Lecture Notes for the Module
“Monitoring of Forest Resources”
by
Prof. Dr. Christoph Kleinn

with contributions by:
Dr. Philip Beckschäfer, Netra Bhandari, Dr. Lutz Fehrmann, Dr. Hans Fuchs, Prof. Dr. Christoph Kleinn, Dr. TzengYih Lam, Dr. Paul Magdon, Dr. Sebastian Schnell, Dr. Dominik Seidel, Dr. Haijun Yang

Chair of Forest Inventory and Remote Sensing
Burckhardt-Institute
Faculty of Forest Sciences and Forest Ecology
Georg-August-Universität Göttingen
Germany

October 2015
Preface

These lecture notes were compiled as supporting material to the lecture “Monitoring of Forest Resources” as delivered at the Faculty of Forest Sciences and Forest Ecology at Georg-August-Universität Göttingen. Selection of topics follows, therefore, largely the structure of that course. That does also mean that these lecture notes cover above all the topic of field based monitoring, touching only marginally on remote sensing techniques – which is the subject of other lectures for which other material is available.

These lecture notes started by my students Mr. Thzeng Yih Lam and Mr. Netra Bhandari during my lectures in winter semester 2004/2005, covering all subjects that had been lectured in that semester. Mr. Haijun Yang did a further review and Mr. Hendrik Heydecke did a thorough editorial check. They did a great job and I am very grateful to them for their efforts!

In the course of the years, various updates have been made, some topics added and some eliminated. Numerous students and research associates of the Chair of Forest Inventory and Remote Sensing at Göttingen University, and also many students taking the course contributed to this never-ending optimization work. Great thanks to all these two colleagues!

Of course, there may still be mistakes in the text. You are very much welcome and encouraged to explicitly search for them and let the authors know, so that we can continue gradually improving this learning material: any observations on structure, style, etc. of these lecture notes are very welcome!

This collection of materials is thought to accompany the lectures. I doubt that it can replace attending lectures and tutorials on a regular basis and/or reading further texts and articles, as recommended.

You may also wish to visit our “AWF Wiki”, the first Wiki that deals specifically and comprehensively with the fields of forest mensuration, forest inventory and forest monitoring and which is globally intensively accessed in the meantime. The AWF Wiki has been established in 2009 at the Chair of Forest Inventory and Remote Sensing (“AWF” = Abteilung Waldinventur und Fernerkundung) as an initiative of Dr. Lutz Fehrmann: http://wiki.awf.forst.uni-goettingen.de/wiki (or search for „AWF Wiki“ in any internet search machine).

I hope that this material proves useful and helps you getting even more interested in the exciting topic of monitoring techniques for forests and natural renewable resources.

Christoph Kleinn
and the team at the Chair of Forest Inventory and Remote Sensing
(= AWF = Abteilung Waldinventur und Fernerkundung)
Göttingen, October 2015
# Table of Contents

## 1. INTRODUCTION

1.1 BACKGROUND AND OBJECTIVES  
1.2 BRIEF COMMENTS ON THE HISTORY OF FOREST INVENTORY  
1.3 GEOGRAPHICAL LEVELS  
1.3.1 FOREST INVENTORIES AT LOCAL LEVEL  
1.3.2 FOREST INVENTORIES AT NATIONAL LEVEL  
1.3.3 FOREST ASSESSMENTS AT GLOBAL LEVEL  
1.4 INFORMATION  
1.4.1 DATA AND INFORMATION  
1.4.2 FOREST INVENTORIES AS ELEMENT OF DECISION PROCESSES

## 2. FOREST MENSURATION RECAP

2.1 DEFINITIONS IN FOREST INVENTORY  
2.1.1 INTRODUCTION  
2.1.2 DEFINITION OF “TREE”  
2.1.3 DEFINITION OF “FOREST”  
2.1.3.1 General observations  
2.1.3.2 Components of a forest definition  
2.1.3.3 “Forest” definition of FAO  
2.1.3.4 Examples of forest definition  
2.1.3.5 Minimum crown cover  
2.1.3.6 Some discussion points referring to forest definitions  
2.1.4 FOREST BOUNDARY  
2.1.5 SPECIES COMPOSITION  
2.2 MEASUREMENT OF DIAMETER  
2.2.1 INTRODUCTION  
2.2.2 THE DIAMETER AT BREAST HEIGHT  
2.2.3 INSTRUMENTS FOR MEASURING DIAMETER AT BREAST HEIGHT  
2.2.3.1 Caliper  
2.2.3.2 Diameter tape  
2.2.4 CALIPER VS. DIAMETER TAPE  
2.2.5 MEASURING UPPER STEM DIAMETERS  
2.2.5.1 Why measuring upper diameters?  
2.2.5.2 Finn caliper  
2.2.5.3 Optical caliper (parallel beams)  
2.2.6 THE PRINCIPLE OF MEASURING UPPER DIAMETERS WITH ANGLE MEASUREMENTS  
2.2.7 MEASURING UPPER DIAMETERS WITH THE RELASCOPE  
2.3 MEASURING HEIGHT  
2.3.1 GENERAL COMMENTS  
2.3.2 DIRECT MEASUREMENT OF TREE HEIGHT  
2.3.3 THE TRIGONOMETRIC PRINCIPLE OF MEASURING TREE HEIGHT  
2.3.4 THE GEOMETRIC PRINCIPLE OF MEASURING TREE HEIGHT  
2.4 MEASURING DISTANCE  
2.5 MEASURING SLOPE  
2.6 SOME FEW FURTHER ATTRIBUTES  
2.6.1 GENERAL OBSERVATIONS  
2.6.2 BARK THICKNESS
2.6.3 CROWN ATTRIBUTES 29
2.6.4 DIAMETER INCREMENT 31
2.6.5 WOOD DENSITY 32
2.6.6 QUALITY 33
2.6.7 TREE SOCIOLOGICAL POSITION 33
2.6.8 CHARACTERIZATION OF STEM SHAPE 34
2.6.8.1 Form of tree 34
2.6.8.2 Form factor 34
2.7 TERRESTRIAL LASER SCANNING – TAKING 3D PHOTOGRAPHS 36
2.8 DETERMINING VOLUME 38
2.8.1 GENERAL OBSERVATIONS 38
2.8.2 CALCULATING VOLUME 38
2.8.2.1 Direct measurement 38
2.8.2.2 Volume calculation by section 38
2.8.2.3 The taper curve 39
2.9 FUNCTIONS AND MODELS IN FOREST INVENTORY 41
2.9.1 GENERAL OBSERVATIONS 41
2.9.2 ON THE TERM “ALLOMETRIC MODELS” 41
2.9.3 SOME NOTIONS OF LINEAR REGRESSION 42
2.9.4 HEIGHT CURVE 44
2.9.5 VOLUME FUNCTIONS 46
2.9.6 BIOMASS FUNCTIONS AND CARBON ESTIMATION 50
2.9.7 OTHER MODELS 53

3. INTRODUCTION TO SAMPLING 54
3.1 GENERAL OBSERVATIONS 54
3.2 POPULATION VS. SAMPLING FRAME 54
3.3 STATISTICAL SAMPLING 55
3.4 SAMPLING DESIGN AND PLOT DESIGN 56
3.5 STATISTICAL ESTIMATIONS 56
3.6 SAMPLE SIZE 60
3.7 SAMPLING INTENSITY VS. SAMPLE SIZE 61

4. PLOT DESIGN 63
4.1 INTRODUCTION 63
4.1.1 SPATIAL AUTOCORRELATION 64
4.2 FIXED AREA PLOTS 65
4.2.1 GENERAL OBSERVATIONS 65
4.2.2 THE INCLUSION ZONE CONCEPT 66
4.2.3 THE PLOT EXPANSION FACTOR 67
4.2.4 CLUSTER PLOTS 68
4.2.5 NESTED SUB-PLOTS 68
4.2.6 SLOPE CORRECTION 70
4.2.6.1 Effects of slope correction 72
4.3 FIXED AREA PLOTS AT THE STAND BOUNDARY 72
4.4 BITTERLICH SAMPLING (ANGLE COUNT SAMPLING) 74
4.4.1 INTRODUCTION 74
4.4.2 THE PRINCIPLE OF BITTERLICH SAMPLING 75
4.4.3 CHOICE OF BASAL AREA FACTOR 77
4.4.4 DETERMINING THE BASAL AREA FACTOR OF YOUR THUMB 78
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.4.5 BITTERLICH SAMPLING ON SLOPED TERRAIN</td>
<td>78</td>
</tr>
<tr>
<td>4.4.6 BITTERLICH SAMPLING: ESTIMATION OF NUMBER OF STEMS</td>
<td>79</td>
</tr>
<tr>
<td><strong>4.5 DISTANCE BASED PLOTS</strong></td>
<td>81</td>
</tr>
<tr>
<td>4.5.1 CONCEPTS</td>
<td>81</td>
</tr>
<tr>
<td>4.5.2 EMPIRICAL APPROXIMATIONS</td>
<td>83</td>
</tr>
<tr>
<td>4.5.3 UNBIASED ESTIMATOR</td>
<td>84</td>
</tr>
<tr>
<td><strong>4.6 COMPARISON OF THE STATISTICAL PERFORMANCE OF FIXED AREA PLOTS,</strong></td>
<td>84</td>
</tr>
<tr>
<td>BITTERLICH PLOTS AND DISTANCE BASED PLOTS</td>
<td></td>
</tr>
<tr>
<td>4.7 NON-RESPONSE</td>
<td>86</td>
</tr>
<tr>
<td><strong>4.8 TWO DIFFERENT APPROACHES TO POPULATIONS OF SAMPLE PLOTS</strong></td>
<td>87</td>
</tr>
<tr>
<td><strong>5. SAMPLING TECHNIQUES</strong></td>
<td>91</td>
</tr>
<tr>
<td><strong>5.1 SIMPLE RANDOM SAMPLING (SRS)</strong></td>
<td>91</td>
</tr>
<tr>
<td>5.1.1 GENERAL OBSERVATIONS</td>
<td>91</td>
</tr>
<tr>
<td>5.1.2 RANDOM SELECTION</td>
<td>91</td>
</tr>
<tr>
<td>5.1.3 NOTATIONS USED</td>
<td>94</td>
</tr>
<tr>
<td><strong>5.2 STRATIFIED SAMPLING</strong></td>
<td>97</td>
</tr>
<tr>
<td>5.2.1 INTRODUCTION</td>
<td>97</td>
</tr>
<tr>
<td>5.2.2 STATISTICAL CONCEPT</td>
<td>98</td>
</tr>
<tr>
<td>5.2.3 NOTATION</td>
<td>99</td>
</tr>
<tr>
<td>5.2.4 ESTIMATORS IN STRATIFIED RANDOM SAMPLING</td>
<td>99</td>
</tr>
<tr>
<td>5.2.5 SAMPLE SIZE IN STRATIFIED RANDOM SAMPLING</td>
<td>101</td>
</tr>
<tr>
<td>5.2.6 SUMMARIZING</td>
<td>103</td>
</tr>
<tr>
<td><strong>5.3 SAMPLING WITH CLUSTER PLOTS</strong></td>
<td>105</td>
</tr>
<tr>
<td>5.3.1 INTRODUCTION</td>
<td>105</td>
</tr>
<tr>
<td>5.3.2 NOTATION</td>
<td>106</td>
</tr>
<tr>
<td>5.3.3 ESTIMATORS FOR SAMPLING WITH CLUSTER PLOTS</td>
<td>107</td>
</tr>
<tr>
<td>5.3.4 CAUTIONS IN CLUSTER SAMPLING</td>
<td>108</td>
</tr>
<tr>
<td>5.3.5 COMPARISON TO SRS</td>
<td>111</td>
</tr>
<tr>
<td>5.3.6 SPATIAL AUTOCORRELATION AND PRECISION</td>
<td>113</td>
</tr>
<tr>
<td>5.3.7 CLUSTER DESIGN PLANNING CRITERIA</td>
<td>115</td>
</tr>
<tr>
<td>5.3.8 AN EXAMPLE OF CLUSTER DESIGN OPTIMIZATION</td>
<td>115</td>
</tr>
<tr>
<td><strong>5.4 ADAPTIVE CLUSTER SAMPLING</strong></td>
<td>117</td>
</tr>
<tr>
<td>5.4.1 INTRODUCTION</td>
<td>117</td>
</tr>
<tr>
<td>5.4.2 GENERAL PROCEDURE OF SAMPLING WITH ADAPTIVE CLUSTER PLOTS</td>
<td>118</td>
</tr>
<tr>
<td>5.4.3 TERMINOLOGY</td>
<td>119</td>
</tr>
<tr>
<td>5.4.4 ESTIMATORS</td>
<td>120</td>
</tr>
<tr>
<td>5.4.5 CHARACTERISTICS OF ADAPTIVE CLUSTER SAMPLING</td>
<td>120</td>
</tr>
<tr>
<td><strong>5.5 SYSTEMATIC SAMPLING</strong></td>
<td>123</td>
</tr>
<tr>
<td>5.5.1 GENERAL DESCRIPTIONS OF SYSTEMATIC SAMPLING</td>
<td>123</td>
</tr>
<tr>
<td>5.5.2 SAMPLE SIZE IN SYSTEMATIC SAMPLING = NUMBER OF OBSERVATION POINTS</td>
<td>124</td>
</tr>
<tr>
<td>5.5.3 SOME ADVANTAGES OF SYSTEMATIC SAMPLING</td>
<td>125</td>
</tr>
<tr>
<td>5.5.4 SOME PREOCCUPATIONS WITH SYSTEMATIC SAMPLING</td>
<td>126</td>
</tr>
<tr>
<td>5.5.5 IMPLEMENTATION OF SYSTEMATIC SAMPLE SELECTION</td>
<td>126</td>
</tr>
<tr>
<td>5.5.6 THE VARIANCE ISSUE IN SYSTEMATIC SAMPLING</td>
<td>128</td>
</tr>
<tr>
<td>5.5.6.1 Empirical approximation of error variance</td>
<td>128</td>
</tr>
<tr>
<td>5.5.6.2 Employing the SRS estimators</td>
<td>128</td>
</tr>
<tr>
<td>5.5.6.3 Random differences method</td>
<td>128</td>
</tr>
<tr>
<td>5.5.6.4 Pair difference technique</td>
<td>129</td>
</tr>
<tr>
<td>5.5.7 CONSEQUENCES OF VARIANCE APPROXIMATION IN SYSTEMATIC SAMPLING</td>
<td>131</td>
</tr>
<tr>
<td>5.5.8 COMPARISON OF DIFFERENT GRID SHAPES IN SYSTEMATIC SAMPLING</td>
<td>131</td>
</tr>
</tbody>
</table>
5.6 THE RATIO ESTIMATOR  
5.6.1 INTRODUCTION  
5.6.2 NOTATION  
5.6.3 ESTIMATORS  
5.6.4 EFFICIENCY  
5.6.5 CHARACTERISTICS OF RATIO ESTIMATOR  
5.6.6 REGRESSION ESTIMATOR  
5.7 DOUBLE SAMPLING  
5.7.1 INTRODUCTION  
5.7.2 DOUBLE SAMPLING FOR STRATIFICATION (DSS)  
5.7.3 DOUBLE SAMPLING WITH RATIO OR REGRESSION ESTIMATOR  
5.7.4 Examples of application  
5.8 LINE SAMPLING  
5.8.1 INTRODUCTION  
5.8.2 LINE INTERCEPT SAMPLING  
5.8.3 LINE INTERSECT SAMPLING  
5.8.4 Applications of line intersect sampling  
5.8.5 Using sample lines as sample selection tools  
5.9 SAMPLING WITH UNEQUAL SELECTION PROBABILITIES  
5.9.1 INTRODUCTION  
5.9.2 LIST SAMPLING = PPS SAMPLING  
5.9.3 BITTERLICH SAMPLING  
5.9.4 RANDOMIZED BRANCH SAMPLING (RBS)  
6. SOME SPECIFIC ESTIMATION ISSUES  
6.1 NOTIONS ON ESTIMATING CHANGES  
6.1.1 GENERAL OBSERVATIONS  
6.1.2 PERMANENT PLOTS  
6.1.3 GROWTH COMPONENTS  
6.1.4 SAMPLING WITH PARTIAL REPLACEMENT  
6.2 ESTIMATING FOREST AREA  
6.2.1 GENERAL OBSERVATIONS  
6.2.2 AREA ESTIMATION BY SAMPLE POINTS  
6.2.3 AREA ESTIMATION BY LINES OR CLUSTERS OF POINTS  
6.2.4 ESTIMATION OF LENGTH FROM THE ESTIMATION OF AREAS  
6.3 ESTIMATING THE LENGTH OF THE FOREST EDGE  
6.3.1 GENERAL CONSIDERATIONS  
6.3.2 MAPPED PLOTS  
6.3.3 LINE INTERSECT SAMPLING  
6.3.4 COUNTING THE BORDER PLOTS
6.4 ESTIMATING NUMBER OF SPECIES 171
6.4.1 GENERAL OBSERVATIONS ON THE PROBLEM OF ESTIMATING NUMBER OF SPECIES 171
6.4.2 ESTIMATORS 172
6.4.3 THE ISSUE OF SPECIES IDENTIFICATION 173
6.4.4 SPECIES ESTIMATION IN LARGE AREA FOREST INVENTORY 174

7. PLANNING ISSUES IN FOREST INVENTORIES 176
7.1 PLANNING A FOREST INVENTORY 176
7.1.1 INTRODUCTION 176
7.1.2 “GOOD” FOREST INVENTORY 176
7.1.3 PROCEDURE OF PLANNING 177
7.1.4 FIELD TEAMS 178
7.1.5 FOREST INVENTORY REPORTING 179
7.1.6 SOURCES OF ERRORS 181

8. THE UN-FCCC AND ITS IMPLICATIONS FOR FOREST MONITORING 183
8.1 INTRODUCTION 183
8.2 IPCC 183
8.3 UN-FCCC 184
8.4 CONFERENCE OF PARTIES (COP) 184
8.5 MRV 185
8.6 THE KYOTO PROTOCOL 185
8.7 EMISSIONS TRADING 186
8.8 JOINT IMPLEMENTATION (JI) AND CLEAN DEVELOPMENT MECHANISM (CDM) 186
8.9 ADDITIONALITY AND LEAKAGE 187
8.10 REDUCING EMISSIONS FROM DEFORESTATION AND FOREST DEGRADATION (REDD) 187
8.11 REDD AND REDD+ 188
8.12 FOREST MONITORING IN THE UN-FCCC CONTEXT 189
8.13 ROLE OF REMOTE SENSING 191

9. LITERATURE CITED 192

10. SELECTED TEXTBOOKS 197
1. Introduction

1.1 Background and objectives

It is well known that forests play an important role for biodiversity, for livelihoods and for local and national economies. Regardless of whether one looks at forests primarily as an ecosystem or as a resource – planning data is required for “informed decisions” in forest management, forest conservation and forest policies. In general, basic data and information are required when a renewable natural resource – such as forest – is to be managed sustainably. Eventually, there is quite some truth in the saying “If you cannot measure it you cannot manage it”.

Forest inventory is the activity of data collection that helps generating the required information base of the forests within a defined area of interest. Commonly, forest inventories are organized as projects with a defined duration.

The term forest monitoring is used in a wider sense and does commonly embrace the observation and assessment of status and changes. Forest monitoring systems have a long-term character, are organized as programs and embrace repeated implementations of forest inventories.

Information requirements regarding forests are as manifold as are the interests in forests which may basically be viewed (1) as a resource (people-centered) and (2) as an ecosystem (nature-centered). Parties interested in information on forests are above all decision makers and researchers in forestry and related fields. Forest owners, forest managers and forest politicians are those who demand information about the forest resource, but also regional planners and the wood industry; and conservation biologists, ecologists and tourism managers may be interested in forest ecosystem information. Once the group of actually and potentially interested parties can clearly be identified, it is straightforward to plan an inventory according to their expressed needs and expectations. In some cases – and in particular in large area forest inventories - one needs to plan an inventory in a flexible manner so that many different potentially interested users are addressed – without yet knowing all of them and their needs exactly from the outset.

Experience of the past decades has shown that the expectations towards forest inventories are getting wider and wider. The traditional forest inventory that focuses only and exclusively on timber production is, of course, still in use in forest plantation companies where trees are very intensively managed much like agricultural crops. However, forests are more and more managed for multiple services and functions, which is also reflected in the range of topics that are addressed in forest inventories. In some regions, forest inventories have developed towards tree inventories including also non-forest lands, or even to comprehensive land use assessments.

These lecture notes shall give you an insight into forest inventory from an implementation point of view and also from a research point of view. The major part of the lecture and the lecture notes is on sampling and plot design, which is applied statistics. The principles of statistical sampling are not only relevant in the forest inventory context but in any other empirical discipline as well; it has largely to do with statistical methods of empirical research.

The lecture notes shall help you to understand the principles of forest inventories. You should be able to plan your own inventory in a methodologically sound manner and according to statistical principles. You should know how to write good inventory reports but also how to critically read inventory reports of others, and how to ask the right and relevant questions.

A most important point eventually is that you should never look at a forest monitoring exclusively from the mere technical point of view (on which we are actually focusing in this lecture!), but you should clearly recognize that forest monitoring does always serve a specific goal and is always embedded in decision processes, generating information in order to – in the ideal case – facilitate what is called informed decisions.