

Hans Pretzsch

Forest Dynamics, Growth and Yield

From Measurement to Model

 Springer

Contents

1	Forest Dynamics, Growth, and Yield: A Review, Analysis of the Present State, and Perspective	1
1.1	System Characteristics of Trees and Forest Stands	1
1.1.1	Differences in the Temporal and Spatial Scale Between Trees and Humans	2
1.1.2	Forest Stands are Open Systems	6
1.1.3	Forests are Strongly Structurally Determined Systems	8
1.1.4	Trees, Forest Stands, and Forest Ecosystems are Shaped by History	11
1.1.5	Forests are Equipped with and Regulated by Closed Feedback Loops	12
1.1.6	Forest Ecosystems are Organised Hierarchically	14
1.1.7	Forest Stands are Systems with Multiple Output Variables	20
1.2	From Forest Stand to Gene Level: The Ongoing Spatial and Temporal Refinement in Analysis and Modelling of Tree and Forest Stand Dynamics	21
1.2.1	Experiments, Inventories, and Measurement of Structures and Rates	22
1.2.2	From Proxy Variables to “Primary” Factors for Explanations and Estimations of Stand and Tree Growth	24
1.2.3	From Early Experience Tables to Ecophysiologically Based Computer Models	26
1.3	Bridging the Widening Gap Between Scientific Evidence and Practical Relevance	29
1.3.1	Scale Overlapping Experiments	29
1.3.2	Interdisciplinary Links Through Indicator Variables	31
1.3.3	Link Between Experiments, Inventories, and Monitoring by Classification Variables	32

1.3.4	Model Development.....	33
1.3.5	Link Between Models and Inventories: From Deductive to Inductive Approaches	35
	Summary	37
2	From Primary Production to Growth and Harvestable Yield and Vice Versa: Specific Definitions and the Link Between Two Branches of Forest Science	41
2.1	Link Between Forest Growth and Yield Science and Production Ecology	41
2.2	General Definitions and Quantities: Primary Production, Growth and Yield	42
2.2.1	Gross and Net Primary Production	44
2.2.2	Gross and Net Growth	46
2.2.3	Gross and Net Yield	47
2.3	Specific Terminology and Quantities in Forest Growth and Yield Science	48
2.3.1	Growth and Yield of Individual Trees	50
2.3.2	Growth and Yield at the Stand Level	56
2.4	Stem and Merchantable Volume Growth as a Percentage of Gross Primary Production	64
2.4.1	From Standing Volume or Stem or Merchantable Wood Volume to Total, Biomass	66
2.4.2	Ephemeral Turnover Factor t_{org} for Estimation of NPP	72
2.4.3	Deriving Harvested Volume Under Bark from Standing Volume over Bark	76
2.4.4	Conversion of Merchantable Wood Volume to GPP	78
2.5	Dead Inner Xylem	81
2.6	Growth and Yield and Nutrient Content	84
2.6.1	From Total Biomass to the Carbon Pool	85
2.6.2	Nutrient Minerals	85
2.7	Efficiency of Energy, Nitrogen, and Water Use	89
2.7.1	Energy Use Efficiency (EUE)	90
2.7.2	Nitrogen Use Efficiency (NUE)	93
2.7.3	Water Use Efficiency (WUE)	94
	Summary	95
3	Brief History and Profile of Long-Term Growth and Yield Research	101
3.1	From Rules of Thumb to Sound Knowledge	101
3.2	Foundation and Development of Experimental Forestry	104
3.3	From the Association of German Forest Research Stations to the International Union of Forest Research Organizations (IUFRO)	105
3.4	Growth and Yield Science Section of the German Union of Forest Research Organisations	105

3.5	Continuity in Management of Long-Term Experiment Plots in Bavaria as a Model of Success	107
3.6	Scientific and Practical Experiments	110
3.7	Establishment and Survey of Long-Term Experimental Plots	112
3.7.1	Establishment of Experimental Plots and Trial Plots	112
3.7.2	Measuring Standing and Lying Trees	115
	Summary	118
4	Planning Forest Growth and Yield Experiments	121
4.1	Key Terminology in the Design of Long-Term Experiments	121
4.2	The Experimental Question and its Four Component Questions ...	123
4.2.1	Which Question Should Be Answered?	123
4.2.2	With What Level of Accuracy Should the Question be Answered?	124
4.2.3	What Level of Spatial–Temporal Resolution is Wanted in the Explanation?	124
4.2.4	Why and for What Purpose Should the Question be Answered?	124
4.3	Biological Variability and Replicates	125
4.3.1	Total Population and Sample	125
4.4	Size of Experimental Plot and Trial Plot Number	126
4.5	Block Formation and Randomisation: Elimination of Systematic Error	128
4.6	Classical Experimental Designs	129
4.6.1	One-Factor Designs	130
4.6.2	Two-Factor or Multifactor Analysis	133
4.6.3	Split-Plot and Split-Block Designs	137
4.6.4	Trial Series and Disjunct Experimental Plots	139
4.7	Special Experimental Designs and Forest Growth Surveys	141
4.7.1	From Stand to Individual Tree Experiments	141
4.7.2	Experiments and Surveys of Growth Disturbances	144
4.7.3	Artificial Time Series or Growth Series	145
	Summary	148
5	Description and Quantification of Silvicultural Prescriptions	151
5.1	Kind of Thinning	154
5.1.1	Thinning According to Social Tree Classes by Kraft (1884)	154
5.1.2	Thinning According to Combined Tree and Stem Quality Classes from the Association of German Forest Research Stations (1902)	156
5.1.3	Thinning After the Selection of Superior or Final Crop Trees	160
5.1.4	Thinning Based on Diameter Class or Target Diameter ...	164
5.2	Severity of Thinning	166
5.2.1	Thinning Based on a Target Stand Density Curve	167

5.2.2	Approaches for Regulating Thinning Severity and Stand Density	167
5.2.3	Selection of Density Classes	170
5.2.4	Management of Stand Density in Fertilisation and Provenance Trials	171
5.2.5	Individual Tree Based Thinning-Prescriptions	172
5.3	Intensity of Thinning	175
5.4	Algorithmic Formulation of Silvicultural Prescriptions for Forest Practice and Growth and Yield Models	177
	Summary	178
6	Standard Analysis of Long-Term Experimental Plots	181
6.1	From Measurement to Response Variables	183
6.2	Importance of Regression Sampling for Standard Analysis	184
6.2.1	Principle of Regression Sampling	184
6.2.2	Linear Transformation	184
6.3	Determination of Stand-Height Curves	186
6.3.1	Function Equations for Diameter-Height Relationships ..	187
6.3.2	Selection of the Most Suitable Model Function	188
6.4	Diameter-Height-Age Relationships	189
6.4.1	Method of Smoothing Coefficients	191
6.4.2	Growth Function Methods for Strata Mean Trees	193
6.4.3	Age-Diameter-Height Regression Methods	195
6.5	Form Factors and Volume Calculations for Individual Trees	196
6.5.1	Form Factors	197
6.5.2	Volume Calculations for Individual Trees	199
6.6	Stand Mean and Cumulative Values at the Time of Inventory and for the Periods Between Inventories	199
6.6.1	Reference Area	199
6.6.2	Tree Number	199
6.6.3	Mean Diameter and Mean Diameter of the Top Height Tree Collective	200
6.6.4	Mean and Top Height	201
6.6.5	Slenderness h_q/d_q and h_{100}/d_{100}	203
6.6.6	Stand Basal Area and Volume	203
6.6.7	Growth and Yield Characteristics	204
6.7	Results of Standard Analysis	205
6.7.1	Presentation in Tables	205
6.7.2	Stand Development Diagrams	211
	Summary	220
7	Description and Analysis of Stand Structures	223
7.1	Structures and Processes in Forest Stands	225
7.1.1	Interaction Between Structures and Processes	225
7.1.2	Effect of Initial Structure on Stand Development	227

7.2	Descriptions of Stand Structure	229
7.2.1	Tree Distribution Maps and Crown Maps	230
7.2.2	Three-Dimensional Visualisation of Forest Growth	234
7.2.3	Spatial Occupancy Patterns	239
7.3	Horizontal Tree Distribution Patterns	242
7.3.1	Poisson Distribution as a Reference for Analysing Stand Structures	243
7.3.2	Position-Dependent Distribution Indices	246
7.3.3	Distribution Indices Based on Sample Quadrats	252
7.3.4	K-Function	256
7.3.5	L-Function	260
7.3.6	Pair Correlation Functions for Detailed Analysis of Tree Distribution Patterns	261
7.4	Stand Density	266
7.4.1	Stocking Density	266
7.4.2	Percentage Canopy Cover (PCC)	267
7.4.3	Mean Basal Area, mBA, by Assmann (1970)	269
7.4.4	Quantifying Stand Density from the Allometry Between Mean Size and Plants per Unit Area	270
7.4.5	Crown Competition Factor CCF	273
7.4.6	Density of Spatial Occupancy and Vertical Profiles	274
7.5	Differentiation	276
7.5.1	Coefficient of Variation of Tree Diameters and Heights ...	276
7.5.2	Diameter Differentiation by Fuldner (1995)	276
7.5.3	Species Richness, Species Diversity, and Structural Diversity	279
7.6	Species Intermingling	284
7.6.1	Species Intermingling Index by Fuldner (1996)	284
7.6.2	Index of Segregation from Pielou (1977)	285
	Summary	287
8	Growing Space and Competitive Situation of Individual Trees	291
8.1	The Stand as a Mosaic of Individual Trees	292
8.2	Position-Dependent Competition Indices	292
8.2.1	Example of Competitor Identification and Competition Calculation	293
8.2.2	Methods of Competitor Identification	295
8.2.3	Quantifying the Level of Competition	299
8.2.4	Evaluation of Methods	302
8.3	Position-Independent Competition Measures	305
8.3.1	Crown Competition Factor	305
8.3.2	Horizontal Cross-Section Methods	306
8.3.3	Percentile of the Basal Area Frequency Distribution	307
8.3.4	Comparing Position-Independent with Position- Dependent Competition Indices	308

8.4	Methods Based on Growing Area	311
8.4.1	Circle Segment Method	311
8.4.2	Rastering the Stand Area	312
8.4.3	Growing Area Polygons	313
8.5	Detailed Analysis of a Tree's Spatial Growth Constellation	315
8.5.1	Spatial Rastering and Dot Counting	315
8.5.2	Calculation of Spatial Distances	318
8.5.3	Crown Growth Responses to Lateral Restriction	320
8.6	Hemispherical Images for Quantifying the Competitive Situation of Individual Trees	321
8.6.1	Fish-Eye Images as a Basis for Spatial Analyses	321
8.6.2	Methodological Principles of Fish-Eye Projection in Forest Stands	323
8.6.3	Quantifying the Competitive Situation of Individual Trees in a Norway Spruce–European Beech Mixed Stand ..	325
8.7	Edge Correction Methods	326
8.7.1	Edge Effects and Edge Correction Methods	326
8.7.2	Reflection and Shift	327
8.7.3	Linear Expansion	328
8.7.4	Structure Generation	332
8.7.5	Evaluation of Edge Correction Methods	333
	Summary	334
9	Effects of Species Mixture on Tree and Stand Growth	337
9.1	Introduction: Increasing Productivity with Species Mixtures?	337
9.1.1	Fundamental Niche and Niche Differentiation	338
9.1.2	Maximizing Fitness isn't Equivalent to Maximizing Productivity	340
9.1.3	The Balance Between Production Promoting and Inhibiting Effects is Important	341
9.2	Framework for Analysing Mixing Effects	343
9.2.1	Ecological Niche	343
9.2.2	Site–Growth Relationships	344
9.2.3	Risk Distribution	344
9.2.4	Comparison of Mixed Stands with Neighbouring Pure Stands: Methodological Considerations	348
9.3	Quantifying Effects of Species Mixture at Stand Level	351
9.3.1	Cross-Species Diagrams for Visualising Mixture Effects ..	351
9.3.2	Nomenclature, Relations and Variables for Analysing Mixture Effects	352
9.3.3	Mixture Proportion	354
9.3.4	Examining Effects of Species Mixture on Biomass Productivity in Norway Spruce–European Beech Stands: An Example	356
9.3.5	Examining Mean Tree Size in Norway Spruce–European Beech Stands: An Example	360

9.4	Quantifying Mixture Effects at the Individual Tree Level	363
9.4.1	Efficiency Parameters for Individual Tree Growth	363
9.4.2	Application of Efficiency Parameters for Detecting Mixture Effects	365
9.5	Productivity in Mixed Forest Stands	371
9.5.1	The Mixed Stands Issue: A Central European Review and Perspective	371
9.5.2	Benchmarks for Productivity of Mixed Stands Compared to Pure Stands	372
9.5.3	Spatial and Temporal Niche Differentiation as a Recipe for Coexistence and Cause of Surplus Productivity	375
9.5.4	Crown Shyness	376
9.5.5	Growth Resilience with Structural and Species Diversity	377
	Summary	378
10	Growth Relationships and their Biometric Formulation	381
10.1	Dependence of Growth on Environmental Conditions and Resource Availability	381
10.1.1	Unimodal Dose-Effect-Curve	381
10.1.2	Dose-Effect-Rule by Mitscherlich (1948)	383
10.1.3	Combining the Effects of Several Growth Factors	386
10.2	Allometry at the Individual Plant Level	387
10.2.1	Allometry and Its Biometric Formulation	387
10.2.2	Examples of Allometry at the Individual Plant Level	389
10.2.3	Detection of Periodic Changes in Allometry	391
10.3	Growth and Yield Functions of Individual Plants	393
10.3.1	Physiological Reasoning and Biometrical Formulation of Growth Functions	393
10.3.2	Overview Over Approved Growth and Yield Functions	394
10.3.3	Relationship Between Growth and Yield	397
10.4	Allometry at the Stand Level: The Self-Thinning Rules from Reineke (1933) and Yoda et al. (1963)	399
10.4.1	Reineke's (1933) Self-thinning Line and Stand Density Index	400
10.4.2	-3/2-Power Rule by Yoda et al. (1963)	402
10.4.3	Link Between Individual Tree and Stand Allometry	405
10.4.4	Allometric Scaling as General Rule	406
10.5	Stand Density and Growth	407
10.5.1	Assmann's Concept of Maximum, Optimum and Critical Stand Density	409
10.5.2	Biometric Formulation of the Unimodal Optimum Curve of Volume Growth in Relation to Stand Density and Mean Tree Size	411

10.6	Dealing with Biological Variability	415
10.6.1	Quantifying Variability	416
10.6.2	Reproduction of Variability	418
	Summary	420
11	Forest Growth Models	423
11.1	Scales of Observation, Statistical and Mechanistic Approaches to Stand Dynamics	425
11.1.1	Scales of Forest Growth and Yield Research and Models	425
11.1.2	From the Classical Black-Box to White-Box Approaches	426
11.1.3	Top-Down Approach vs Bottom-Up Approach	428
11.2	Model Objectives, Degree of System Abstraction, Database	429
11.2.1	Growth Models as Nested Hypotheses About Systems Behaviour	430
11.2.2	Growth Models as a Decision Tool for Forest Management	430
11.3	Growth Models Based on Stand Level Mean and Cumulative Values	432
11.3.1	Principles of Yield Table Construction	432
11.3.2	From Experience Tables to Stand Simulators	437
11.4	Growth Models Based on Tree Number Frequencies	445
11.4.1	Representing Stand Development by Systems of Differential Equations	445
11.4.2	Growth Models Based on Progressing Distributions	446
11.4.3	Stand Evolution Models – Stand Growth as a Stochastic Process	449
11.5	Individual Tree Growth and Yield Models	450
11.5.1	Overview of the Underlying Principles of Individual- Tree Models	451
11.5.2	Growth Functions as the Core Element of Individual- Tree Models	453
11.5.3	Overview of Model Types	455
11.6	Gap and Hybrid Models	456
11.6.1	Development Cycle in Gaps	457
11.6.2	JABOWA – Prototype Model from Botkin et al. (1972) ..	458
11.7	Matter Balance Models	462
11.7.1	Increasing Structural and Functional Accordance of Models with Reality	462
11.7.2	Modelling of the Basic Processes in Matter Balance Models	465
11.7.3	Overview of Matter Balance Model Approaches	476
11.8	Landscape Models	478
11.8.1	Application of Landscape Model LandClim	481

11.9	Visualisation of Forest Stands and Wooded Landscapes	482
11.9.1	Visualisation Tools TREEVIEW and L-VIS	484
11.10	Perspective	488
	Summary	490
12	Evaluation and Standard Description of Growth Models	493
12.1	Approaches for Evaluation of Growth Models and Simulators	494
12.1.1	Suitability for a Given Purpose	494
12.1.2	Validation of the Biometric Model	496
12.1.3	Suitability of the Software	499
12.1.4	Customising Models and Simulators for End-Users	500
12.2	Examples of Model Validation	503
12.2.1	Validation on the Basis of Long-Term Sample Plots and Inventory Data	503
12.2.2	Comparison with Growth Relationships	508
12.2.3	Comparison with Knowledge from Experience	510
12.3	Standards for Describing Models and Simulators	510
	Summary	512
13	Application of Forest Simulation Models for Decision Support in Practice	515
13.1	Model Objective and Prediction Algorithm	516
13.1.1	Model Objective	516
13.1.2	Prediction Algorithm	516
13.1.3	Database	519
13.2	Site–Growth Model	519
13.2.1	The Principles of Controlling Individual Tree Growth by Means of Site Factors	520
13.2.2	Modelling the Potential Age–Height Curve in Dependence on Site Conditions	520
13.3	Generation of Initial Values for Simulation Runs	525
13.3.1	Stand Structure Generator STRUGEN	526
13.4	Spatially Explicit Modelling of the Growth Arrangement of the Individual Trees	528
13.4.1	Index KKL as the Indicator of the Crown Competition	528
13.4.2	Index NDIST as the Indicator for Competition Asymmetry	528
13.4.3	Index KMA for the Species Mixture in the Neighbourhood of Individual Trees	529
13.5	Application for Scenario Analysis at the Stand Level: A Pure Norway Spruce Stand vs a Norway Spruce – European Beech Mixed Stand	530
13.5.1	Growth and Yield at the Stand Level	530
13.5.2	Growth and Yield on Tree Level	532
13.5.3	Modelling Structural Diversity	532
13.5.4	Multi-Criteria Considerations	534

13.6	Growth Models for Dynamic Enterprise Planning	535
13.6.1	Simulation at the Enterprise Level for Long-Term Strategic Planning	536
13.6.2	Application of Models for Decision Support	537
13.6.3	Application of the Munich Forestry Enterprise Forest Management Plan	540
13.7	Estimation of Growth and Yield Responses to Climate Change	543
13.7.1	Dependence of Response Patterns on Site and Tree Species	544
13.7.2	Sensitivity Analysis at the Regional Level	545
13.7.3	Development of Silvicultural Measures for Mitigation and Adaptation to Climate Change	548
	Summary	549
14	Diagnosis of Growth Disturbances	553
14.1	Growth Models as Reference	556
14.1.1	Comparison with Yield Table	556
14.1.2	Dynamic Growth Models as Reference	557
14.1.3	Synthetic Reference Curves	559
14.2	Undisturbed Trees or Stands as a Reference	560
14.2.1	Increment Trend Method	560
14.2.2	Pair-Wise Comparison	565
14.2.3	Reference Plot Comparison	566
14.2.4	Reference Plot Comparison by Indexing	570
14.2.5	Regression–Analytical Estimation of Increment Decrease	572
14.3	Growth Behaviour in Other Calendar Periods as Reference	576
14.3.1	Individual Growth in Previous Period as Reference	576
14.3.2	Long-Term, Age-Specific Tree Growth as Reference (Constant Age Method)	579
14.3.3	Growth Comparison of Previous and Subsequent Generation at the Same Site	580
14.3.4	Diagnosis of Growth Trends from Succeeding Inventories	582
14.4	Dendro-Chronological Time Series Analysis	585
14.4.1	Elimination of the Smooth Component	586
14.4.2	Indexing	587
14.4.3	Response Function	588
14.4.4	Quantification of Increment Losses	589
	Summary	590
15	Pathways to System Understanding and Management	593
15.1	Overview of Knowledge Pathways in Forest Growth and Yield Research	594
15.1.1	Observation, Measurement, and Collection of Data	595
15.1.2	Description	597

15.1.3	Formulation of Hypotheses for Elements of Individual System Elements	597
15.1.4	Test of Hypotheses	599
15.1.5	Models as a Chain of Hypotheses	602
15.1.6	Test of Model Hypothesis by Simulation	603
15.1.7	Application of the Model in Research, Practice, and Education	604
15.1.8	Relationships, Rules, Laws, and Theories	604
15.2	Transfer of Knowledge from Science to Practice	611
15.2.1	Concept of Forest Ecosystem Management	611
15.2.2	Long-Term Experiments and Models for Decision Support	613
	Summary	615
References	619
Index	655