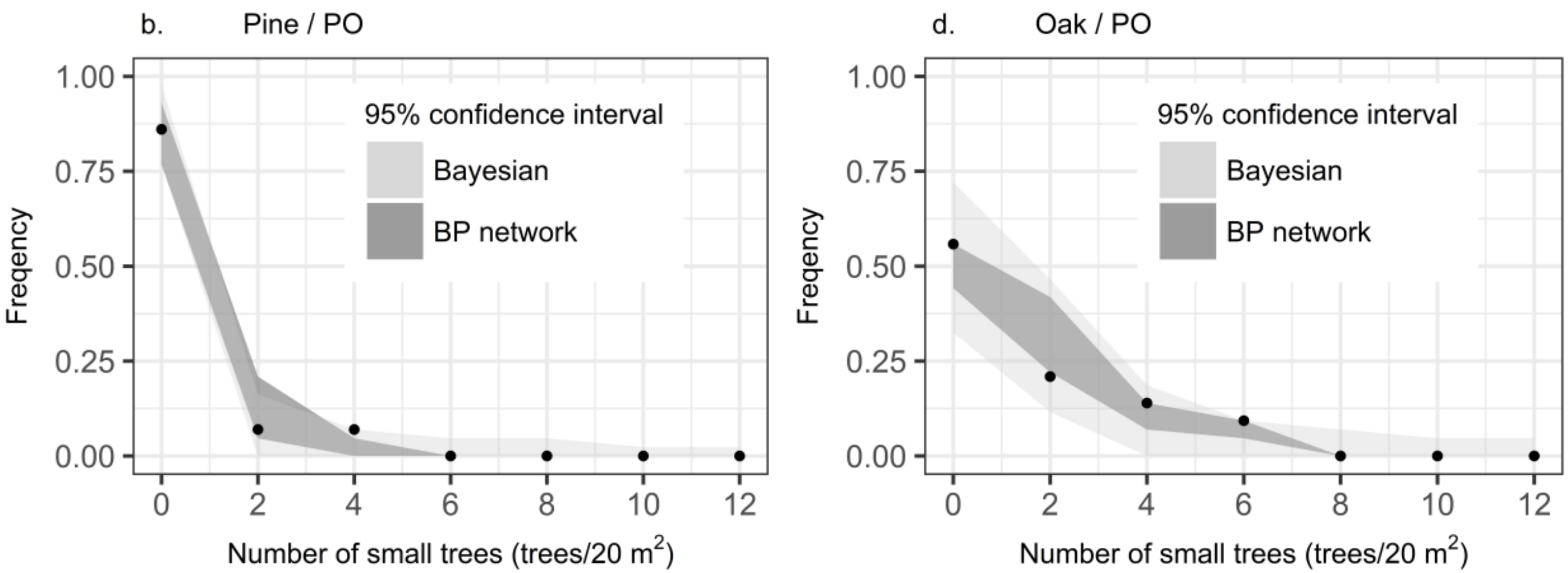
Stage I: observed

Stage II: simulated

Stage III: calibrated

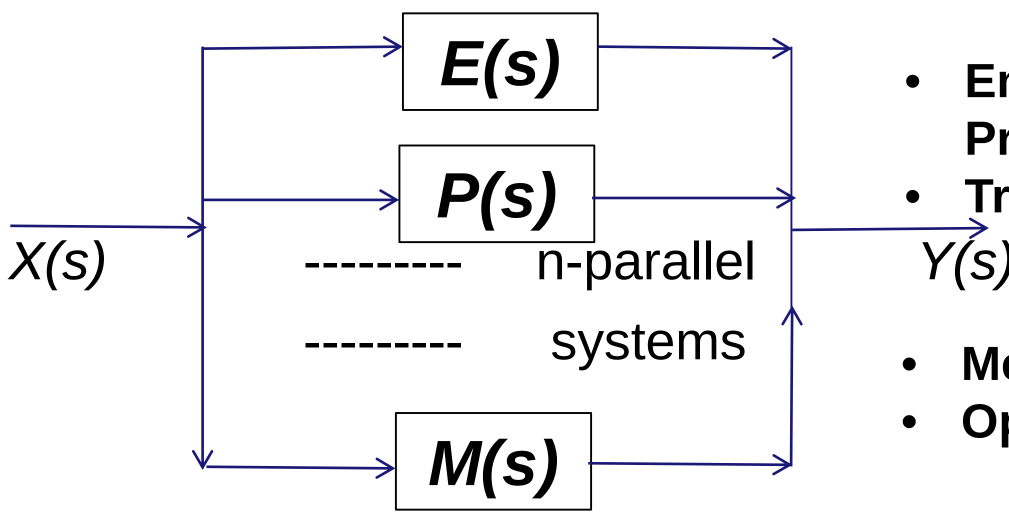


Simulated regener. (Wang & Cao 2019)



Parallel forest simulation systems

■ traditional open-loop systems 开环林分生长模型



- **Empirical / Process**
- **Tree- / Stand-level**

- **Measurement**
- **Optimal control**

■ n-parallel simulation systems 闭环林分平行仿真系统

ACP Methodology (王飞跃等 2012)

人工系统 **A**rtificial systems

- simulation/mathematical models describing the main features of real world;
- Calibration of the artificial systems the to the real ones;

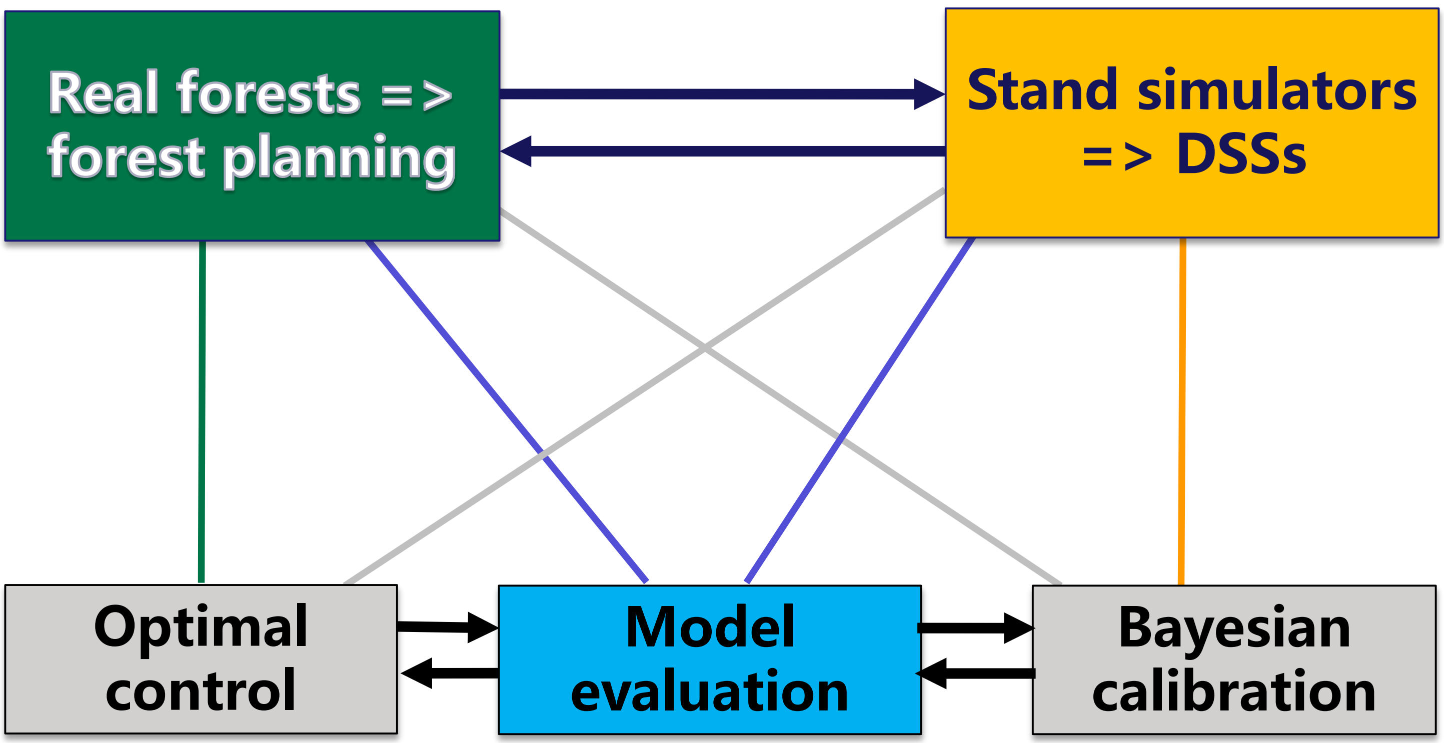
计算实验 **C**omputational experiments

- Test on the artificial/virtual systems;

平行执行 **P**arallel execution

- Management and control of real systems by referring to the virtual ones

Dual closed-loop forest systems

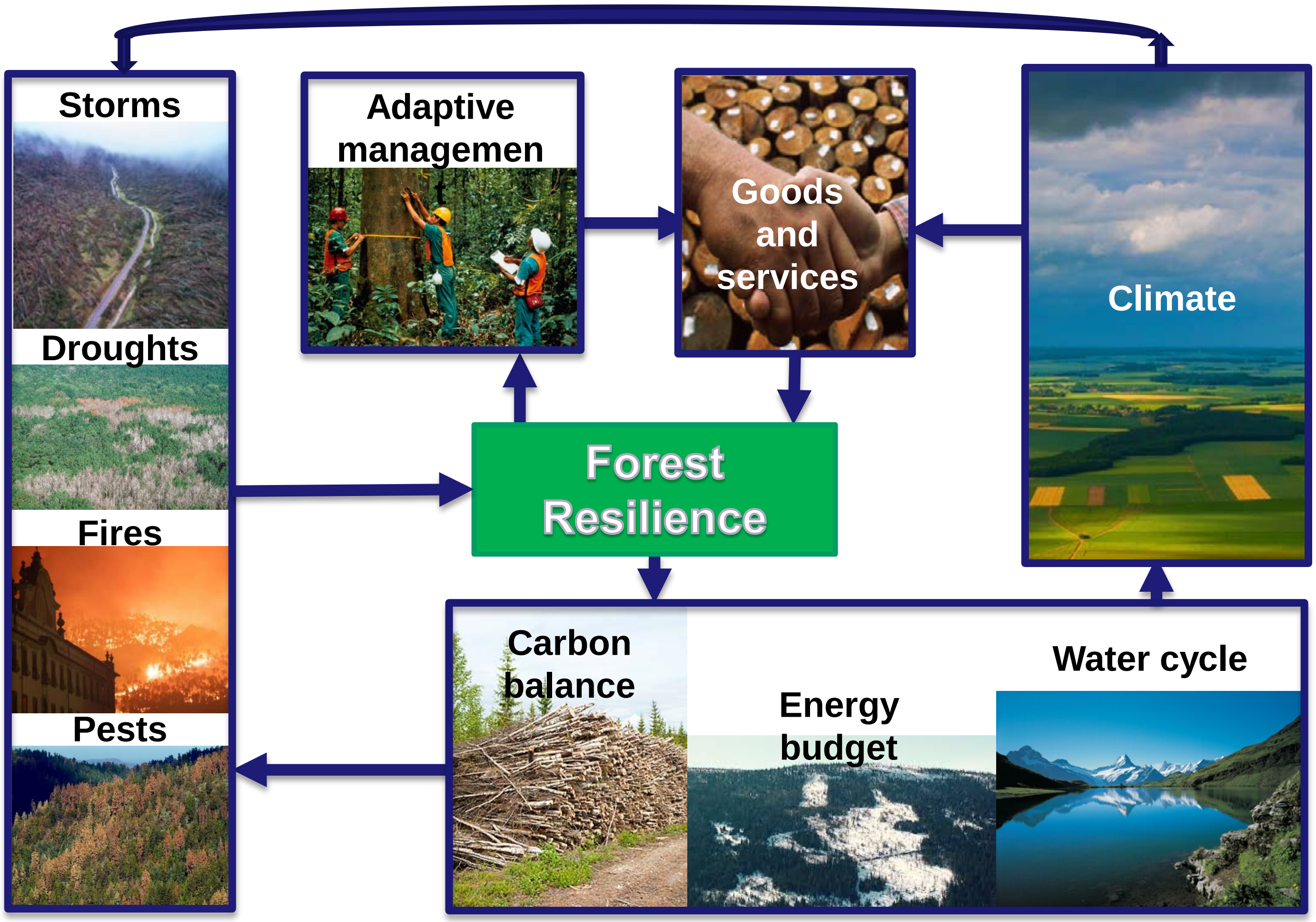


Modified from Wang and Kang (2012)

Ambitions

- Carbon balance,
- Water balance,
- Climate sensitivity and uncertainty,
- Vulnerability assessment,
- Forest biodiversity,
- Forest resilience,
- Tree migration,
- Forest risk management,
- Multi-criteria decision-making,
- Simulation-based optimization.

Climate change impacts



Tools to be used

- **Biological and Ecological Models**:
  - Empirical stand simulator: QUASSI 1.0
  - Process-based models: 3-PG, CROBAS, QUASSI 2.0
  - Soil carbon model: YASSO 07
  - Water balance model: PRELES
  - Nutrient cycling model: ROMUL
  - Hybrid model: QUASSI 3.0

- **Decision Support Systems:**
  - Single-objective : OPTIFOR 1.0
  - Multi-objective : OPTIFOR 2.0
  - Visualization: SIMILE

References

- Cao, T., Tian, X., Sun, S. 2016. Monitoring and Assessment of Forest Resources: Methodology and Applications. Northwest A & F University. 141 pp.
- Davis, L.S., Johnson, K.N., Bettinger, P.S., Howard, T.E. 2001. Forest management: to sustain ecological, economic, and social Values. Fourth Edition. McGraw-Hill. 804 pp.
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生态仿真优化实验室

Simulation Optimization Lab

Thank You!

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