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International Co-operative Programme on Assessment and  
Monitoring of Air Pollution Effects on Forests (ICP Forests)

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# MANUAL

on

methods and criteria for harmonized sampling, assessment,  
monitoring and analysis of the effects of air pollution on forests

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## Part V

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## Tree Growth

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## 1. Introduction

The growth of trees is a key ecological parameter of forests and thus of high importance as an indicator of forest condition. This manual focuses on growth assessment within Level II plots. On Level I plots of the large scale assessment no periodic tree size measurements have yet been made.

Increment is defined as the growth of trees (*shoots in coppice forests*) and stands within a defined period and can be expressed as increment of diameter, basal area, height and/or volume. These parameters can be linked to external as well as internal factors serving as a proxy parameter for the reaction of trees and stands to changes in site and environmental conditions. As the assessments are carried out on fixed plots the calculation of area related estimates is possible. The advantages before other proxies lie in their direct economical and ecological importance. Tree growth is grouped here into periodic increment of all trees on the plot and permanent or continuous tree diameter change of selected trees. In addition to these measurements past growth can be reconstructed using the well developed methods of dendrochronology and may be used as a proxy for past environmental conditions. In addition to growth, stand structure provides information for the interpretation of other assessments carried out, such as development of ground vegetation, crown defoliation, throughfall and others.

## 2. Scope and application

This part of the Manual aims at providing a consistent methodology to collect high quality, harmonized and comparable data at Level II monitoring plots on growth of trees and stands (Table 1). Harmonization of measurements and data processing procedures is essential to ensure comparability of results. To have their data used in the international database and evaluations, National Focal Centres and their scientific partners participating to the UNECE ICP Forests programme should follow the methods described here.

Recommendations for cross-linkages between growth measurements and assessments of e.g. crown condition are given, in order to enhance the scope of periodic measurements. Proposals focus on maximising data collection efficiency and aim towards whole tree assessments. It is recommended that all periodic non-destructive samplings and measurements are carried out on the same sampling area, which is permanently marked and identifiable over time (plot/sub-plot).

Growth studies by periodic non-destructive measurements are mandatory on all Level II plots. A growth assessment over 15 years (i.e. four periodic measurements on identical plot/subplot) will provide information on three increment periods, which is required before reliable information of increment change can be obtained.

Growth assessments on Level I plots are optional.

The increment data collected on the Level II plots will not be suitable for extrapolating to larger areas. In this respect, the plots should be seen as permanent monitoring plots and not as inventory plots. Tree ring analyses on either cores or disks sampled from felled or dead trees are an additional source of information and optional on Level II plots.

Table 1: Variables to be assessed within the growth survey of ICP Forests.

Variables	Status m – mandatory , o – optional			Units	min. resolution	Precision (see also chapter 5.2.5)	
	Level I	Level II	Level I II core				
<b>Plot level</b>							
Growth plot size	o*	m	m	ha	0.0001 ha	90 % @ ± 0.002 ha	
Growth plot design	o	o	o				
Number of assessed trees in growth plot	o	m	m	n/ha	1	90 % @ ± 10	
<b>Tree level</b>							
Tree species	o	m	m			99% ± 0.	
<i>Diameter (periodic measurement)</i>	o	m	m	cm	0.1 cm	90 % @ ±1,0 %	
<i>Diameter (permanent measurement)</i>	no	o	m	cm	0.01 cm	95 % @ ± 0,5%	
<i>Increment (continuous measurement)</i>	no	o	o	cm	0.01 cm	90 % @ ± 1%	
<i>Bark thickness</i>	o	o	o	cm	0.1 cm	90 % @ ±10,0 %	large natural variation
<i>Tree height (conifers)</i>	o	m **	m**	m	0.1 m	90 % @ ± 2 %	
<i>Tree height (broadleaves)</i>	o	m **	m**	m	0.1 m	90 % @ ± 5 %	
<i>Crown base</i>	o	m ***	m***	m	0.1 m	90 % @ ± 10 %	
<i>Crown width</i>	o	o	o	m	0.1 m	90 % @ ± 10 %	
<i>Annual tree ring width</i>	no	o	o	cm	0.001 cm	90 % @ ± 5%	
<i>Annual Early/late wood width (conifers and ring porous trees)</i>	no	o	o	cm	0.001 cm	90 % @ ± 10%	
<i>Annual height increment (stem analysis)</i>	no	o	o	m	0,1 m	90 % @ ± 5 %	
<i>Volume</i>	no	o	o	m <sup>3</sup>	0,001 m <sup>3</sup>	95 % @ ± 10%	Precision depends on measurement and taper function

\* If growth parameters are assessed on Level I plot size is needed to derive area related estimates

\*\* at least subsample

\*\*\* from all trees with height measurement

### 3. Objectives

Compared to more physiological orientated measurements of tree metabolism restricted in space and time the assessment of growth is more integrative in an ecological sense and of much more economical relevance. Compared to crown condition assessment it is a quantitative parameter with longer tradition in research and more reliable based references. Besides the long term of observation, further drawbacks of growth are the unspecific behaviour and often delayed reaction or perception.

In general there is a trade-off between detail, costs, sample size and representativity of assessment. Therefore, a hierarchical approach of measurements and evaluation is appropriate.

Non destructive repeated measurements on identical trees reduce statistical errors but require at least two assessments in time. Longer time series of repeated measurements tend to be less sensitive to individual measurements errors and enable corrections and/or filling of data gaps. While the destructive methods of tree coring and stem discs are restricted to a selection of trees they are more accurate with higher/annual resolution in time and providing possibilities to reconstruct past increment development.

In general, in most regions of Europe growth is a yearly phenomenon driven by climatic seasonality. The proposed five-year interval of growth measurements on all trees on the Level II plot is a compromise between resources and information gain. For specific questions, a higher resolution, such as annual and sub-annual or even hourly measurements, might be needed. For this purpose special methods are available, either non-destructive or destructive. They are also described in the manual.

The methods of growth and yield research are well developed and have been applied for a long time. Therefore, standard procedures are available and expertise in analyses is readily on-hand. Although these quantitative methods are well developed qualitative interpretation needs **references of "normal" growth which are subjective and therefore debatable. Such reference may** be derived from empirical growth models, yield tables, other trees as a reference, past growth of the sample tree and others.

### 4. Location of measurements and sampling

The monitoring of increment is performed by applying four procedures:

- periodic measurements of all the trees (*shoots*) in the plots or subplots (Level II and Level I).
- the application of permanent diameter bands read manually to derive information at least on annual growth or shorter periods (Level II)
- the application of continuous measuring bands to derive information on short intervals (minutes to hours, electronically recorded) (Level II)
- sampling increment cores or disks to establish retrospective growth patterns of the past; sampling for tree ring analysis should be done on several trees (*shoots*) in the surroundings of the plots; more discs from each tree enable also the estimation of height growth pattern (Level II)

Annual information on radial growth can be obtained either by tree ring analyses, by measurement with permanently fixed tapes or electronic devices, but these measurements will never comprise all trees on a plot. Tree ring analyses on either cores or disks sampled from felled or dead trees are an optional supplementary source of information on Level II plots.

## 4.1 Sampling design

### 4.1.1 Sample plots

As the aim of the periodic growth assessment is to derive area related estimates the information on area is essential. When establishing plots, due regard should be given to enable observations over at least 15 years and plots should not be planned for final cutting within this time span. Increment measurements should preferably not be started on a plot within 5 years of any previous thinning, but should be continued through subsequent thinning cycles.

#### 4.1.1.1 Level II

The minimum Level II plot size is 0.25 ha, expressed on a horizontal plane, as specified in Part II of the ICP Forests Manual. This size is sufficient for any assessment of increment that might be undertaken in the plot.

Each Level II site is composed of a monitoring plot and a buffer zone (see Manual Part II). For increment, it is recommended that this buffer zone is equivalent in width to the mean height of the dominant trees (shoots in coppice forests) in and around the plot.

An assessment of the plot prior to any thinning operation is recommended. Maximum use should be made of any removed tree for additional measurements (e.g. stem analysis, biomass assessment, etc.).

As the permanent and continuous growth measurements are not suited to derive area related estimates no information on area is needed. But the mandatory periodic growth measurements should be carried out on these trees as well as crown condition surveys.

#### *Use of sub-plots*

Only in such cases where the stand situation makes the periodic assessment on the whole observation area not feasible (e.g. very large plots or extreme dense stands) a sub-plot may be installed. The size of these sub-plots should be in agreement with the measurement procedures of the country concerned and must be large enough to provide reliable estimates of stand increment over the entire measurement period. The selection method of sub-plots has to be bias-free and in accordance with the other measurements and observations. The exact position and size of any sub-plot must be determined and reported.

**Table 2:** Sub-plot sizes for growth assessments on Level I

MEASUREMENTS	Subplot 1 (r=3.09m) 30 m <sup>2</sup>	Subplot 2 (r=11.28m) 400 m <sup>2</sup>	Subplot 3 (r=25.24m) 2000 m <sup>2</sup>
DBH and species of all woody plants taller than 130 cm (standing and lying, living and dead)	all trees DBH > <b>5*</b> cm (taller than <b>130</b> cm)	all trees DBH ≥ <b>10</b> cm	only trees DBH ≥ <b>50</b> cm

\*3 cm in case of coppice

#### 4.1.1.2 Level I

The determination of plot size for Level I plots is under the responsibility of the National Focal Centres. 2000m<sup>2</sup> are recommended for growth assessments. Plot size for growth assessments needs to be reported. Growth assessments can be carried out on all trees within a certain plot or subplot (see 4.1.1.1) or can be carried out within different subplots depending on the dbh of the trees, following the design of the BioSoil project (Table 2, see as well Part II of the Manual).

#### 4.1.1.3 Sample plot in coppices, maquis and similar vegetation types

For coppice forests, maquis and similar vegetation types see the respective specifications in each paragraph. As a general rule for coppice forests no longer managed but which continue to produce large shoots on each stool (stored coppices) the measurement procedure of coppices will be applied. Thinned coppices undergoing conversion to high forest (only one (two) shoots per stool released) and showing physiognomy and structure similar to stands originated from seeds must be considered as high forests as regards the measurement procedure.

#### 4.1.2 Sample trees

Design is differentiated according to the four procedures as they are different in costs and/or intensity, some are destructive.

##### 4.1.2.1 Periodic measurement (Level II)

###### *Sample selection*

Periodic diameter measurements are to be taken from each tree above the threshold on the whole plot or sub-plot, no other selection allowed. Only in case that not all trees are chosen for height measurement a selection procedure is allowed (see Annex 2).

All trees with at least 5 cm diameter over bark (at least 3 cm for stools and shoots in coppice forests) must be individually identifiable by numbering. The location of dbh measurements must also be indicated at the stem. The spatial co-ordinates of all trees (stools in coppice forests) should be recorded optionally for future relocation of trees as well as for an adequate calculation of competition known to influence tree increment significantly and to provide information of the within stand structure.

###### *Timing and intervals*

A commonly used interval in forest growth and yield studies is 5 years being a good compromise between magnitude of expected changes, sampling errors and costs. A growth assessment over 15 years (i.e. four periodic measurements on identical plot/subplot) will provide information on three increment periods, what is required before reliable estimates of increment change can be obtained.

Basic periodic measurements and assessments of dbh, tree height, height to crown base, removals and mortality (see below) must be undertaken no less than every fifth year. These measurements have to be reported every five years. The first measurement campaign within the programme was carried out in 1994-1995 (from the end of the vegetation period 1994 to the beginning of the vegetation period 1995), the second during winter of 1999-2000, and subsequently every fifth year 2004-2005 and 2009-2010 and so on.

##### 4.1.2.2 Permanent measurement (Level II)

###### *Sample selection*

Permanent determinations of stem diameter changes (circumference) are performed on a sub-sample of trees. Sample size is determined by financial constraints and personal resources. These measurements are aiming at revealing relations between different years, species specific growth reactions and characterising growth behaviour in relation to other environmental factors. Therefore, tree selection procedure need not necessarily be representative for the tree population of the whole plot but the applied selection procedure should be taken into account when drawing inferences or extrapolating the results. For providing absolute values of growth the periodic assessment of all trees is to be used.

Selection criteria and numbers of trees for measurements have been developed. See Annex 3 for detailed explanation.

###### *Timing and intervals*

From weekly to at least annual, fixed intervals are needed. Small increment changes should be interpreted only under consideration of specific climatic condition at the time of assessment

(temperature may influence the extension of measuring tape) or of the period before (longer drought period or strong frost will reduce the reading).

#### 4.1.2.3 Continuous circumference measurement (Level II)

##### *Sample selection*

Continuous circumference measurements are performed on a sub-sample of trees. Sample size will be even more severely limited by financial constraints and technical restrictions. The representativity is here even less important than with permanent measurements. So some species or social classes assumed to be more sensitive in the reaction in question than others and maybe therefore preferentially selected or only trees of one single species may be selected (see manual on Crown assessments for the definition of social class). The measurements are aiming at relations between changes in stem circumference or stem size and environmental factors (i.e. reactions on water supply, effects of drought, frost shrinkage). Also the onset and cessation of radial growth may be detected with these instruments. The significant reaction in volume of bark and partially wood on water availability can be used when validating precipitation data to detect data gaps or measurement errors.

Selection criteria and numbers of trees for measurements have been developed. See Annex 3 for detailed explanation.

##### *Timing and intervals*

Depending on technical equipment (data storage capacity) intervals between some minutes or hours will be adequate.

#### 4.1.2.4 Tree ring analyses on tree cores and stem discs (Level II)

##### *Sample selection*

Increment cores or tree disks should not be sampled from the alive trees (shoots) within the plot, as this will influence some of the monitoring results. Trees (shoots) cut for thinning purposes should be used for stem analyses, where possible.

Trees (shoots) to be felled for stem analysis should be selected sufficiently far from the plots in order to avoid changes to trees in the plots (e.g. extra light, more available root space etc.), but close enough to represent similar site conditions.

Trees (shoots) selected for coring and stem analysis should not deviate evidently from individuals in the stands.

##### *Timing and intervals*

The timing and intervals are determined by management purposes (harvest or thinning interventions) or specifically timed assessments. The retrospective character of these analyses makes it reasonable to be carried out after some years when other observations enable synchronous evaluations.

## 4.2 Sampling equipment

### 4.2.1 Sampling equipment with periodic measurements

For determining the diameter or circumference the traditional equipment of forest growth studies is a calliper or measuring tape. For determining height of tree top or other interesting points (e.g. crown base) a hypsometer is used (like Forestor Vertex); several types of hypsometer are available, differing in costs, accuracy and handling. For small trees a measuring rod up to ca. 9 m may be used.

A tool for recording measurements and remarks in adequate manner is needed. This may be a field book or a data acquisition device. Different such devices are available depending on the software installed they will enable data checks already outside on the plot.

#### 4.2.2 Sampling equipment with permanent measurements

Normally permanent diameter measurements are aiming at the assessment of changes with an accuracy 1/10 of mm. Usually a permanent girth band tightened by a spring, a scale (with nonius reading) enables this precision when permanently fixed on the tree to avoid variation due to differing measurement positions. Information on such permanent girth bands on <http://www.ums-muc.de/produkte/pflanzenmesstechnik/d1.html> for example. The position of the girth band should be marked during installation to detect a change still possible in placement.

A tool for recording these readings and remarks in adequate manner is needed. Electronical devices will enable some checks of permanent measurements already on the plot.

Trees for permanent measurement within the growth plot being already numbered should keep this number, trees being in the buffer zone or outside the plot should get a new number starting with "P" for permanent.

#### 4.2.3 Sampling equipment with continuous measurements

Various types of equipment are available; a review of some types is given by Drew&Downes (2009). Further information maybe obtained from the homepage of different suppliers (<http://www.emsbrno.cz/p.axd/en/Dendrometer.html?view=1>, <http://www.ecomatik.de/>, <http://www.ums-muc.de/produkte/pflanzenmesstechnik/d6.html>, <http://www.dynamax.com/DEX.htm>, <http://www.ictinternational.com/dex.htm>, [http://www.natkon.ch/index.php?option=com\\_content&task=view&id=22&Itemid=43](http://www.natkon.ch/index.php?option=com_content&task=view&id=22&Itemid=43)).

In principle circumference bands and point dendrometers are available. The fixation on the stem is crucial; damage which might influence the measurement should be avoided. The installation of a permanent girth band in addition is highly recommended next to the continuous electronical measuring device which should be mounted some centimetres above 1.3 m height.

The changes measured by electronic continuous devices are transformed into changes in circumference afterwards. Measurement accuracy reaches theoretically 5 µm. Often the data quality is reduced by erroneous values or data gaps, additional information from permanent bands will help to minimize these negative effects.

For data capturing a data logger is needed. A data transfer via GSM is of great advantage enabling immediate detection of system problems and erroneous measurements.

Trees for continuous measurement within the growth plot being already numbered should keep this number; trees being in the buffer zone or outside the plot should get a new number starting with "C" for continuous.

#### 4.2.4 Tree ring analysis

For sampling increment cores an increment borer is used; different products in length as well as for hardwood or softwood are available. Alternatively stem discs may be sampled; if more discs from one tree are sampled the sample height of each disc is to be recorded.

The measurement of tree ring width and other tree ring parameters can be done applying a simple ruler or specific tree measuring devices (like Eklund or Johann) including systems applying picture analyses.

Trees sampled for tree ring analysis (core or discs) within the growth plot being already numbered should keep this number; trees from the buffer zone or outside the plot should get a new number starting with "R" for tree ring analyses.

### 4.3 Sample collection, transport and storage

Samples are only collected for tree core and stem disc measurements. The handling of samples for tree ring analysis needs some effort to take care of not breaking the cores (e.g. using an adequate container) or disks. Specific care is necessary not to contaminate the samples if chemical analysis will follow. The shrinkage of samples and cracking of stem discs when drying is a normal process. Before measuring, the cores need to be submerged to enable expansion.

## 5. Measurements

### 5.1 Parameters to be assessed and reporting units

#### 5.1.1 Selected variables

The list of selected variables and reporting units is given in Table 1. They include periodic, permanent and continuous measurements to be made on a mandatory or optional basis.

#### 5.1.2 Periodic measurements (mandatory)

The following measurements every five years are mandatory on Level II and optional on Level I:

- dbh of all trees (shoots in coppice forests)
- tree height and height to crown base of all trees (shoots in coppice forests) in the plot in order to calculate crown length which is to be submitted. In case that not all trees are measured a selection procedure is allowed (see Annex 2) Non measured heights can be derived from an appropriate dbh-height function,

For measurement details see Annex 1. Calculations of stand mean height and dominant height as well as stem volume and other measurements of other indices (see also Annex 1) on the plot or sub-plots are optional.

Tree mortality and removal (mandatory): It should be reported if a tree has died, fallen or disappeared. For the recording of tree mortality and removal the two digit coding system is applied. These are complementary with those used with crown condition assessment, a few additional codes have been added. As tree growth measurement takes place regularly only every fifth year it will sometimes not be possible to identify causes for removals or mortality. In these cases the codes for unknown reason or unknown cause is to be used.

Codes for tree status, removal or mortality are defined in the forms document and the respective explanatory item for survey GR. New codes 07, 08, 19, 39, and 49 were introduced in order to **allow for a better description of the trees' status.**

#### 5.1.3 Permanent measurements (optional on Level II plots, but mandatory on core plots)

These measurements are based on a manual reading of changes in circumference on fixed girth bands, an annual (or monthly) measurement without fixed girth bands is not recommended as the measurement errors are high compared with the expected increment. The shorter the interval between readings the more detailed information is gathered. But only annual values of diameter are to be reported.

#### 5.1.4 Continuous measurements (optional)

This measurement technique provides increment values for short period. Depending on the type of measurement device the measured values are providing information on changes in circumference or on the radial expansion/shrinkage at one single point. Like with the other

measurement they are assessing not only increase in wood, but also in bark. The variation in tree dimension during the day is strongly influenced by changes in water saturation and temperature being **often larger than the “real” increase in volume. Deriving daily rates needs therefore great care** and an evaluation of short term fluctuation should take this into account with proper respect. Periodical increment of longer periods (a week or month) is **less burdened by this “noise”** and therefore often better suited for evaluation.

### 5.1.5 Tree ring analysis (optional)

Increment cores or tree disks must not be sampled from the alive trees (shoots) on the plot, as this will influence some of the monitoring results. But trees (shoots) cut for thinning purposes in the course of normal management should be used for stem analyses, wherever possible.

Trees (shoots) to be felled for stem analysis should be selected sufficiently far from the plots in order to avoid changes to trees in the plots (e.g. extra light, more available root space etc.), but close enough to represent similar site conditions.

When evaluating the results of tree ring analysis the circumstances of sampling should be taken into account with proper respect. Inference from these trees to the whole stand should be restricted to cases where a representative and bias-free sampling was possible. All mandatory growth parameters must also be taken on sampled trees.

Unlike with the other measurements tree ring analyses are assessing only the increase in wood, not including the bark.

### 5.1.6 Stand records

The history of the stand is essential for interpreting increment and its development. Data on thinning, fertilization, other relevant interventions and changes to the forest stand are of great help when interpreting the results. All details of management operations undertaken on the plot since its establishment are essential. The fate of each individual tree from the start of the monitoring is implicitly traceable over the whole observed period by the periodically undertaken assessments. The assessment of crown condition may provide additional information.

## 5.2 Quality Assurance and Quality Control

For forest growth measurements, quality control is particularly important, because many of the measured variables will be used in combination to compute additional values. If data remain unchecked, this will lead to a propagation of errors. It is important to distinguish the different possible types of errors and whether these are systematically different from the true value or fluctuate randomly around it. Sampling errors arise when only a portion of the population is assessed on sub-plots. Observation errors arise when measurements or observations deviate from the true value. If the determination of the plot area is erroneous all area related estimates will be wrong consequently.

The following causes of measurement and assessment errors may be distinguished:

Systematic errors:

- instrument bias (faulty diameter bands or callipers or height measuring devices);
- neglecting the influence of temperature on the measurement device
- measurement inaccuracy (including rounding errors).

Random errors:

- ambiguous definition of assessment variables (e.g. the usually difficult definition of the tree crown base);

- insufficient training (e.g. an observer targets the outer branches and not the tree top for the height measurement);
- measurement inaccuracy (e.g. if the scaling unit is one degree using a clinometer);
- measurement conditions (irregular stems, dense understorey, large round-shape crown or leaning trees for tree height measurement);
- writing/typing errors, hearing mistakes

### 5.2.1 QA/QC procedures

QA/QC procedures need to be applied before, during and after data collection.

#### 5.2.1.1 QA/QC at the planning stage

The following procedures should be applied during the planning stage:

- Critical review of parameters to be assessed (in respect to achievable precision, costs, objectivity and reliability)
- Clear definition of the parameters to be assessed;
- Optimal choice of instruments and assessment methods (precision versus costs);
- Selection of qualified field teams;
- **Selection of an unbiased sampling design, e.g. an "impartial" design that does not allow the subjective (prejudiced and/or influenced) selection of the sample trees;**
- Determination of a sufficient sample size (precision versus costs);

#### 5.2.1.2 QA/QC before the data collection

The following procedures should be applied before data collection:

- adequate training of field teams;
- calibration of instruments;

#### 5.2.1.3 QA/QC during the data collection:

The following procedures should be applied during the data collection:

- adequate plausibility tests in the field (preferably with a hand-held data recorder); data that will not be recorded can be taken from previous assessments (for example georeferences to help identify each tree) or derived through modelling; for repeated assessments of tree size, previous values should not be available to the field team, but can be used with hand-held data recorders to test for impossible values and to ask for a second measurement;
- minimisation of the variation of assessment circumstances, for example: (i) to mark the measurement height for dbh which is mandatory on growth plots (ii) fix the position from which the height measurement is taken, (iii) limit the allowable weather conditions when measurements are carried out (no measurement when temperature below zero);
- independent controls (5 to 10% of the data, or an adequate minimum from repeated observations). It is important to carry out the control survey near to the time when the field crew carries out the field measurements in order to minimise possible sources of variations due to e.g. different measurement conditions. But the field crew and the control team should make separate assessments; at best the field team should neither be aware of the second assessment nor know the results;
- repeated training exercises (in particular if a shift in assessment methods becomes apparent);

- continuous calibration of instruments (in particular for mechanically-sensitive instruments; for example distance measuring instruments sensitive to air temperature and barometric-pressure used for tree height assessment should be calibrated and tested against a known distance before a measuring campaign);
- repeated measurements (e.g. two or more repetitions per tree) for tree height and height to crown base in order to check their consistency and reliability.

#### 5.2.1.4 QA/QC after the data collection

The following procedures should be applied during the planning stage:

- adequate plausibility tests and defined standards for minimum and maximum values when data are imported into the data-base;
- adequate plausibility checks during data analysis (test whether certain value combinations are possible or not, e.g. the ratios between dbh and height or others);
- assigning flags to each measured parameter in order to provide information on the quality status. For each measured variable (dbh, height, height to crown base, crown width, bark thickness, coordinates) one column with information on data check procedure is to be given. Correction values may be derived from models or expertise or by interpolation over time. If no corrections possible or feasible an adequate error flag should indicate the situation.

Respective codes for the submission of the data quality information are specified in the ICP Forests forms document.

#### 5.2.1.5 Use of data

When using the data:

- any analysis and subsequent interpretation of results must be undertaken taking into account the observed or expected measurement accuracy and precision.
- consider data quality information.

### 5.2.2 Plausibility limits

A proposal for data plausibility checks in the participating countries is given in Table 3. Adaptations to country or tree species specific values may be used in order to develop more powerful data checking procedures.

**Table 3:** Plausibility limits for forest growth variables

variable	unit	minimum	maximum	
Species	list			No change allowed
Dbh	cm	5,0*	200,0	
Height	m	1,5	50,0	
Height to crown base	m	0	40,0	less than height
Crown width	m	0,1	20,0	
Bark thickness	cm	0,1	9,9	
Tree ring width	cm	0,0	3,0	0 for missing rings
Early/late wood width	cm	0,0	3,0	
h/dbh ratio (height in m and dbh in cm)		0,25	3,0	

Volume (single tree)	m <sup>3</sup>	0,001	40,000	
Change in dbh within 5 years	cm	-0,0	20,0	
Change in dbh within one year	cm	-0,0	6,0	

\* 3 cm in case of coppice

### 5.2.3 Data completeness

The data of periodic as well as permanent dbh measurements have to be complete. Measurement of height might be impossible or not meaningful in some cases; the reason is to be given by the respective codes. Such missing heights can be replaced by dbh-height functions; this is indicated by data quality code 8.

The data from electronic devices are prone to be incomplete as the equipment is quite sensitive. The results of manually read girth bands enable adjusting the electronic read data when data gaps occur and to convert measured changes from electronic dendrometers into increment in mm. The higher the frequency of the reading from permanent girth bands is, the higher the possibility for the adjustment. The procedure of checking, filtering, compiling, summarizing the raw data is to be developed and reported. Only proofed and aggregated data should be submitted.

### 5.2.4 Data quality objectives or tolerable limits

Values of expected and desired accuracy and precision of total height, height to crown base, diameter measurements and tree ring width are given in Table 1. These values should be considered as guidelines for an evaluation of potentially problematic parameters. All reported values should have been measured according to the methods described in this manual.

### 5.2.5 Data quality limits

The results are considered of sufficient quality when –based on the control survey – a respective share of data fall within the tolerable limits (Table 3).

## 6. Data handling

### 6.1 Data submission procedures and forms

Submission procedures are described in part II of the manual. Forms and guidelines are available at the ICP Forests homepage.

### 6.2 Data validation

Data validation of growth data can be quite rigid compared to other assessments. Repeated growth measurements on single trees have the great advantage of having strong correlation over time. Furthermore the changes within a collective of trees within one stand will not differ extremely unless there are evident disturbances and the allometric behaviour of many parameters allows for further validations. When validating growth data as much use as possible should be made from these peculiarities through checking the development over time as well as comparing the development with other individuals of the same site

### 6.3 Transmission to co-ordinating centres

As periodic measurements are assessed only every 5 years, while permanent and continuous measurements have at least an annual resolution, data will in the first case be submitted every 5 years and in the second case annually.

### 6.4 Data processing guidelines

The following sections are provided only as a guideline; individual countries remain free to analyse the data from their Level II plots in whichever way is felt to be most appropriate.

With available height information it is possible to estimate single tree volume and derive volume increment ( $\text{m}^3$ ). However, the error associated with estimates of volume increment may be considerable, particularly in older trees. Volume per tree or per ha should be calculated using the best available equations for the species and local conditions. The range of validity of taper functions should be observed, any extrapolation should be avoided. Normally the percentage of increment of basal area corresponds quite well with the percentage of volume increment and can be used if no height information available.

In-growth presents a problem as mandatory dbh measurements are only to be taken with a diameter of 5 cm over bark (3 cm in coppice forests). Where basal area increment of trees is recorded in year  $t$  but not in year  $t-1$ , the initial diameter should be taken as 0 cm.

Removed or standing dead trees are to be included in the assessment of volume and basal area, to enable the calculation of total growth for correct estimation of increment. The proportion of removed or dead trees is reported. For growth assessment, removed or dead trees need only be reported once.

The calculation of mean diameter or height from the collective of larger trees (e.g. to 100 largest trees per hectare) provides often a better information than the average of the total stand.

Given the variety of tree species, site qualities and management regimes in European forests, it is highly unlikely that data collected on Level II plots will be suitable for making more than superficial comparisons in stand growth rates across Europe. While such comparisons are possible, the sample sizes required are so large as to effectively prohibit any degree of statistical control over the data. Consequently, the majority of analyses are likely to be site-specific.

Within a plot, the available sample sizes may be sufficient to undertake a number of analyses. However, because of the initial sampling design, it will not be possible to extrapolate the results to larger areas.

The following analyses are suggested for individual plots:

- derive diameter – height functions in order to check measured heights and to be able to replace erroneous or missing heights
- derive diameter – increment curves for each species
- calculate density measures like stand density index (Reineke, 1933) or relative spacing (Avery&Burkhart, 2002),
- evaluate the relationship between increment and other measures of crown condition
- evaluate site quality indices by comparing increment with other information on site quality
- evaluate the responses of annual increment to climatic influences
- Derive plot specific structure information, when coordinates are available.

## 6.5 Data reporting

Data reporting formats and deadlines are annually defined by the Programme Coordinating Centre of ICP Forests and need to be adopted by the Programme Task Force

## 7. References

Suggested further reading:

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## Annex 1: Guidelines for measurements

The following guidelines are to be used for measurements of the main tree dimensions (dbh, tree height and height of crown base). Where methods are compatible, individual countries may continue using their national systems. Dbh and other physical parameters are not to be measured during the growing season or strong frost. Height estimates of broad-leaved trees are usually more accurate when no foliage is present.

### Diameter at breast height (mandatory)

The diameter at breast height [dbh] (1.3 m height from ground level) of **all trees in the plots/sub-plots** with a diameter of 5.0 cm over bark (*and of all shoots with a diameter of 3.0 cm over bark in coppices*) or greater must be measured every five years. Diameters are to be measured perpendicular to the longitudinal axis of the stem (i.e. at an angle on leaning trees).

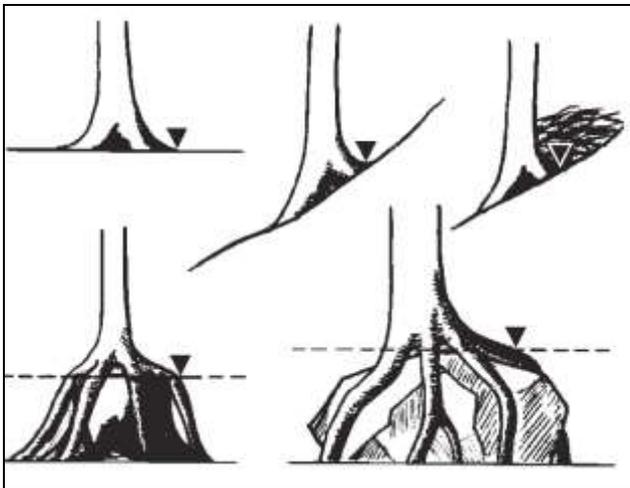


Figure 1: Definition of ground level under different conditions

Forked trees, with the fork below 1.3 m, are to be treated as two separate trees, problems may arise if these trees will unify after a while. Coppice shoots originating from a single stool are to be treated as separate trees (*e.g. stool 123, shoots 1,2,3, ...; stool 124, shoots 1,2,...*). If there is an irregularity at 1.3 m, diameter measurements are to be taken at points above and below the irregularity and the averaged value is to be reported. Trees with root buttresses above ground level are to have their diameters measured 1.3 m above the ground on the upper side of the tree. If the tree shows important irregularities at 1.3 m two diameters one below 1.3 and the other at the same distance above should be measured and the average reported.

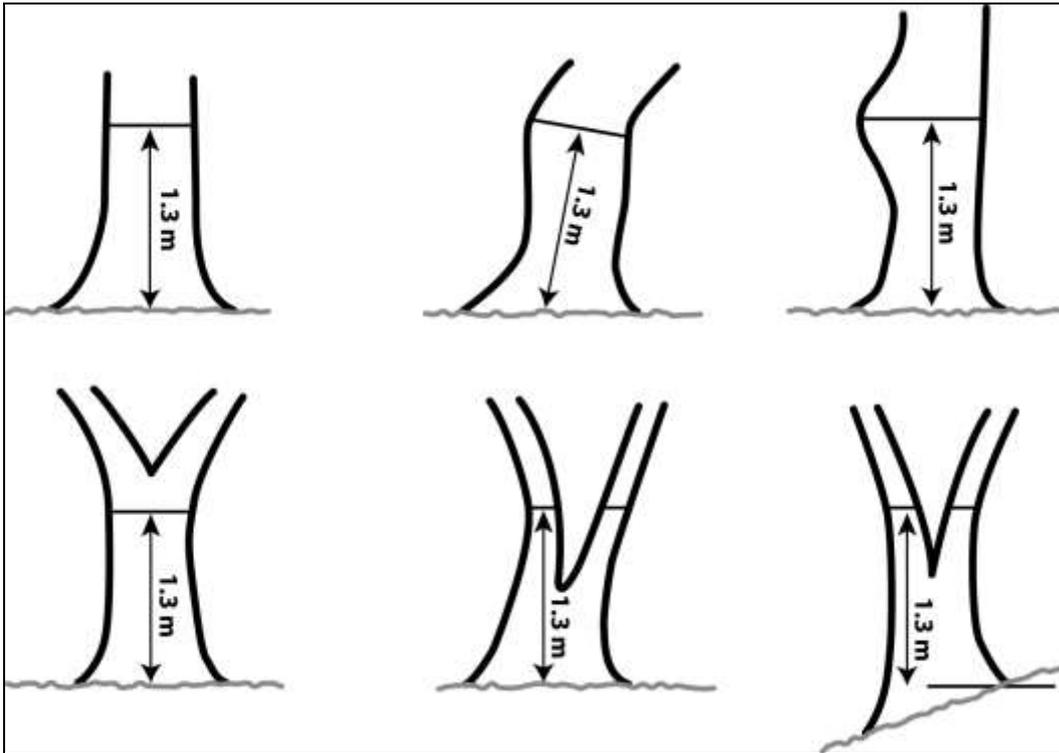
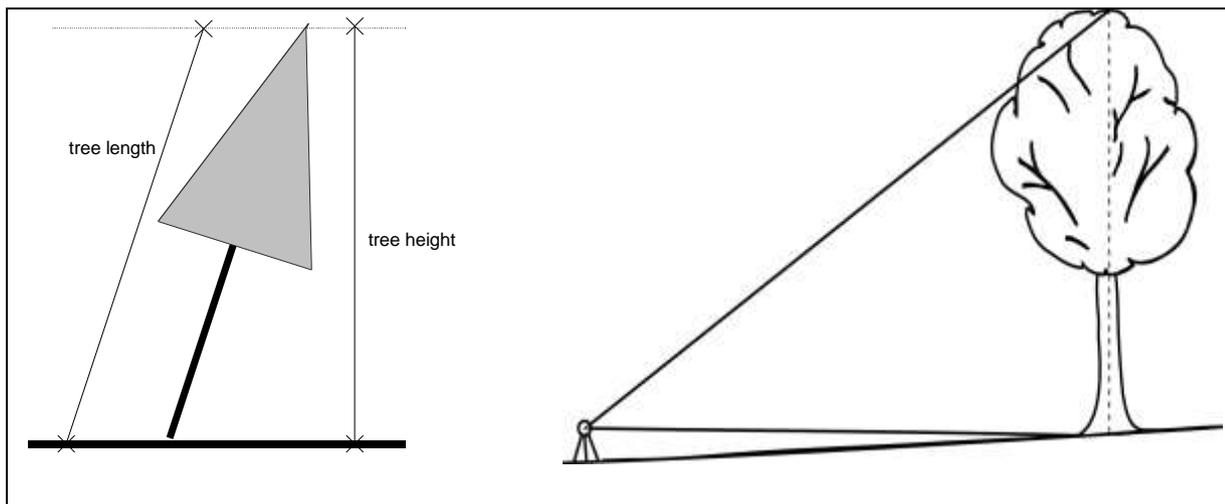


Figure 2: Where to measure dbh on trees with different form

Lichens and loose debris are to be removed prior to the measurement. Measurements are to be made using a diameter tape or a calliper of similar accuracy, and are to be recorded to the nearest 0.1 cm. The point(s) of measurement are to be clearly marked on the tree. Two points being necessary when using callipers at which the maximum diameter is measured and a second point at right-angles to this. Measurements are not to be made under frosty conditions, because tree stems shrink substantially.

### Tree height (mandatory)

The periodic measurement of tree (*shoot*) height is also mandatory. Tree (*shoot*) height is defined as the vertical distance between the highest point of the crown and the ground surface. It differs from tree (*shoot*) length, which is defined as the bole length from ground level to the tip of the tree (*shoot*; Fig. 1). Where possible, measurement is to be made to the nearest 0.1 m; it is recognised that this level of accuracy may not be achieved always, but is to be attained where possible. It is advised to record the position (e.g. distance from the tree and azimuth) from which the measurement is carried out in order to allow future measurements from the same standing position. Alternatively, measurement positions can be marked permanently on the ground. Although it is recognised that conditions of visibility may change after 10 or 20 years (growth of the understorey, crown development, ...), this is one way of limiting measurement errors.



**Figure 3:** To be observed when measuring tree height on broadleaved and leaning trees.

Hint: in some cases (e.g. dieback, shoot death), the top of the tree is defined as the highest "living" bud of the crown. Although it is not easy to see the top when measuring deciduous trees during winter, this may avoid measuring dried dead branches at the top of the tree and which have a tendency to break off prior to the onset of spring.

Hint: for leaning trees, it is advised to take height measurements perpendicular to the direction of leaning (see fig. 3).

Hint: when a tree stands on a slope, it is advised to take height measurements from the same contour line as the tree base or from above.

Hint: starting the measurement from the mark at dbh and adding 1,3 m to the result eliminates errors originating from different perceptions of ground.

## Height to Crown Base (mandatory) and Crown Width (optional)

The periodic measurement of height to crown base is mandatory on each tree where tree height is measured. Crown width (crown occupancy) measurement is optional and should be measured on trees for which height is assessed. Although desirable in order to ensure maximum connection between the different surveys carried out on Level II plots, it is recognised that growth **measurements do not necessarily express the same "crown volume" as that determined by assessments of crown condition.**

The height to the crown base is defined as the vertical distance between the crown base and the ground level (measured from the dbh mark as described above). The crown base is defined as the base of the lowest significant volume of foliage (or buds, if measurements are taken at winter time) and not the point where the branches supporting the foliage are attached to the trunk; epicormic branches are not included. When this is variable, average should be taken. If the crown is not continuous, the lowest part is considered to be the lowest branch with a minimum diameter of 3 cm within 2 m of the main part of the crown. If the accepted national method differs from the described method the national method can be used. This must be documented in the data accompanying report. In coppice forests, the crown of the stools is made up by the elementary crowns of the shoots and is considered as a whole. Height to crown base is therefore measured on each stool.

It is advised that recording of the crown base be carried out in the same position and at the same time as the tree height measurement. Care should be taken to ensure subsequent assessments are carried out from the same spot. If possible height to crown base should not be measured when tree crowns are covered with snow.

Crown width is defined as the mean of two or more measurements of crown projection taken perpendicular to each other and excluding epicormic branches. At least four radii being vertical to each other should be measured (Figure 2), with eight or more radii required to accurately map tree crowns in stands. Each radius should be measured from the stem, with an addition being made to allow for the radius of the stem. Measurements should be made to the nearest 0.1 m and reported as a mean for the tree. Coppice forests: follow the procedure stated above for the assessment of crown length (measurement at stool level).

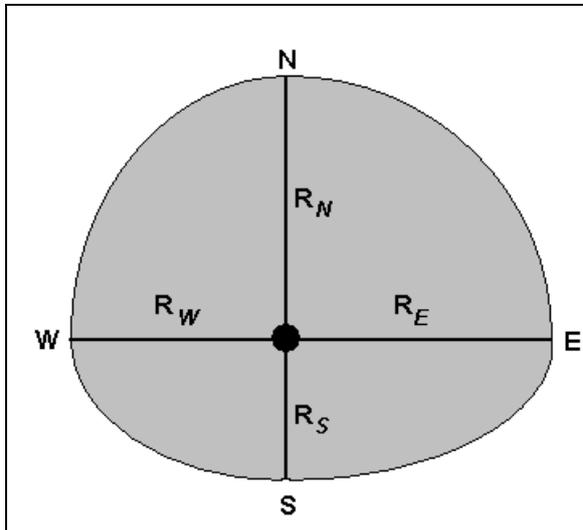


Figure 4: Measurements of crown diameter (4 radii).

### Bark thickness (optional)

Bark thickness is defined as the average thickness of the bark, measured from the surface of the bark to the wood using a handheld gauge to the nearest 1 mm at measurement height for dbh in 1.3 m. Measurements of bark thickness should only be taken on dead, fallen or felled trees because of potential damage to the vascular cambium, in such cases the measurement can be repeated around the stem to reduce the variation of bark thickness.

## Annex 2: Sampling procedure for stand height

### Definitions for tree heights

1. Mean stand height: Mean stand height is defined as the height of the mean basal area diameter tree as derived from the diameter-height curve.
2. Dominant height: Dominant height can be defined as follows:
  - as the arithmetic mean height of a group of selected trees;
  - as derived from the diameter-height curve, using the mean basal area diameter of the dominant tree group.

The classification of dominance used must be defined in the DAR-Q, for example, for the 100 or 200 thickest or highest trees per hectare, by Kraft classes, etc. The 100 thickest trees are recommended.

### Tree selection for stand heights

In those cases where not all trees in the plot/sub-plot can be measured, the following sampling procedures are recommended:

*Height samples for the estimation of mean stand height:*

Sort numbered trees in the plot with a diameter of 5 cm (shoots of 3 cm) and above, in ascending order of measured dbh. A minimum of 30 trees (or 20%, or number for the desired level of precision to be agreed) through the diameter distribution will be selected using the sampling fraction as calculated below:

- Select every ' $n^{\text{th}}$ ' tree where  $n = (\text{total number of trees of 5 cm diameter and above}) / \text{number of sampled trees (not less than minimum)}$
- Start selection at the tree at position  $n/2$
- Examples: 360 plot trees > 5 cm dbh and 30 samples required,  $n = 12$  start with the 6<sup>th</sup> tree and take every 12<sup>th</sup> tree or 360 plot trees > 5 cm dbh and 35 samples required,  $n = 10$  start with the 5<sup>th</sup> tree and take every 10<sup>th</sup> tree.

Using this method at each periodic measurement, different trees may be selected for height measurement. If the same trees are to be measured at each periodic measurement, then the selection process is carried out only once. A number of the trees selected may also be top height sample trees.

*Height measurements for the estimation of top height/dominant height:*

The 100 largest diameter (dbh) trees per hectare will be selected and measured for total height (i.e. 25 trees on plots with 0.25 ha). The method of averaging for top height/dominant height is to be specified, e.g. arithmetic mean, height of dominant mean dbh, another function ...

Where a sub-sample is used, the sampling design must be described.

## Annex 3: Suggestions for Permanent and Continuous Tree Circumference Measurements

In addition to the five-year periodic growth measurements - which will be continued - within demonstration action D1 a permanent measurement of diameter and/or continuous measurements of the change in diameter or radius on a sub-sample of trees is expected. These measurements may be realized by either of two methods: (1) by electronic dendrometers (continuous measurements) and/or (2) permanent girth bands to be read manually (permanent measurements). Both allow not just the recording of annual increment values but also the distribution of increment and swelling and shrinking of the bark and wood during the year with different resolution in time and different need for technical infrastructure. They serve, therefore, to identify stem growth and tree physiological reactions to seasonal climatic conditions, in particular water availability. Stem growth is one indicator of tree condition and tree vitality (Dobbertin 2005) and thus an essential measurement in D1. Where electronic girth bands are installed it is strongly recommended that they should be supported with the addition of manually read girth bands also.

While five-year tree growth should be measured on all trees in the (sub)plot (for details see the ICP Forests Manual on Forest Growth, which will be revised until 2010), trees for girth bands or dendrometers are selected according to different criteria. To be representative of the stand however, trees should be selected according to the observed diameter distribution across the plot, and should allow the estimates of both the relative growth of the stand and the uptake of carbon to be calculated. Selection of trees should allow comparison with periodic measures of increment (five year intervals measured on all trees in the plot).

### Permanent measurements with manually read girth bands

#### *Tree selection procedures*

It is recommended to select at least fifteen trees of the main tree species of the plot for measurement. If it is a mixed stand then the species may be selected in proportion of their percentage in the canopy. Trees can be selected randomly or stratified randomly using the diameter distribution of all trees in the plot, or using the social class (i.e. selecting dominant or co-dominant trees, see Manual on Crown assessments for the definition of social class) or both of the latter two. For example, trees could be ordered by stem basal area and total basal area cumulated. Trees will then be randomly selected from within certain even sized proportion of this cumulative distribution (for example 3 trees from the lowest 20% of the basal area distribution, 3 trees from the next 20% etc.). Bear in mind that to end the sampling interval with data from for example ten trees it may be prudent to install more than ten bands as in a given year some may be lost or damaged due to e.g. animal or other disturbance.

The stems of the selected trees should not have any visible damage or injuries at the measuring height, should have no branches or knots at the measuring height and no visible resin flow from above. Their cross section should be as circular as possible with little irregularities. Avoid extreme thick bark if possible.

#### *Installation of the girth bands*

For trees with naturally thick bark or bark that peels off in chunks, the outer bark has to be carefully removed. This should be reported as comment in the submission forms. This can happen with a knife or sickle for the larger parts and with a steel brush to remove loose dead bark. Mosses and lichens should also be removed around the stem where the circumference band will be placed. Care should be taken not to remove or disturb the live bark.

The measurement instrument (girth band) consists of a band (metal or plastic), a spring and a scale (preferable a nonius scale - also called vernier scale - which allows accuracies to 0.1 mm). Short springs are favourable and spring tension at installation is important. The band may need

to be moved on the tree until it fits tightly and well. The girth band should be selected with an appropriate length and the spring positioned to allow measuring for several years without having to readjust the spring or replace the band. The spring should be placed in a way that only the end of the spring facing the nonius scale need to be replaced and can be hooked into the next hole. By this way the band remains tight around the stem.

The position on the stem should be permanently marked on the stem and should be slightly above breast height to not interfere with the periodic measurements. To see if the girth band had been moved along the stem, it is useful to mark the position of the band at two to three points along the stem with a color spray. When spraying, cover the girth band, **otherwise you won't be able to read the scale anymore and don't spray to close to the nonius scale**. If necessary you can repeat the spraying during the annual reading. Control the tightness and the position of the spring each time you perform a reading. Make sure that the spring is not touching the nonius scale. In stands with high UV radiation, plastic bands may most likely weaken sooner and should be checked more frequently (bleaching of the color is an obvious sign of such weakening of the material).

#### *Timing of Installation and Reading of Girth Bands*

Installation should ideally take place in winter which would allow trees with shrinking and **swelling during and following frost events to 'adjust' into the girth bands**. When readings are made several times during winter a stable reading may be obtained. If the band is not tightly fixed to the stem, the first-year reading will underestimate growth. When bands are installed in late winter or early spring some tree species may show bark shrinkage and first-year growth may be overestimated. For annual readings it seems that in central and northern Europe mid to late fall is the best date to compare readings (less influence due to drought shrinkage and frost shrinkage). In southern Europe other dates may be better suited. When the relative inter-annual change in bark thickness changes due to humidity is larger than the actual increase in wood a longer observation period is needed to get reliable information on increment.

#### *Sampling Intervals*

Sampling intervals may vary from annual to weekly recordings. It may be useful to carry out readings at four-weekly (monthly or even two weekly) intervals when collections of deposition samples at the plot are being carried out. Sampling frequency may be increased during the growing season. It is strongly recommended to conduct measurements at least monthly during the growing season. For annual increment calculations, the values of approximately the same date in the autumn of every year should be selected. Air temperature at the time of reading should be recorded.

## Continuous recording of stem changes with electronic dendrometers

There are two types of dendrometers: point dendrometer (the radius change at one point of the stem is measured) and band dendrometers (a wire or metal tape is placed around the stem to measure its changes). For a detailed review we refer to the attached publication by Drew and Downes (2009). Automatic dendrometers are typically connected via cable to a data logger, which collects the reading. The number of trees that can be measured is restricted by the capacity of the data logger. Readings may be collected, for example hourly (or even every 15 minutes!) and either stored directly or first averaged and stored. One at the moment frequently used dendrometer band (UMS München) uses a Teflon mesh, which is placed between the bark and the invar steel cable.

#### *Sample tree selection*

As dendrometers are expensive, require a central data logger and their distribution is therefore restricted by cable length, only few trees per stand and fewer sites will be selected. Therefore sampling can not be representative for the stand growth as in the case for periodic measurement or girth bands. Instead, trees should be selected to be dominant or codominant, because small or

understorey trees grow slow and often have higher seasonal fluctuations of stem diameter due to swelling or shrinking of the bark than annual growth.

#### *Installation of band dendrometers*

Installation of band dendrometers follows essentially the same procedures than that for the manual girth bands (see above).

A teflon mesh can also be used around the tree to reduce the friction of the cable and to protect it from icing, resin or callousing. Expansion and contractions of the tree stem is recorded here via a strain-gage clip-censor as the change of measured voltage (or amperage if a measuring amplifier is used) of the strain gage as a function of the change of the clip. This change is stored in the data logger and therefore the voltage must be known to calculate voltage change to increment values. Some band dendrometers have the advantage that they can be easily fixed to the trunk without any damage to the bark or disturbance of growth, while other dendrometers are fixed with screws on the stem. Disadvantages of dendrometer bands are that they are somehow more sensitive to temperature changes due to the long cable or bands and also to disturbance by animals, snow or ice.

Point dendrometers have the disadvantage that they require a permanent fixation to the stem. This can in the long-run alter the recorded growth due to increased callus cells. Therefore, point dendrometers should not be installed closed to where the periodic measurements are conducted. The advantage of point dendrometers is, that the bark needs to be removed at only one position around the stem. They may also be less sensitive to temperature changes and can be more easily protected against biotic or abiotic damages. Continuous electronic dendrometers may be used with measuring amplifiers or without. These amplifiers are recommended as they allow cables of more than 10m to be used.

#### *Sources of error*

It is important to remember that there are sources of error associated with continuous dendrometers, such as frost expansion, animal disturbance, electrical errors and general damage. Therefore, one band can be installed for a certain time period to a fixed material to study the effect of the instrument on temperature changes (i.e. a rock or a plastic tube of deposition sampling). All electronic dendrometers needs cables and these may be damaged by animals. Remotely, automatical uploading of data at certain intervals will help to detect malfunctioning of the dendrometers.

#### *Note:*

It is strongly recommended that manually read girth bands are also installed along with electronical dendrometers in the event of damage or failure of equipment or power supply in order to adjust the relative stem changes to actual stem changes. The dendrometer should be installed above the manually read girth band to avoid disturbance.

#### *Accuracies*

Manually read girth bands should allow an accuracy of reading of 0.1 mm. Electronic dendrometers should reach a recording accuracy of 0.02 mm (Accuracy of UMS Clip sensor is 5  $\mu\text{m}$ ).

## Annex 4: Ring test for data validation and evaluation

To compare the national procedures of data validation and evaluation a ring test was developed and was distributed in 2010. The data set originates from real measurements and comprises the standard parameters of periodic measurements on two plots at four assessments with a five year interval (four files of type IPM) and one plot file (file type PLI). To make the “test” more effective some typical errors were added and some values were deleted.

Four exercises should be done and can be evaluated separately:

- Find out and mark the errors with the appropriate data quality code
- Correct or amend the data as necessary
- **Calculate the volume of each single tree based on the added “international” taper function and secondly on the locally used taper function, add information which volume is calculated (e.g. total stem wood, merchantable timber above 7 cm or others).**
- Summarize the standard stand characteristics per hectare separately for each tree species and for all together: stem number, basal area and volume per ha (both for the remaining and removed stand as well as for total). Derive for each species separately the diameter of basal area mean tree and the periodic annual increment of volume as well as the top height of the 100 largest trees form main species. For reporting these stand characteristics a specific form is available, furthermore the checked and amended data file should be submitted.