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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 XVII
Canopy Leaf Area

Version 2020-1

Prepared by:

ICP Forests Expert Panel on Meteorology, Phenology, and Leaf Area Index

ICP Forests Expert Panel on Foliage and Litterfall

(Stefan Fleck, Stephan Raspe, Matjaz Cater, Patrick Schleppi, Liisa Ukonmaanaho, Martin Greve, Christian Hertel, Wendelin Weis, Sabine Rumpf, Anne Thimonier, Francesco Chianucci, Philip Beckschäfer)

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Programme Co-ordinating Centre of ICP Forests
Alfred-Möller-Str. 1, Haus 41/42
16226 Eberswalde
Germany

Email: pcc-icpforests@thuenen.de

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1 Introduction

Leaves represent the largest proportion of the total forest canopy surface area and also the main surface for physiologically active exchange with the atmosphere. Processes like photosynthetic light absorption, carbon uptake and assimilation, transpiration of water, and emission of volatile organic compounds are nearly exclusively performed via leaf surfaces, while processes like element deposition, interception of rain, evaporation, and susceptibility to wind damage are in part also dependent on the surface area of woody canopy elements. The increasing need to quantify and simulate such interactions between forest canopies and the atmosphere with models has led to a growing demand for reliable information on the surface area of leaves in the canopy. This manual part provides a guideline for direct measurements as well as indirect assessments of leaf area index (LAI) in the framework of ICP Forests.

Numerous methods have been developed to assess LAI, including direct contact methods, passive optical methods (based on the radiation of the sun) and active remote sensing methods (based on actively emitted radiation). This manual can only focus on a few of them that are most often used or were considered most reliable or best comparable. Also this third version of the manual will need to be updated and extended during the coming years, based on new measurements and methodological comparisons that improve our judgement. The fast technological development of optical (terrestrial and remote sensing) methods will most probably lead to necessary changes in the future. The author names of each method-related sub-chapter are therefore added below the headlines in order to facilitate the feedback of other experts to the small team that prepared these guidelines. The most direct way to discuss items of the manual will be the discussion within the Expert Panel on Meteorology, Phenology and Leaf Area Index.

2 Scope and application

Different methods and approaches exist to assess LAI. The methods are already applied on many ICP Forests plots. Countries are free to select any of the described methods described below. However, within these methods they have to follow the prescription of the Manual part and have to document and submit additional method specific variables as described in the subchapters.

LAI (measured in m^2/m^2) is here defined as half the total leaf area of the forest canopy divided by the ground area below the canopy (Chen & Black 1991). This is still the most often used definition, though principally other definitions exist (e.g. Myneni et al. 1997, Chen & Black 1992, compare Jonckheere et al. 2004). Another difficulty in the definition is that the annual cycle of leaf production and fall prohibits to measure “the” LAI of a forest stand, since this varies with time. We considered that it is important for most model applications to know the maximum LAI that is reached during the vegetation period, since the annual development of leaves may well be derived from this value. So it is indeed the maximum LAI in the vegetation period (LAI_{max}) that the manual focuses on and all described methods are applied in a way to extract this quantity. As a consequence, any method considered in this manual had to prove that it is able to measure maximum LAI in the given definition, which is most reliably measured using litter traps in a deciduous forest.

Different definitions do also exist for the lower border of the forest canopy to assess, since it is usual to measure either on the ground, or in different heights up to 2m above the floor. This and other settings do influence the comparability of results from different countries and from different approaches and have been revised in this part of the manual.

The variability of settings and evaluations for the more sophisticated optical methods has as well been revised and the decision has been taken to select one common evaluation approach.

The application of this manual on a yearly basis is only foreseen for the most intensively investigated Level II plots in order to get reliable information on the considerable interannual variation of leaf area displayed by the forest canopy. On other plots it may be sufficient to derive information from time to time. In the long-term, average LAI values only change as a consequence of forest management, storm or insect calamities, or – over several years – due to growth. It is therefore recommended to measure LAI on all standard Level II plots after events that may have led to fundamental changes of LAI, but at least every 5 or 10 years. On severely disturbed and inhomogeneous plots, a spatially distributed measurement of canopy closure and/or LAI is mandatory to characterize the heterogeneity of the overstorey. Next to the measured maximum LAI, also the date of the measurement and the method used shall be provided to the database. An overview of the measurement frequency and the minimum set of variables to be reported on the different sorts of plots is given in table 1. Additional method specific parameters have to be delivered and these are defined in the sub-chapter belonging to each of the methods.

Table 1: Variables to be reported

Variable	Level II	Level II core	Reporting unit	DQO	Measurement resolution
Date of measurement$_i$	m*	m**	DDMMYY	± 0	1d
used method	m*	m**	number code***	± 0	0
LAI_{max}	o*	m**	m²/m²	± 1	0.1 m²/m²
Canopy closure	m*	m*	%	± 10	1 %
Method-specific parameters	m*	m**	See sub-chapter	See sub-chapter	See sub-chapter

*: At least one LAI measurement every 5 or 10 years and after changes in canopy structure is recommended. On severely disturbed and inhomogeneous plots, a spatially distributed measurement of LAI or at least canopy closure is mandatory at least every 5 years (see sub-chapter 5: Indirect optical methods for LAI and canopy closure assessment and in Table 2 in Manual Part II: Basic design principles for the ICP Forests Monitoring Networks).
**: annually
***: 10 = Litter Trap Method
21 = Plant Canopy Analyzer LAI-2000 / LAI-2200
22 = Canopy Analyzer TRAC
30 = Hemispherical Photography
41 = SunScan Ceptometer
51 = Airborne LiDAR
61 = Biomass Harvest

3 Objectives

These guidelines are foreseen to standardize LAI measurements and assessments in a way that allows all participating National Focal Centers to provide comparable LAI values based on a variety of methods that are currently in use. The harmonization of assessment and evaluation procedures is the key to achieve the same sort of information from all methods, even when they are applied to completely different forest stands by different operators.

Another goal of these guidelines is to provide a standardization that eliminates error sources in the comparison of different methods. The high number of methods to assess LAI and the multitude of possible settings and evaluations for the more sophisticated optical methods seem to produce a confusing diversity of LAI-like quantities. The guidelines are designed to clarify relationships between the different methods and quantities in use.

The main goal of these guidelines is that they are understandable for the reader and provide sufficient information for experts that plan and perform the data collection.

The following chapters will lead through 6 different methods of LAI assessment.

4 Direct measurements

In terms of accuracy, the direct measurement methods provide the most reliable assessment of LAI that serves as a standard to validate the indirect and remote sensing methods. Since they are usually more laborious than other methods, they are less frequently applied. Improvements of indirect and remote sensing methods need to be judged based on this reliable information.

4.1 Litterfall measurements

(Patrick Schleppi, Liisa Ukonmaanaho, Stefan Fleck)

The litterfall method for LAI derivation is a semi-direct estimation that has been frequently used in the past for broadleaf stands (Bréda 2003: Thimonier et al. 2010). By definition, deciduous trees completely lose their foliage each year. The cumulated leaf area that they carry during their vegetation period is thus equal to the area of the leaf litter they lose within a year. With respect to LAI_{max} it has to be considered that a certain amount of leaves does already fall before the maximum amount of leaves in the canopy is formed, which is usually the case at the end of July (e.g. Bréda & Granier 1996). Adapted to the seasons of the northern hemisphere, a whole year is often defined from March to February, but this may need to be adapted regionally according to the vegetation period. The goal of the method described here is to obtain an estimation of LAI_{max} based on the leaves falling after LAI_{max} has been reached as well as the yearly cumulated area of foliar litter per tree species.

4.1.1 Location of measurements, measurement design and equipment

Litterfall is collected according to the method described in *Sampling and Analysis of Litterfall* (ICP Forests manual, part XIII). Here we describe the work related to the estimation of leaf area index (LAI) and specific leaf area (SLA), or its inverse, the leaf mass per area (LMA). LAI is a dimensionless ratio (m^2/m^2), SLA is usually given in cm^2/g and LMA in g/m^2.

4.1.2 Measurement theory

SLA of tree species i (SLA_i) is its leaf(-litter) area (A_i) divided by the corresponding dry mass (m_i):

$$SLA_i = A_i / m_i$$

Because it is much more time-consuming to measure the area than the dry mass of large amounts of leaf litter, it is common to measure SLA on a sub-sample (SLA_s) and to use it, along with the total dry mass of the subsample, to calculate the total leaf area per species:

$$SLA_i = SLA_s = A_s / m_s$$

$$A_i = SLA_s \cdot m_i$$

The cumulated leaf area index per species ($LAI_{cum,\,i}$) is then calculated as the leaf-litter area divided by the area of the litterfall collectors (B):

$$LAI_{cum,i} = A_i / B$$

The leaf area and LAI can finally be summed up for all species over the whole year to derive LAI_{cum}:

$$A = \Sigma A_i$$

$$LAI_{cum} = \Sigma LAI_{cum,i}$$

A summation for all species over the months from August[1] to end of February yields LAI_{max}.

$$LAI_{max} = \Sigma LAI_{cum,Aug\text{-}Feb,i}$$

LAI can be calculated this way only for deciduous species. For evergreen species, the average age of foliage at abscission would have to be known. A representative harvest at different levels within the canopy is necessary to assess this parameter. See section 4.2.3.2. for details.

4.1.3 Methodology

4.1.3.1 Sample preparation for leaf area measurement

SLA has to be determined for each main tree species from a random subsample of litter leaves. Because the goal is to obtain a value of SLA to be multiplied with the total dry mass, the subsamples should be representative of the total: at least 100 leaves from all used traps and preferably from the time span of highest litterfall activity. If several subsamples per species are measured separately to assess the spatial and/or the temporal variability, then their composite SLA has to be calculated from the spatially or temporally integrated area and dry mass.

If the area of litter leaves is measured fresh after collection, they may need to be cleaned and flattened beforehand.

If litterfall leaves are dry, either naturally following abscission, or through storage or oven treatment, they will be more fragile than green leaves. Dried litter leaves can be folded or curled, making it necessary to soak them to enable the measurement of their area. This is possible for most broadleaves. Excessive soaking may cause components like humic acids to leach out, and weight loss can thus occur. Occasionally for very thin leaves (e.g. *Fraxinus excelsior*), area losses may also occur. In the case of desiccated *Fagus sylvatica* leaves that fold into a concertina, a brief soaking in hot water (60-70°C) has been found to flatten leaves sufficiently for measurement, but weight losses of 5% have been recorded after longer overnight soaking. However, for *Quercus robur* and *Q. petraea* leaves, weight loss is minimal over the same time period. For thinner leaves such as *Corylus avellana* or *Fraxinus excelsior*, soaking for approximately an hour is sufficient and recommended, as weight losses of up to 15% have been recorded after overnight soaking. A test on each species

[1] : LAI_{max} may be reached a bit earlier in very dry years or later under more favourable weather conditions. Due to local variations, the exact point in time has to be determined by local experts.

collected should be conducted to establish a standard treatment and thus to quantify possible losses[2]. The estimation of such relative losses would then need to be incorporated into the SLA calculation as a correction factor. The use of flattening devices, such as a plant press, has been found helpful to ensure accurate expansion of soaked broadleaves.

LAI of evergreen tree species such as conifers is better determined by destructive sampling, where SLA is needed as well. Its determination is described here for this purpose. For short conifer needles which have dried (e.g. *Picea* sp.), area measurement is often obtainable after only preliminary cleaning, as they remain woody in nature and do not change area. However, finer needles (e.g. *Larix* sp.) are difficult to prepare, and twist on drying. These would need a short soak and would be best measured on a leaf area machine where they can be laid on a flat bed under slight pressure. Longer needles (e.g. some *Pinus* sp.) also twist on drying, and are difficult to soak out, as they then break up. Area measurements are best made from these if they can be kept damp from abscission.

All samples should then be dried at maximum 70°C until they reach a constant weight (usually 24 hours are sufficient) before weighing for calculation of SLA. Previously soaked leaves must not be used for chemical analysis.

4.1.3.2 Area measurement

Measurement of leaf (needle) area can be sorted into three categories: use of specific devices, use of a general-purpose scanner and photography. Specific devices are either portable (like CID CI-203, TOP Instr. YMJ, Envco CI-202, ADC AM300) or to be used on a lab bench (like Li-Cor LI-3000). Refer to the corresponding manual for their use. The same applies for scanner and software or camera and software when they are obtained as bundles (like Delta-T WinDIAS).

4.1.3.2.1 Scanner

General-purpose scanners can be used for the measurement of leaf area in conjunction with an appropriate software. Common scanners have only a front-side illumination: objects are illuminated and scanned from the same side (like for a photograph). This has the disadvantage that there may be shadows on the scanned image, especially for needles. The shadows have to be removed prior to area assessment with a suitable software (see 4.1.3.2.4.), if this is possible, or an estimation of the error induced by the shadows has to be made by measurements on a test sample. It is therefore recommended to use a scanner with back-side illumination: objects are illuminated from one side and scanned in transparency from the other side, which provides high contrast and no shadows (same principle as for slides). While this is good to obtain precise area measurements, it does not reproduce correctly the different colours of the leaves. If the leaf area has to be classified into green *vs.* yellow or brown or dead, then it is not advisable to scan by transparency. Scanning can be done in colours (24 bits per pixel, bpp), in grey tones (8 bpp) or in black-and-white (1 bpp). If the colours and/or the contrast are not very good, it is preferable to keep a higher bpp and to classify the colours or grey tones later, during image analysis. However, if the classification into black-and-white has been tested, then it is possible to scan directly into black-and-white, thus reducing the file sizes and simplifying the analysis. The threshold has to be tested within a calibration procedure (see below)

The resolution of the pictures should be 600 dots per inch (dpi) for needles, but for broadleaves 200 dpi are sufficient. In order to simplify the work flow, it is possible to lay the needles or leaves first on a glass plate, and then the glass plate onto the scanner.

[2]: It would be advantageous if this test is performed in a harmonized way in different institutes.

4.1.3.2.2 Photography

Similarly to scanners, a better contrast can be achieved with back-side illumination, which means here to lay the leaves or needles on a light-box, i.e. a depolished glass illuminated from below. This also avoids shadows. A calibration is necessary for any specific setting (camera, lens, focal length and camera-to-object distance) and should give a resolution similar to those given for scanners, i.e. 200 dpi for leaves and 600 for needles.

4.1.3.2.3 Calibration

The nominal resolution of a scanner should be checked once by scanning a ruler in both X and Y directions. The resolution of photographs must be measured the same way after any change in the material setting (camera, lens, focal length and camera-to-object distance). For narrow objects, the correct classification of the pixels along the borders is crucial and depends on the threshold setting. This can be calibrated by scanning or photographing a wire of precise diameter and known length.

4.1.3.2.4 Image analysis

Scanned pictures are analysed by computer, with any appropriate software, either commercial (like WinSeedle, WinFolia) or freeware (more or less powerful and complex, like Image J or Pixstat). For needles, it is easier if the software can count the objects, because it is then not necessary to manually count them, only to count them approximately or to weigh them. The required result is in any case the total leaf area corresponding to the known dry mass, which allows to calculate SLA.

If the pictures are in colours or in grey tones, their analysis is based on the classification of these colours or grey tones into either black = leaf or white = background. The easiest way to do this is to apply a threshold on the lightness. A correct threshold is especially important for narrow objects and should be defined by calibration as explained above. In some cases, more classes of colours may be defined in a first step. For example, it may be useful to recognise separately a light background and shadows before summing them up to the whole background. Similarly, green and yellow parts of leaves may be recognised separately, then combined as total leaf area.

In the case of non-flat leaves and needles, the measured leaf area does only represent projected leaf area and has to be multiplied with a species-specific conversion factor between projected area and leaf area (see annex, to be developed).

$A_{needles} = A_{needles,\ image} * c$

After the area measurements, leaves are dried and weighed to obtain their dry mass.

4.1.4 Variables measured and reporting units

The specific leaf area has to be reported per species i (SLA_i), as well as the whole year cumulative leaf area index per species ($LAI_{cum,\ i}$). Only one number has to be reported per plot for total cumulative LAI over all species (LAI_{cum}) and for maximum LAI (cumulated only from the date of maximum foliation to end of the vegetation period: LAI_{max}). If repeated measurements are available, standard deviations should also be reported. Average area of leaves or needles needs to be reported along with the corresponding standard deviation.

Table 2: Variables to be reported annually in case that the litterfall method is applied

Variable	Reporting unit	DQO	Measurement resolution
date_start (begin of sampling period)	DDMMYY	± 0	1d
date_end (end of sampling period)	DDMMYY	± 0	1d
date_analysis (completion of sample evaluation)	DDMMYY	± 0	1d
code_tree_species (tree species of the sampled material)	code		
traps_number	amount of traps used	± 0	1
total_sampling_area (of traps)	m²	± 0.0001	0.0001 m²
SLA_i	cm²/g	± 1%	0.01 cm²/g
$LAI_{cum, i}$	m²/m²	± 0.1	0.01 m²/m²
$LAI_{max, i}$	m²/m²	± 0.1	0.01 m²/m²
Average leaf area	cm²	± 0.1	0.01 cm²
Standard Deviation of Average leaf area	cm²	± 0.01	0.01 cm²
Date of maximum foliation	DDMMYY	± 0	1d

4.2 Biomass harvesting

(Stefan Fleck, Stephan Raspe, Wendelin Weis, Sabine Rumpf)

In cases where the determination of LAI from litterfall during one year is not possible (e.g. for most coniferous trees), biomass harvests provide an alternative direct measurement of leaf or needle area. This is probably the most laborious method of LAI determination, but as well the most accurate method for LAI estimation of evergreen coniferous trees. It provides also the only direct measurement of woody element surface area of the canopy, which is usually expressed as stem area index (SAI) in an analogous definition to LAI. Due to its destructive nature, care has to be taken that no other measurements on the plot are affected.

4.2.1 Location of measurement, measurement design, and equipment

Due to the high workload for biomass harvests they are not foreseen to be performed regularly. It is rather recommended to harvest biomass when a regular felling is planned on the plot or in its neighborhood and to apply in parallel one of the indirect LAI assessment methods mentioned in this manual in order to calibrate it for the local conditions. While the optimum timing for biomass harvesting would be the time of maximum foliation (LAI = LAI_{max}), it is also possible to perform the biomass harvest in another season (except winter) and then to adjust the measurement with the indirect method chosen, which then needs to be applied under maximum LAI conditions as well. When both methods are combined, the indirect method should also be applied shortly before and shortly after felling.

4.2.1.1 Measurement design

Biomass harvests basically comprise felling of a subsample of trees from a forest stand, stem measurements, and selection of a sample of branches, whose leaves or needles are collected for weight and area measurements.

At least 7 trees per main species should be chosen that are representative for the main instrumented part of the plot. They should represent

- the distribution of diameter at breast height (DBH) of the stand (1 tree per DBH-quantile)
- the prevailing growth form (e.g. no forked trees, typical tree height and crown length, all social classes)
- the prevailing tree vitality (e.g. no crown breakage, excessive sweeps or crooks)
- the typical stand conditions (e.g. not in gaps or close to landings or on non-representative soil, no adjacent tree crowns due to overrepresentation of local conditions)

The distributions of DBH, tree height and crown length of the plot need to be assessed prior to the tree selection.

After felling, branch sampling has to be performed. From the numerous designs for branch selection in the canopy, the selection procedure with probability proportional to squared branch diameter has been shown to deliver most accurate needle biomass estimations (Temesgen et al. 2011).

An alternative method is upscaling via fresh weight: All branches of the tree are sampled and fractionated into different classes (twigs with needles and different branch diameter classes) and then a larger representative subsample from each class is used for upscaling via fresh weight. Both methods are described in the following sections.

4.2.1.2 Measurement equipment

The necessary equipment comprises

- Inclinometer for height measurements on standing trees
- Vertically balanced sighting tube for crown projection measurement
- Tree felling and leaf sampling equipment (chainsaw, ropes, handsaws, large and small bags)
- Field scales for fresh weight determination (if needed)
- Caliper for DBH measurements
- Meter tapes for branch diameter and tree height measurements on felled trees
- Scanner for needle/leaf area measurements (see 4.1.3.2.1.)
- Drying oven
- Laboratory scales for dry weight determination

4.2.2 Data collection, transport and storage

4.2.2.1 Felling

Before felling, DBH and 8-point-crown projections (into 8 compass directions) of the sample trees should be measured. Breast height (1,3m) should be marked with a line encompassing the stem to facilitate the height measurement. Crown projection area, crown length and tree leaf area may later on be used to estimate canopy leaf area density, which helps to judge the suitability of indirect methods.

Felling should be done carefully in a way to minimize crown breakage, so preferably into a gap between other trees.

Total height of the felled trees is then measured from the base of the stump to the tip of the tree. The height of crown base is measured at the position of the lowest living branch belonging to the contiguous crown. The contiguous crown is then divided into two parts of equal length (shade and sun crown) that are treated separately.

4.2.2.2 Branch selection/subsampling

Branch selection of the crown segments is based on the distribution of basal diameters of all branches in each of the two crown segments. When measuring the basal diameter of all branches they often need to be measured in a fixed distance (e.g. 1cm) from the stem due to bulges at the branch insertion point. For the diameter distribution, living branches below crown base should be assigned to the shade crown. Eight to ten first order branches per crown segment are then selected in a way to represent

- the distribution of squared branch diameters (1 branch per squared branch diameter quantile),
- the prevailing distribution of growth forms (e.g. whorl branches and interwhorl branches), and
- the prevailing branch vitality (e.g. number of needle age cohorts, no damaged branches)

The freshweight-based upscaling requires all branches of both crown compartments to be divided into different diameter classes, which are collected in the field.

- needles + twigs (Ø < 1 cm)
- branches Ø 1 - 2 cm with needles
- branches Ø 1 - 2 cm without needles
- branches Ø 2 - 3 cm
- branches Ø 3 - 4 cm
- branches Ø 4 - 5 cm
- branches Ø > 5 cm

4.2.3 Measurements

4.2.3.1 Fresh weight determination

Fresh weight can optionally be used as a quality control for branch diameter based upscaling. In this case the selected branches are separated into twigs (foliated) and branches (non-foliated) along a species-specific diameter threshold, usually about 1cm, and fresh weight of both fractions of each branch separately is immediately determined in the forest. All other branches including the tree top (diameter threshold: 7cm) are separated the same way and the summed fresh weight of all non-selected branches and the sum of their twig fresh weight is measured.

For freshweight-based upscaling, the total fresh weight of each fraction has to be determined and a representative aliquot from each must be selected. The aliquot needs to comprise at least 20 branches/twigs per fraction in the shade crown and at least 30 in the sun crown.

For SAI estimation, the stem is segmented into 1m to 2m long pieces, and the diameter at the base and at the top of each segment as well as its length are determined.

4.2.3.2 Laboratory measurements

The selected branches are transported to the laboratory and the number of needle age cohorts on each selected branch is counted or assessed by eye and will be averaged for the database.

Projected area of the fresh needles or leaves of each selected branch is measured on a subsample of at least 100 needles or 20 leaves representative for each twig and each needle cohort of the branch (or twig regions in the case of leaves: tip, medium, basal part of the twigs).

The dry weight of the same needles or leaves is then determined after drying at up to 70°C until constant weight is achieved. After drying, also the dry weight of the remaining needles or leaves is determined. It is mostly easier to separate needles from twigs after drying.

4.2.4 Calculation

4.2.4.1 LAI calculation

Dry weight and area measurements of the needle or leaf subsamples are used to calculate specific leaf area for each branch (SLA_{branch}, see sections 4.1.2. and 4.1.3.2. for area measurement). The total leaf area of each sample branch (A_{branch}) is then derived from SLA and the total branch leaf mass (m_{branch}):

$$A_{branch} = SLA_{branch} * m_{branch}$$

For branch diameter based upscaling, the allometric relationship between leaf area of the sample branches and their basal area (BA_{branch} , determined from the basal diameter) is determined by linear regression and the whole tree's leaf area (A_{tree}) is calculated using the sum of all branch basal areas of the tree and this relationship.

$$A_{branch}(BA_{branch}) = a_1 * BA_{branch} + b_1,$$ (a_1 and b_1 are empirically determined)

$$A_{tree} = a_1 * \Sigma BA_{branch} + b_1$$

For freshweight-based upscaling, dry weight and area measurements of the needle or leaf subsamples are used to calculate specific leaf area for each aliquot of a fraction with needles ($SLA_{aliquot}$).

The total leaf area of a fraction with needles ($A_{fraction}$) is then derived from SLA and the total leaf mass of the fraction, which is derived from the total freshweight ($FW_{aliquot}$) to dry mass of leaves ($m_{aliquot}$) relationship of the aliquot:

$$m_{aliquot} = a_2 * FW_{aliquot} + b_2,$$ (a_2 and b_2 are empirically determined)

$$m_{fraction} = a_2 * FW_{fraction} + b_2$$

$$A_{fraction} = SLA_{aliquot} * m_{fraction}$$

The total leaf area of the tree (A_{tree}) is calculated as the sum of all fractions with needles:

$$A_{tree} = \Sigma A_{fraction}$$

A_{tree} is then upscaled to the plot leaf area A_{plot} via the allometric relationship between A_{tree} and DBH in the form:

$$A_{tree}(DBH) = a_3 * DBH^{b3}, \quad (a_3 \text{ and } b_3 \text{ are empirically determined})$$

$$A_{plot} = a_3 * (\Sigma DBH)^{b3}$$

Dividing A_{plot} by the ground area of the plot finally yields the plot LAI at the time of measurement (LAI_{date}), which needs to be adjusted via indirect LAI measurement methods to deliver LAI_{max}, if it was not measured at the time of maximum leaf area.

4.2.4.2 SAI calculation

SAI calculation is based on the surface calculation of truncated cones (stem segments) and on the dry weight to projected area relationship of branches that needs to be assessed in a separate investigation or derived from literature.

4.2.5 Quality assurance and quality control

Branch diameter-based upscaling may be complemented by freshweight-based up-scaling in order to assess the potential error in the measurement and calculation method described above:

In this case, the relationship between the needle or leaf dry weight of each sample branch and the fresh weight of all twigs belonging to the branch (FW_{twigs}) is determined and a linear regression is built between both quantities over all sample branches. The relationship is subsequently used to determine whole tree leaf dry mass (m_{tree}) from the measured whole tree twig fresh weight.

$$m_{branch} = a_4 * FW_{twigs} + b_4, \quad (a_4 \text{ and } b_4 \text{ are empirically determined})$$

$$m_{tree} = a_4 * \Sigma FW_{twigs} + b_4$$

m_{tree} is then multiplied with the weighted average SLA of all sample branches for whole tree leaf area calculation based on fresh weight:

$$SLA_{sample\ branches} = \frac{\sum A_{branch,i}}{\sum m_{branch,i}}$$

$$A_{tree,\ FW} = m_{tree} * SLA_{sample\ branches}$$

4.2.6 Variables measured and reporting units

Since biomass harvests are the most laborious method of LAI determination it is important to use this information as well as possible to accurately assess LAI_{max} and to improve later LAI measurements of the site. Several quantities with relevance for long-term monitoring of LAI at the stand or for modelling may be derived from the variables reported:

- LAI per tree and leaf area density may be calculated from each tree’s leaf area and its crown projection.

- LAI of the plot may additionally be derived from needle litter collections over several years, when using the average number of needle age cohorts and considering their needle survival proportions.
- SAI of the plot may be estimated from the stem's surface area and dry mass of branches, if external information is used.
- R^2 and RMSE of the used regression functions help to identify the most reliable estimation of LAI

Table 3: Variables to be reported in case that biomass harvesting method is applied***

Variable	Reporting unit	DQO	Measurement resolution
Dates of felling (each felled tree)	DDMMYY	-	-
Dates of indirect measurements *	DDMMYY	-	-
Quantiles of the plot's DBH distribution	m	±0.01	0.001
Crown Length (each felled tree)	m	±0.1	0.01
DBH (each felled tree)	m	±0.01	0.001
Branch dry mass (each felled tree)	g	±10	1
Foliage dry mass (each felled tree)	g	±10	1
Foliage area (each felled tree)	m²	±0.01	0.0001
Crown projection area (each felled tree)	m²	±1	0.1
Stem surface area (each felled tree)	m²	±0.1	0.01
Quantiles of the branch diameter^2 distribution (each felled tree)	m	±0.001	0.001
Average number of needle age cohorts ±SD (each felled tree)	-	±0.2	0.1
$A_{tree,FW}$ (each felled tree)	m²	± 0.1	0.01
SLA_{branch} of the sun crown (Min, Max, weighted Average)	cm²/g	± 1	0.1
SLA_{branch} of the shade crown (Min, Max, weighted Average)	cm²/g	± 1	0.1
$SLA_{sample\ branches}$	cm²/g	± 1	0.1
SAI*	m²/m²	± 0.1	0.1
LAI_{Date} **	m²/m²	± 0.1	0.1
LAI_{max}	m²/m²	± 0.1	0.1
R^2 and RMSE of A_{branch}-BA_{branch} regression	-	-	-
R^2 and RMSE of $m_{aliquot}$-$FW_{aliquot}$ regression*	-	-	-
R^2 and RMSE of A_{tree}-DBH relationship	-	-	-
R^2 and RMSE of m_{branch}-FW_{twigs} regression*	-	-	-

*: if applicable **: if different from LAI_{max} ***: The variables given here are foreseen, but not yet implemented in the central database

5 Indirect optical methods for LAI and canopy closure assessment

The LAI assessment strategy behind indirect optical methods is to quantify light penetration through the canopy in the foliated stage and then to calculate the amount of leaf area that would produce the observed relationship between light above the canopy and light below the canopy. This approach has been realized with several different instruments employing diffuse or direct radiation, directional light distributions or spatially averaged values, and different parts of the visible spectrum. The most severe limitation of these methods is the measurement at very low light penetration rates, since already a leaf area index of 6 causes penetration rates of about 5% that are a challenge for the optical instruments (Gower et al. 1999). All indirect methods presented in this manual are therefore differential measurement methods that build their calculations on measurements of both, light above the canopy and light below the canopy. Since maximum LAI of the vegetation period is the primary target variable, measurements are in all cases to be performed in the month of expected maximum LAI.

On severely disturbed and inhomogeneous plots, canopy closure is an additional target variable. Canopy closure is defined as the proportion of sky hemisphere obscured by vegetation when viewed from a single point, and so clearly distinguished from canopy cover that is the vertical projection of tree crowns (cf. Jennings et al. 1999). Canopy closure is directly measured with optical methods. A view angle of 45° (equalling 3 rings of the LAI-2200 sensor) is to be employed during its assessment in ICP Forests for standardization purposes. It represents the complement of the measured gap fraction:

Canopy closure = 100% - gap fraction

Also optical measurements to derive canopy closure should preferentially be made in the month of maximum foliation and should follow the steps described in this chapter. Slightly deviating from these steps, the measurements need to be performed along a 10m x 10m grid of marked points *covering the whole plot* in order to characterize differences in canopy structure of the complete area of the inhomogeneous plot. On 0.25ha this equals usually up to 25 measurement positions, depending on the plot shape. On plot sizes above 0.5ha it is sufficient to measure canopy closure with lower density, but at least on 25 points. The most south-westerly position of this grid is considered the origin of the coordinate system (compare Figure 1 for the LAI measurement grid).

Alternative to hemispherical lens-based assessments (see 5.1, 5.2), conventional measurements of canopy closure that were validated with hemispherical methods are also possible, as long as they are made along the 10m x 10m grid covering the whole plot. These conventional methods include spherical densiometer, moosehorn, canopy scope, and the purely observational crown illumination index - see Smith & Ramsay 2018, Brown et al. 2000 for an overview of methods).

Table 4: Variables to be reported for a canopy closure assessment

Variable	Reporting unit	DQO
Canopy Closure (for each grid position)	%	± 5
Field of view used for Canopy closure assessment	°-	± 1
Grid position Easting (relative to origin)	m	0.1
Grid position Northing (relative to origin)	m	0.1
Method applied	code	
Date of measurement	DDMMYY	± 0
Date of maximum foliation (assumed)	DDMMYY	± 14d

5.1 Hemispherical photography

(Matjaz Cater, Christian Hertel, Stefan Fleck, Patrick Schleppi)

Hemispherical photography (also fish-eye photography), quantifies potential solar radiation at the viewpoint and characterizes plant canopy using photographs taken looking upward through an extreme wide-angle lens which approaches or equals 180-degrees. The theory of hemispherical photography represents the common theory of most indirect optical methods for LAI estimation in its purest form, since the photographs contain the angularly most comprehensive optical information in its highest resolution, while other devices often use lower resolution or angularly less comprehensive information.

LAI derivation is based on inverting a theoretical gap formula based on the angular distribution of gap fraction.The large field of view of hemispherical images also allows estimation of the leaf angle distribution and foliage clumping. The measurement and evaluation procedure comprises photograph acquisition, registration, classification, and calculation.

Photograph acquisition requires conditions without direct light in order to avoid the effects of light beam reflections and blooming effects, when light beams penetrate gaps. Known orientation (zenith and azimuth) is essential for proper registration with the hemispherical coordinate system used for analysis. A self-levelling mount can facilitate acquisition by ensuring that the camera is oriented to point straight up toward the zenith.

Photograph registration involves aligning the photographs with the hemispherical coordinate system used for analysis, in terms of centering, size (coincidence of photograph edges and horizon in coordinate system), and rotation (azimuthal alignment with respect to compass directions).

Photo classification involves determining which image pixels represent visible (non-obscured) versus non-visible (obscured) sky directions. Automatic classification is preferable.

Calculation uses algorithms that compute gap fraction as function of sky direction, and compute desired canopy geometry and/or solar radiation indices including LAI.

5.1.1 Location of measurement, measurement design, and equipment

5.1.1.1 Location and measurement design

Photographs are generally acquired on a 10m x 10m grid (30m by 30m in total) to represent an observed area of 0.25ha (minimum size of the Level II plots). The edges of the Level II plot need to be more than one tree height away from the grid points. The acquisition of 16 photographs along this regularly spaced grid is obligatory. This is described by the following figure:

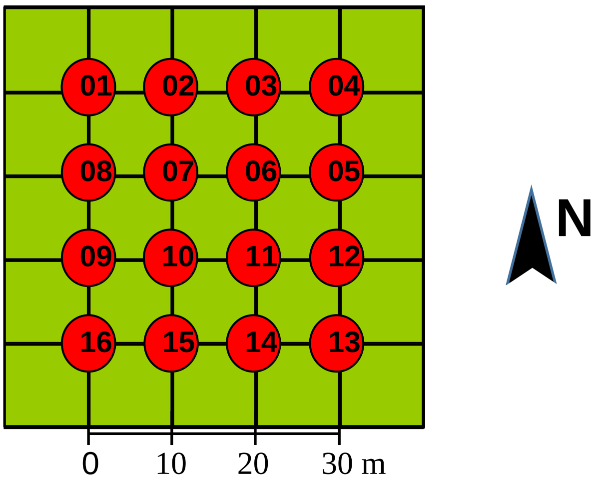

Figure 1: Measurement positions

If a measurement position is too close to an obstacle (tree stem, branches, installation), the measurement position needs to be moved such that the visual angle of the obstacle is horizontally less wide than 11.5° of the 360°-image. The choice of this threshold means that the distance between measurement position and the obstacle needs to be at least 5 times its diameter. E.g. for a stem of DBH 40 cm the measurement position needs to be at least 2 m away from the stem location. A leaf or other material above the lens needs to be in a distance of at least 10 times its diameter or should otherwise be removed. Each measurement position must be marked permanently. A standard measurement height of 1.3 m for photographs (lens position) is defined. This height should avoid disturbances by lower shrubs or installed litterfall or deposition samplers which may disturb the light sphere at the point of view. The location of each measurement point has to be documented by relative X,Y-coordinates. The origin of the coordinate system is the most south-west corner point of the 10m x 10m grid (point 16 in Figure 1), with axes pointing towards the North and East direction. If another metric coordinate system is already established, the respective coordinates may be submitted instead. Deviations from the fixed measurement grid may be necessary in some cases in order to avoid interference with other measurements.

In order to have a quantification of the spatial situation of the surveys, the coordinates of sampling devices have to be documented in the same way: For instance, a litterfall sampler situated 18 m west and 15 m south of the origin of the coordinate system has to be documented with the coordinates X = -18 and Y = -15.

The temporal frame for field surveys is split into summer and winter photographs. Summer photographs must be taken during the stage of maximum foliation (e.g. between mid July and mid August for Central Europe, depending on the local conditions in the actual year). Winter photographs especially for deciduous tree species should be taken after all leaves are fallen. Here the optimum point in time is shortly before budburst in spring.

5.1.1.2 Measurement equipment

Camera and lens

The camera needs to be a digital lens reflex camera with at least 12.3 Mpix (effective pixels) and an image sensor enabling an ASA/ISO range up to 10,000 or higher. Image sensors with a high dynamic range (range of exposure values at ISO 100) should be preferred. The camera should provide the possibility for remote control or self-timer. The fish-eye lens used needs to have a field of view of nearly 180°, recommended is the Sigma lens 4.5 mm F2.8 for most cameras or the Sigma lens 8 mm for full frame cameras.

Accessories

The camera needs to be held by a tripod with bubble level, alternatively the bubble level can also be attached to the camera body. In the forest it is necessary to measure lens height above the floor (1.3m) with a meter stick and to use a North-finder (Winscanopy), GPS, or a compass to orient the top of the image towards the North. On slopes steeper than 10° it is necessary to measure the slope and its aspect with an inclinometer or alternative devices.

Registration parameters of camera-lens combination

The pixel coordinates of the optical centre and the radius of the image for the given camera-lens combination need once to be determined as a permanent reference. Different methods exist: For the optical centre, one possibility is to photograph a marked point on the ceiling with the lens position plumbed down to be exactly vertically below it. Given that the floor is horizontal, the tripod-camera-lens combination can then be turned around the vertical axis in a few steps and several photographs taken. The pixel coordinates of the marked point on the photographs can then be determined (e.g. with many different free software packages) and they should all lie on a circle, if the measurement set-up was accurate. The pixel coordinates in the centre of this circle is the coordinates of the optical centre for the given camera-lens combination.

The image radius of the camera-lens combination can be determined within the same set-up by placing the camera lens in exactly the same height as e.g. two tables on both sides of it, where the closest point to the camera is marked. These marked points represent the 180° field of view and their average distance to the optical center is the radius of the hemisphere on the photograph. The angular distribution between optical centre and the border of the image is lens specific and may be found as a projection function for some lenses in annex 1.

Software and additional equipment

The hemispherical photo analysis system includes instruments which are needed for the determination of LAI and are listed below. It is preferable that the analyzing software supports evaluation of digital photos in batch mode and color classification. Furthermore, automatic threshold determination is recommended, since it reduces subjective impacts.

Table 5: Preferable equipment

HemiView	WinScanopy	Can-Eye	DHP	Hemisfer
- self-levelling camera mount - tripod - remote control - HemiView Software (black/white analysis only)	- self-levelling o-mount with digital North-finder - tripod - remote control - sun blocker (optional) - WinScanopy Software	- free - software only	- free - software only	-software only
http://www.delta-t.co.uk	http://www.regent.qc.ca	https://www6.paca.inra.fr/can-eye	Sylvain Leblanc	http://www.wsl.ch/dienstleistungen/produkte/software/hemisfer/

5.1.2 Data collection, transport and storage

For all taken photographs, the magnetic north direction has to be indicated within the image. If the North direction is not marked, North must be aligned to the top of the image. Optimal weather conditions for photographs are either uniformly overcast sky or the time of day, where no direct solar radiation is present. These conditions are required to avoid reflections on the lens or in the canopy that lead to misclassifications and also to avoid blooming effects within the images. Measurements before sunrise or after dawn are possible during the short period when enough light for the correct exposure setting is given and even the upper canopy is not illuminated by direct radiation. Additional considerations with regard to the weather conditions are: no rain causing drops on the lens, no visible fog in the canopy, no snow on the trees and no heavy wind causing twigs to move.

Furthermore, images must be saved to make additional or later analyses possible.

The photographs should be taken in RAW-format and maximum resolution. For the data storage system the format .JPG (high image quality settings) is suggested to get reproducible results.

The format of data storage is defined by the ICP Forests data submission forms.

5.1.3 Measurement and Calculation

Photograph acquisition

The experimental setup is already described in chapter 5.1.1.1. Several presets must be considered before photograph acquisition: All camera internal software filters (e.g. “sharpen the picture”) need to be turned off. If the camera permits it, the photographs should be shot in RAW image format (MacFarlane et al. 2014, Hwang et al. 2016). The conversion of RAW images to TIFF or JPEG (as input for image evaluation software) needs to follow the instructions given in Explanatory Item Number 400. For non-DSLR cameras, the “Fish-Eye setting” means that the zoom is fixed at the widest angle and focus is set to infinity. Generally, the ISO setting should be 200, but directly before sunrise or after sunset (ISO 400), as well as on windier days with slightly moving canopy elements (ISO 800), higher numbers may be adequate. The camera should be equipped and started with a remote control or self-timer in order to avoid camera movements. The operator needs to take care not to stand in the field of view.

Most image sensors are not able to fully capture the variability of light intensities (dynamic range) that may occur in the different view directions. The goal in photograph acquisition must therefore be to keep the maximum intensity occurring on the photograph as high as possible without overexposing it (by lowering aperture and increasing shutter speed), thereby avoiding to make the darker parts of the photograph indiscernible. The safest way to achieve this is to make a row of 5 pictures with different exposure and select the one with highest exposure, which does not contain overexposed pixels (bracketing). This bracketing can start around the expected adequate settings, which may be found based on the brightness of the sky (method 1) or estimated from the automatically found settings by the camera (method 2).

Method 1: Take a reference photograph outside of the forest or through a large gap using a narrower lens and the automatic exposure settings of the camera or use a spotmeter for a luminosity measurement. Record the settings of this reference photograph, change your camera to manual mode, and increase the exposure by +1.5 stops for photographs in the forest.

Method 2 comprises the use of automatic camera settings based on an aperture setting of F8. Most of the newer cameras allow for checking the image for overexposed pixels and provide a histogram on the produced grey values, where the overexposure is visible. This option should be used and shutter speed increased until nearly no overexposed pixels, i.e. no peak of overexposed pixels in the histogram, are detected on the image. Additionally the image can also be checked for visible blooming effects (vegetation elements disappearing in the surrounding light).

Photograph classification and LAI calculation

Image processing is performed according to the manual of the used software system. LAI is estimated following the Ellipsoidal method of Norman and Campbell (1989), using a field of view of 120° (analogous to 4 rings of the plant canopy analyzer) – only in case of steep slopes it may be necessary to deviate from this setting. No manipulations of the photographs with image processing software should be done

Pixel classification into sky and non-sky pixels is often peformed using single binary thresholding: the most common methods are edge detection (Ishida 2004, Rosin 2001) and iterative clustering (Ridler & Calvard 1978). Use of dual thresholding to classify mixed pixels has also been suggested by some authors in case of very dense canopies (MacFarlane 2011). If available, the Ridler & Calvard (1978) method should be used.

Systems like *HemiView* currently only provide manual thresholding in black and white classes. In this case and in cases where the automatic algorithms obviously failed, the threshold must be set manually in a way that all biomass is considered. Best is zooming in to a random biomass detail in the middle of the image and set the current range. The result of this threshold value has to be checked with regard to (1) blooming effects and the disappearance of (2) canopy objects or (3) gaps when compared to the original image. The optimum threshold is then found by completely avoiding blooming and minimizing the other two effects.

In the case of sloping terrain (slopes steeper than 10°), the photographs should be corrected by the used software for slope induced directional heterogeneity of penetrating radiation (compare Cao et al. 2015). If the slope is visible even in the fourth ring (equivalent to the plant canopy analyzer, i.e. in the 120° field of view), this ring should be excluded from the calculation (90° field of view).

5.1.4 Variables measured and reporting units

The resulting LAI value after Norman & Campbell (1989) is the effective plant area index (PAI_{eff}), i.e. the raw estimate without corrections for clumping or woody surfaces. In order to make sure that PAI_{eff} is correctly determined, the used software environment needs to provide the possibility to average gap fractions of the 16 photographs per plot before LAI is calculated (Ryu et al. 2010). PAI_{eff} of each grid point is delivered to the database. Due to the unreliable measurement of very small gap fractions, the average PAI_{eff} for the plot is only delivered, if it is a value below 6, otherwise it is reported as -1. Also the plot average of LAI_{max} is reported as -1 in this case, while the single grid point values are delivered for eventual later evaluations.

LAI_{max} is derived from PAI_{eff} values by correction for clumping and the contribution of woody surfaces according to the equations below (Chen 1996). The element clumping coefficient Ω can be determined from a hemispherical photograph using appropriate software (e.g. Hemisfer) or with external devices (e.g. TRAC, see section 5.2.3.2.). An additional correction is necessary for coniferous tree species with regard to their needle-to-shoot area ratio γ. Species-specific values of γ for the main species are documented in Annex II.

The contribution of woody surfaces is derived from SAI measurements in winter (deciduous forests) or from species-specific SAI estimations based on biomass harvests that are upscaled via DBH measurements to the whole plot (evergreen forests, compare section 4.2.6). LAI_{max} is then calculated as

$$LAI_{max} = PAI_{eff} \times \gamma / \Omega - SAI,$$

with γ , the needle-to-shoot area ratio, being 1 in the case of broadleaved forests. If SAI of coniferous or other evergreen trees may not be derived from own measurements, species-specific values for the woody to total plant area ratio α may be applied (see annex). α equals SAI / LAI, so LAI_{max} may be calculated in this case as:

$$LAI_{max} = PAI_{eff} \times \gamma / \Omega \times (1 - \alpha)$$

The SAI calculation based on winter photographs is performed analogously to LAI, but without corrections for woody area and with γ =1.

Table 6: Variables to be reported in case that hemispherical photography is applied

Variable	**Reporting unit**	**DQO**
LAI_{max} (per point and averaged per plot) PAI_eff (average without clumping correction) + used software for image evaluation Field of view, if reduced due to slope Rings: number of PCA-rings equivalent to the field of view used for PAI calculation Gap fraction summer (per point)	m²/m² m²/m² ° - %	± 1 ± 1 ± 1 ± 0.5 ± 5 %
α γ Ω (plot average and/or by measurement point)	- - -	± 0.1 ± 0.1 ± 0.1
SAI (per point and averaged per plot) + used optical device SAI_eff (= PAI_eff in winter) Field of view, if reduced due to slope Gap fraction winter (per point)	m²/m² m²/m² ° %	± 1 ± 1 ± 1 ± 5%
Sky conditions	Standard overcast/cloudy Clear sky	n.a.
Sun conditions	Sun below the horizon Sun above horizon	n.a.
Exposure Value	-	± 0
Date of measurement	DDMMYY	± 0
Date of maximum foliation (assumed)	DDMMYY	± 14d

5.1.5 Quality assurance and quality control

Quality is assured by providing photos for each measurement point. Every photo is numbered and named according to following format: XXPPPPNNNNDDDDDDTTTTTTSS.jpg where:

XX - country code (ICP Forests manual)

PPPP - plot number (ICP Forests manual); replaced by "9" and 3 further letters which define a location not being an ICP Forests / FutMon plot

NNNN - measurement point number

DDDDDD - date of image production (YearMonthDay: e.g. 990731)

TTTTTT - time of image production (HHMMSS)

SS - sequence number in case that more than one photo is made in the same time (01, 02, 03, …).

In order to get reliable values for LAI, uniform settings for field work and for the analysis, additional values (latitude & longitude, altitude, exposition, and slope) have to be defined and documented as they are needed for later evaluations. Parameters are submitted to the data centre using the specific data forms.

5.2 Plant Canopy Analyzer

(Stefan Fleck, Martin Greve)

The plant canopy analyzer (LAI-2000, LAI-2200) uses small hemispherical lenses for light detection above and below the canopy. While it does not differentiate azimuthally between the directions of incoming light (light is averaged in each of 5 concentric rings of the polar projected light record), it uses only the blue part of the electromagnetic spectrum (320 nm – 490 nm), where the contrast between leaves and sky is highest and it simultaneously measures light above the canopy with a second sensor. Like the hemispherical photographs, plant canopy analyzer measurements require diffuse light conditions.

5.2.1 Location of measurement, measurement design, and equipment

5.2.1.1 Location and measurement design

The below canopy readings are performed using the same sampling design described for hemispherical photographs with principally the same restrictions regarding distance to objects in the field of view (section 5.1.1.1.) The measurement is regularly done at 1.3 m height, but a quarter of the sensor’s field of view has to be covered with a viewcap in order not to measure the light blocked by the operator. The disadvantage of the use of viewcaps is that they have to be oriented towards the same compass direction during the whole measurement sequence (16 measurement points) as the viewcap on the above canopy sensor that needs to be installed in this case. Care has to be taken that the compass is not influenced by iron devices during the measurement procedure. Viewcaps may also be necessary on sloping terrain in order not to measure the light blocked by a nearby mountain or in those cases, where the above canopy sensor stands in a very small clearing. The interference with other measurements on the plot needs to be avoided and may result in deviations from the fixed measurement grid.

The above canopy sensor needs to be placed in a nearby clearing with the same sky conditions as the monitoring plot, so in a maximum distance of 1 km. The clearing must permit unobstructed view to all 5 sky bands measured by the sensor, alternatively, the measurement can be restricted to the innermost 4 or 3 sky bands, which lowers the necessary opening angle. The angle between a line from the above canopy sensor to the highest points in the surrounding vegetation and the horizon needs to be measured with an inclinometer in order to ensure that the vegetation is less than 16 ° (or 32° or 47° , respectively, depending on the rings used for evaluation) off the horizon. The use of viewcaps enables to perform the above canopy measurement even in smaller clearings: If three quarters of the sensor are covered, a clearing diameter of 3.5 times tree height is sufficient for a measurement comprising all 5 rings of the sensor (Figure 2).

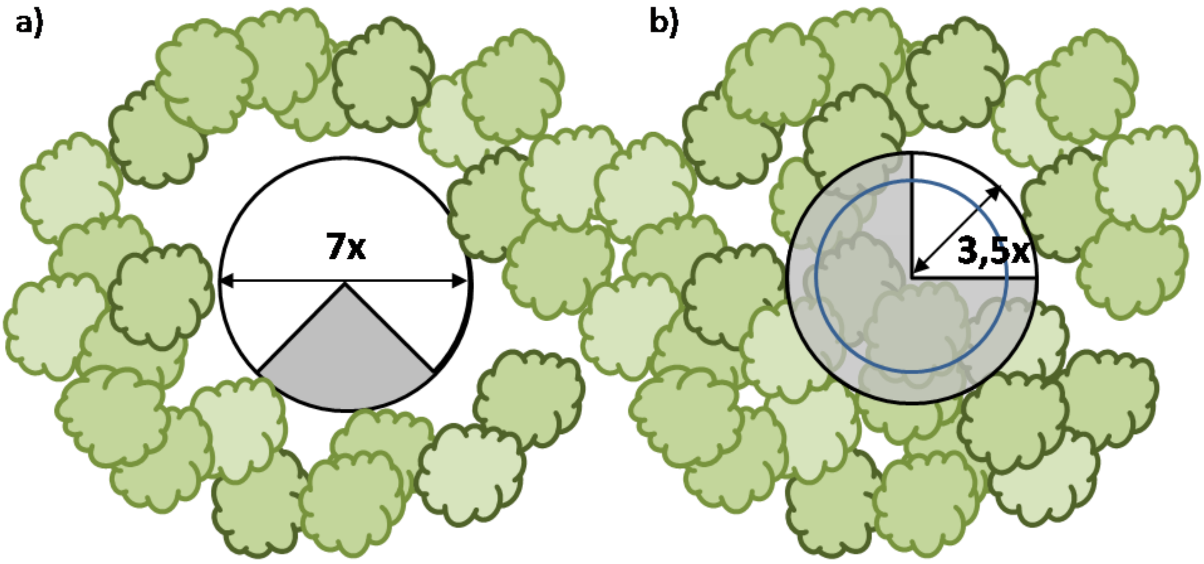

Figure 2: A minimum clearing diameter of 7 times tree height is required for the full field of view (5 rings) without the use of viewcaps, while the use of larger viewcaps that cover three quarters of the sensor enables to use clearings with a minimum diameter of 3.5 times tree height

The above canopy sensor may also be placed on a tower or an elevated platform in order to meet the requirement of unobstructed view of the sky. When levelling the sensor, it is important to watch the bubble level vertically from above or vertically from below.

5.2.1.2 Measurement equipment

The necessary equipment comprises:

- Two plant canopy analyzer sensors with logging units
- 50% viewcap on sloping terrain
- 75% viewcap on small opening
- software in its actual version
- hemispherical photographs or TRAC for clumping index
- compass (optional)
- tower, elevating platform (optional)

5.2.2 Data collection, transport and storage

The required light conditions are different for the LAI-2200 sensor and the LAI-2000 sensor: Only the LAI-2200 sensor enables a scattering correction for measurements under sunny conditions after Kobayashi et al. (2013). In this case the preferred conditions are a stable bright sky with the sun high above the horizon. If there are not many clouds and they do not move too much (stable sunny conditions), measurements under direct radiation conditions are possible.

On slopes steeper than 10°, however, this measurement is not possible and the preferred conditions are then – as with the LAI-2000 - uniformly overcast sky conditions, generally the same as for hemispherical photography (see section 5.1.2).

If measurements are made early in the morning (shortly before sunrise) or late in the evening (shortly after sunset), it should be tested, if the sensor reacts to an obstacle moving in a distance of 10cm above the sensor, otherwise it is too dark. It is also too dark, when leaves cannot be distinguished by eye. On days with uniformly overcast sky, no shade should be visible on the ground. No rain, dust, fog or snow should be in the atmosphere while measuring. It is good practice to measure always in the same order of grid points.

5.2.3 Measurement and Calculation

5.2.3.1 Instrument specific settings

The above canopy sensor should log a measurement every 15 seconds. For the below canopy reading it is recommended to repeat every measurement by a second reading directly thereafter in order to make sure that no measurement is missing due to any malfunction. The number of readings should be controlled at the end of the sequence. A repetition of the first measurements taken is a good possibility to check the stability of light conditions.

Calculation of the effective plant area index (PAI_{eff}) is performed with the instrument's software using the settings for 4 rings by multiplying the LAI value (Variable "EllipLAI" is the relevant LAI calculated after Norman & Campbell 1989) with the apparent clumping factor ("ACF" as given by the instrument's software). The procedure for SAI_{eff} determination in deciduous forests in winter is the same as for PAI_{eff}.

Unlike hemispherical photography, PAI_{eff} from the plant canopy analyzer is calculated at site level, which allows in the described way to undo the influence of the apparent clumping factor on the PAI_{eff} estimate (Chianucci et al. 2015).

As the plant canopy analyzer has no ability to correct LAI estimates for element clumping index, independent estimates from hemispherical photographs or TRAC-measurements are required to determine the element clumping index Ω. Clumping correction and correction for the contribution of woody surfaces are performed as described in section 5.1.4..

5.2.3.2 TRAC measurements

If TRAC measurements are performed, 12 transects of 10m length need to be established on the plot with markers on the ground. The transects must be perpendicular to the sun beams and shall cover the whole plot. TRAC measurements should best be taken when the solar zenith angle is near 60°. The range between 35° and 60° is acceptable.

TRAC must be setup for measurements by resetting the clock and clearing the memory immediately before the measurements are taken. Direct sunlight is blocked by positioning of the black plastic diffusion strip on the TRAC. The TRAC is held in a position that allows to control the bubble level and a timer while walking with constant speed at approximately 1 meter per 3 seconds. Deviations from the horizontal orientation and from constant speed are only tolerated, if they take less than one second. If this is not possible e.g. due to understorey plants or other obstacles it is better to use hemispherical photographs instead of TRAC. Further details are given in the TRAC manual.

Due to the subjectively estimated walking speed, the correct execution of TRAC measurements needs to be controlled with a portable computer in the field. The data are transferred to the computer with TRAC-Win software and only transects with more than 850 readings are accepted. For the calculation of clumping indices, the mean element width of foliage elements needs to be determined. The mean element width is defined as the square root of half the largest projected leaf area for broad leaves. For conifer shoots close to cylindrical or spherical shapes, it can be approximated as the square root of the product of shoot length and diameter.

5.2.4 Variables measured and reporting units

Table 7: Variables to be reported in case that plant canopy analyzers are used

Variable	Reporting unit	DQO
LAI_{max} (per point and plot average) PAI_eff (plot average without clumping correction) Number of rings used for PAI calculation Gap fraction summer	m²/m² m²/m² - %	± 1 ± 1 ± 0 ± 10%
SAI (per point and plot average) SAI_eff (plot average without clumping correction) Number of rings used for SAI calculation Gap fraction winter	m²/m² m²/m² - %	± 1 ± 1 ± 0 ± 10%
α γ Ω ((plot average and/or by measurement point) clumping method used software used for image analysis to derive Ω (if applicable)	- - - code: photos or TRAC code	± 0.1 ± 0.1 ± 0.1
Mean element width (in case of TRAC measurements)	cm	± 10%
View cap used (percentage covered)	%	± 0%
Sky conditions	Standard overcast/cloudy Clear sky	n.a.
Sun conditions	Sun below the horizon Sun above horizon	n.a.
Date of measurement	DDMMYY	± 0

5.2.5 Quality assurance and quality control

The light conditions of the above canopy readings should be verified in order to test them for data range and the expected trend. Values above 1000 units should not be accepted. While measurements in the early morning should show a continuously increasing trend, the measurements during the day should not show any strong trend and those in the evening a continuously decreasing trend. Short-term fluctuations in the above canopy readings are a reason to repeat the measurement, since the measurement resolution of 15 seconds cannot guarantee that above canopy reading and below canopy reading were done under the same conditions in this case.

Next to the variables measured or calculated, the original above and below canopy readings for 3 rings, 4 rings, and 5 rings at all 16 points are delivered to the database as a text file.

The text file is named XXPPPPDDDDDDTTTTTT.txt , with:

XX - country code (ICP Forests manual)

PPPP - plot number (ICP Forests manual); replaced by "9" and 3 further letters which define a location not being an ICP Forests / FutMon plot

DDDDDD - date of measurement (YearMonthDay: e.g. 990731)

TTTTTT - time of measurement (HHMMSS)

5.3 SunScan Ceptometer

(Martin Greve, Stefan Fleck)

The SunScan ceptometer uses high amounts of direct radiation and is based on simultaneous measurements above and below the canopy with two sensors. It is one of several ceptometers available (compare AccuPAR LP-80) and since it was used during the Futmon project, it has been incorporated in this manual in order to represent LAI measurements with ceptometers. More detailed guidelines for the other instruments available still need to be developed.

5.3.1 Location of measurement, measurement design, and equipment

5.3.1.1 Location and measurement design

The sampling design should use a denser grid because of the punctual measurement of at least 3,33m x 3,33m resolution to cover an area of 0.25ha which is defined in the manual of ICP Forests to be the minimum size of the Level II plots excluding the edges of the area. At least 100 measurements along this regular spaced grid cells are obligatory. This is described by the following figure. The larger dots represent the grid also used for other optical measurements (compare Figure 1), the smaller dots the additional points for the measurements with SunScan.

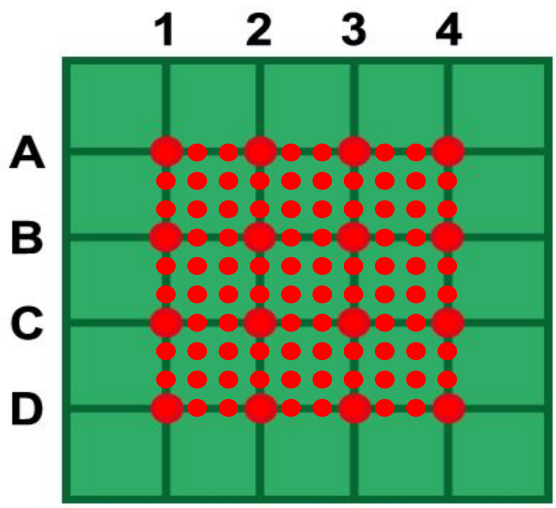

Figure 3: SunScan measurement positions

The interference with other measurements on the plot needs to be avoided and may result in deviations from this fixed measurement grid.

For practical reasons a measurement height of 1,5 m is defined. If a measurement point is situated within a distance of less than 0,5 m from an obstacle on the same height or above the sensor (e.g. tree trunk, large branch, or plot border) the measurement point must be moved to a position where the distance to the obstacle is at least 5 times its diameter in order to avoid shading of the sensor.

The temporal frame for field surveys is split into summer and winter measurements. Summer-time measurements must be taken during the stage of maximum foliation (e.g. between 16th July and 15th August for Central Europe). Winter-time measurements especially for deciduous tree species should be taken after all leaves are fallen. Here the optimum point in time is shortly before budburst.

5.3.1.2 Measurement equipment

- Beam fraction sensor (BFS): This Sensor is used to measure the above canopy radiation.
- PAR probe (PARP): This Sensor is used to take measurements below the canopy.
- Datalogger: The Datalogger is connected to the PARP and stores the measured values.
- Radio-Link or cable-connection: The BFS and PARP have to bee connected during the measurements by cable or wireless connection.
- Software to calculate LAI: The software is preinstalled on the Datalogger. Data has only to be transferred to a computer after the measurements.

5.3.2 Data collection, transport and storage

The distance between the beam fraction sensor for the above canopy readings and the PAR probe for the below canopy readings is limited by cable-length or radio range. Radio range in forests is about 80 meters but can vary by varying stand properties. In some cases it is possible to log the PAR probe and beam fraction sensor separately and calculate LAI later.

For the time of measurement a high proportion of direct radiation (> 1000 µmol/m²/s above the canopy) and no clouds should be present. The sun should be at a high zenith angle ($\theta < 60°$). Also no dust, rain, fog and snow should interfere with the measurements.

The diameter of the clearing for the beam fraction sensor should exceed 3 times tree height. When no such opening is available, the beam fraction sensor should be set up in an elevated position to relatively reduce the height of the surrounding trees. The sensor has to be leveled by watching the bubble level vertically from above.

Following settings have to be defined by the user in the software installed on the datalogger before the measurements:

- Ellipsoidal leaf angle distribution parameter (ELADP) is important for calculation of the correct light absorption of the canopy. The ELADP or the mean leaf angle has to be measured in the field by counting the number of leaves with an angle greater and lower than 45° from the vertical (see SunScan manual, Potter et al. 1996) or by calculating the mean leaf angle by hemispherical photography or plant canopy analyzer measurements (compare annex 3 for species-specific examples). Wang & Jarvis (1988) presented a way to calculate the ELADP from the mean leaf angle or the mean leaf angle from the ELADP:

$$MLA = \frac{1}{0{,}0066 \cdot ELADP + 0{,}0107} \quad (ELADP \leq 1) \quad \Big| \quad r^2 = 0{,}996$$

$$MLA = \frac{1}{0{,}0103 \cdot ELADP + 0{,}0053} \quad (ELADP > 1) \quad \Big| \quad r^2 = 0{,}998$$

- The absorption should be set to 0,85 if the respective absorption of the leaves is unknown and cannot be measured.
- Latitude, longitude, date and time have to be set correctly, because these values are used to calculate sun position

Before each measurement the PAR probe has to be leveled by watching the bubble level vertically from above. It is also very important to avoid shading of the PAR probe by the user.

5.3.3 Measurement and Calculation

A correction for the contribution of woody surfaces is performed in the same way as for hemispherical photographs (5.1.4), while a correction for clumping is not necessary, since the assumption of stochastic gap size distribution is not used.

5.3.4 Variables measured and reporting units

Only the mean value of LAI, PAI (summer) and SAI (winter) for the plot has to be reported. All additional relevant information is stored in the datafile which also has to be sent to the database.

Table 8: Variables to be reported in case that SunScan Cepometers are used

Variable	Reporting unit	DQO
LAImax PAI (plot average)	m²/m² m²/m²	± 1 ± 1
SAI (plot average)	m²/m²	± 1
Date of measurement	DDMMYY	± 0

5.3.5 Quality assurance and quality control

The standard error of the mean should not exceed 5%. If the stand is this heterogeneous it is recommend to do four measurements per measurement point, one measurement to each point of the compass.

Quality is assured by providing the datafile. It is named according to following format:

XXPPPPDDMMYY.prn where:
XX - country code (ICP Forests manual)
PPPP - plot number (ICP Forests manual); replaced by "9" and 3 further letters which define a location not being a ICP Forests / FutMon plot
DDMMYY - date of measurement

5.4 Airborne LiDAR

(Stefan Fleck)

Unlike the other indirect optical methods, Airborne LiDAR (Light Detection And Ranging) or short: Airborne Laser Scanning (ALS) involves active emission of radiation. Knowing the time of light emission and the velocity of light, the backscattered signal is used to derive the exact 3D-position and eventual other informations belonging to the reflecting material. From all methods included, airborne LiDAR is the method that is best suited for large areas from several square kilometres to complete regions. While it is not expected that this method is selected for an LAI-measurement campaign on a single ICP Forests plot, the comparability with more local measurements needs to be established in order to be able to use existing information from large scale surveys, where ICP Forests plots are included.

5.4.1 Location of measurement, measurement design, and equipment

Like with all indirect methods, the LAI measurement with airborne LiDAR should be performed in the stage of maximum foliation in order to be able to derive LAI_{max}. Since the availability of the appropriate LiDAR unit and aircraft may not always be given for this point in time, it is recommended to perform on the same day measurements with any other method of LAI estimation and to repeat these measurements in the stage of maximum foliation, in order to scale the ALS-derived LAI (LAI_{date}) to maximum LAI.

5.4.1.1 Location and measurement design

In order to use the data from an ALS survey, the flight strip must cover the main instrumented plot with this part of the plot being more than 100m away from the border of the flight strip and more than 1km away from the beginning or end of the flight strip. The exact positioning of the plot inside the flight strip must be possible based on recognizable features such as towers, apex of characteristic or outstanding trees, posts or markers on a clearing nearby. Full waveform LiDAR data are preferred, since they permit to also refind features in the lower part of the canopy, if it is not too dense.

The x,y,z-coordinates of the features need to be determined on the ground either relative to each other, if they are at least 4 features (e.g. by theodolite measurements, triangulation) or with real-time kinematic GPS / differential GLONASS, if they are less. It is also possible to combine several GPS / GLONASS measurements on clearing(s) nearby with triangulation measurements towards features on the plot or the plot borders. It must be assured that the features on the plot may be recognized in the dataset (preferably full waveform LiDAR). The GPS reference station should be less than 50km away from the plot.

The ALS measurement needs to be calibrated with other indirect or direct measurements (LAI-2000, hemispherical photos, leaf litter collections), potentially on a similar stand somewhere in the measured swath. Alternative, the calibration of an earlier measurement campaign with the same system may be used.

5.4.1.2 Measurement equipment

- Preferably full waveform ALS. The system should have been calibrated with independent LAI measurements in a previous study.
- Real-time kinematic GPS or GLONASS receiver using differential measurement mode
- Markers like small buildings or posts
- Local weather station to provide wind measurements and precipitation at the exact time of measurement

5.4.2 Data collection, transport and storage

The scanner and flight settings should be such that they enable a point density of at least 5 pulses per m². The footprint diameter should, thus, be below 50cm. The scan angle must not deviate by more than 15° from vertical. The output files should contain information on the 3D-coordinates of each reflection as well as the scan angle, distance between scanner and object, and the number of pulses.

Exact GPS / GLONASS measurements are difficult in dense forests, since the satellite signal needs to penetrate the canopy and signals from satellites at low angles above the horizon may not be received therefore. The remaining satellites are often so close to each other that the position calculation gets imprecise (so-called positional dilution of precision, PDOP). It is therefore recommended to perform the position measurements of constant positions in winter (less leaves / needles) or to select a time with many available satellites for the measurement in summer. PDOP during the measurement must be below 6.

5.4.3 Measurement and Calculation

The ALS-based plant area index (PAI_{ALS}) is generally calculated from canopy and ground echoes after the formula

$$PAI_{ALS} = c \cdot Ln\left(\frac{1t_1 + \frac{1}{2}t_2 + \frac{1}{3}t_3 + \frac{1}{4}t_4 + \dots}{1g_1 + \frac{1}{2}g_2 + \frac{1}{3}g_3 + \frac{1}{4}g_4 + \dots}\right)$$ (adjusted based on Solberg et al. (2009))

Here, t_1, t_2, t_3, etc. are the total echo counts of pulses with 1, 2, 3,… echoes and g_1,g_2, g_3, etc. are the ground echo counts of pulses with 1,2,3,… echoes. Ground echoes are all echoes below the effective measurement height of ground-based LAI assessments (2m). c is the calibration factor of the system relating ALS-measurements to local LAI measurements with other methods (LAI_{local}):

$$c = LAI_{local} / Ln\left(\frac{1t_1 + \frac{1}{2}t_2 + \frac{1}{3}t_3 + \frac{1}{4}t_4 + \dots}{1g_1 + \frac{1}{2}g_2 + \frac{1}{3}g_3 + \frac{1}{4}g_4 + \dots}\right)$$

Separate calculations using this formula should be performed for different sorts of echoes (first pulse, first and last pulse, all pulses) according to Fleck et al. (2011).

Depending on the calibration measurements, PAI_{ALS} does or does not contain the clumping correction and the correction for woody surfaces, so that clumping coefficient (Ω) and proportion of woody surfaces (α) have eventually to be determined separately using hemispherical photographs or TRAC (sections 5.1. or 5.2.3.2.) and SAI-measurements (for deciduous forest: from winter measurements with plant canopy analyzer or hemispherical photographs; for coniferous forests: from biomass harvests or using species-specific values given in the annex).

The clumping correction is then performed as described in section 5.1.4.. Finally, the derived LAI for the specific day of ALS-measurement (LAI_{date}) needs to be adjusted with local measurements at the time of maximum foliation to yield LAI_{max}.

5.4.4 Variables measured and reporting units

Table 9: Variables to be reported in case that airborne LiDAR is used*

Variable	Reporting unit	DQO
LAI_{max} $PAI_{ALS, all pulses}$	m²/m² m²/m²	± 1 ± 1
$PAI_{ALS, first pulse}$ $PAI_{ALS, first and last pulse}$	m²/m² m²/m²	± 1 ± 1
SAI SAI_eff (and used method)	m²/m² m²/m²	± 1 ± 1
Ω (plot averages for summer and for winter)	-	± 10%
GPS-/GLONASS-positions of features (east, north, height, PDOP) or relative local coordinates (east, north, height)	(m/m/m/-)	± 10%
Date and time of the ALS measurement	DDMMYY, HH:MM:SS	± 10 min

*: not all variables are yet implemented in the central database

6 Data Handling

6.1 Data submission procedures and forms

The procedures for data submission are method-specific: In several cases, there are original data files or photographs to be delivered along with the variables that are reported to the database. These cases are explained and defined in the Quality assurance chapter belonging to each method.

The relevant forms for submission of all method-specific data are the forms .PLA (reduced plot file on LAI measurements), .LAC (coordinates of LAI measurement points and other surveys), .LAP (LAI photo documentation, also used for data files, depending on the method), .LAM (LAI results of hemispherical measurements, this includes photographs and LAI-2000 measurements), .LLF (LAI results of litterfall measurements), and .LAM (LAI measurement outcome).

6.2 Data validation

The data validation is treated in the quality assurance chapter belonging to each method.

6.3 Transmission to coordinating centres

All validated data should be sent yearly to the European central data storage facility at the ICP Forests Programme Co-ordinating Centre. A detailed time scheduled is provided by the relevant bodies.

For the submission of the data to PCC the forms are to be used as indicated in Table 10.

Table 10: Forms for submission of LAI data

Reduced plot file information and plot representative results	.PLA
LAI-photo documentation	.LAP
LAI results of hemispherical measurements	.LAM
LAI results of litterfall measurements	.LLF

6.4 Data processing guidelines

The data processing guidelines are given in detail in the subchapter concerned with each LAI measurement method.

6.5 Data reporting

The procedures for data reporting are given in detail in the chapters belonging to each measurement method. Each National Focal Centre must submit information on deviations from these recommended procedures or changes of methods. Periodical quality control evaluations may be requested by the Programme Co-ordinating Centre to be part of integrated evaluations. References to any publications arising from the work on the Level I/ II plots should be notified so that they can be listed on the ICP Forests web site.

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Annex I – Hemispherical Lens Specifications

Lens specific projection functions as determined by Schleppi et al. (2007). The parameters are coefficients of the polygon $R = a + bx + cx^2 + dx^3 + ex^4 + fx^5$, x being the vertical angle in radians and R the relative radius on the image.

Lens name	**a**	**b**	**c**	**d**	**E**	**f**
Sigma 4.5mm	0	0.69513	0.03835	-0.048128	0	0
Sigma 8mm	0	0.75276	-0.073937	0	0	0
Nikon FC-E8	0	0.681	-0.028253	0	0	0
Nikon FC-E9	0	0.6427	0.0346	-0.024491	0	0
Nikkor 8mm	0	0.9192	-0.1792	-0.000443	0	0
Nikkor OP 10mm	0	1.0168	-0.0573	-0.117603	0	0
Soligor Fish Eye	0	0.677923	-0.029481	-0.022084	0.041495	-0.016644
Raynox DCR-CF185	0	0.5982	0.024459	0	0	0

Annex II – Needle to Shoot Area (γ) and Woody to Total Area Ratio (α)

The needle-to-shoot area ratio γ and the woody to total area ratio α are available for the coniferous species below.

Species	γ	α	Reference
Abies alba	2.3		Cescatti & Zorer 2003
Abies amabilis	2.2		Stenberg et al. 1998
Abies balsamea	1.7		Chen et al. 2006
Casuarina glauca	1.4		Niinemets et al. 2006
Picea abies	1.6		Stenberg et al. 1995
Picea abies (irrigated and fertilized)	1.2		Stenberg et al. 1995
Picea abies	1.3		Palmroth et al. 2002
Picea abies (irrigated and fertilized)	1.4		Palmroth et al. 2002
Picea abies	1.33	0.17	Tagesson 2006
Picea banksiana (young)	1.6	0.04	Chen et al. 1997, Chen 1996
Picea banksiana (old)	1.8	0.225	Chen et al. 1997, Chen 1996
Picea banksiana (young)			Chen et al. 2006
Picea banksiana (88 years old)	1.4		Chen et al. 2006
Picea mariana	2		Chen et al. 1997
Picea mariana			Chen et al. 2006
Picea mariana		0.145	Chen 1996
Picea pungens	1.4		Therezien et al. 2007
Picea sitchensis		0.23	Chen 1996
Pinus contorta	2.2		Oker-Blom et al. 1991
Pinus echinata	1.3		Therezien et al. 2007
Pinus palustris	1.6		Niinemets et al. 2006
Pinus palustris	1.6		Therezien et al. 2007
Pinus palustris (current year shoots)	2.3		Therezien et al. 2007
Pinus patula			Niinemets et al. 2006
Pinus pinaster	1.4		Guyon et al. 2003
Pinus ponderosa		0.29	Law et al. 2001
Pinus radiata	2.7		Niinemets et al. 2006
Pinus resinosa	2.1	0.07	Law et al. 2001
Pinus strobus	1.4		Therezien et al. 2007
Pinus strobus	1.9		Chen et al. 2006
Pinus sylvestris	1.8		Oker-Blom & Smolander 1988
Pinus sylvestris	1.7		Smolander et al. 1994
Pinus sylvestris	1.6		Stenberg et al. 2001
Pinus sylvestris	1.75		Gower et al. 1999
Pinus sylvestris	1.7	0.14	Tagesson 2006
Pinus sylvestris		0.15	Jonckheere et al. 2005
Pinus taeda (sun shoots)	1.6		Therezien et al. 2007
Pinus taeda (shade shoots)	1.1		Therezien et al. 2007

Pinus thumbergiana	1.3		Therezien et al. 2007
Pseudotsuga menziesii	1.65	0.15	Chen et al. 2006
Tsuga canadensis	0.9		Therezien et al. 2007

Annex III – Measured Leaf Angle Distributions

Direct measurements of leaf angle distributions are available from the main forest tree species (exemplary data compiled with support by Jan Pisek and a selection of published angle measurements provided with tools for their evaluation by Chianucci et al. (2018).

Species	Mean Leaf Angle	Standard deviation	Type of distribution	Reference
Acer campestre	50.07	14.98	plagiophile	Chianucci et al. 2018
Acer monspessulanum	20.11	14.8	planophile	Chianucci et al. 2018
Acer platanoides	22.1	15.07	planophile	Chianucci et al. 2018
Acer platanoides	41.37	17.47	plagiophile	Chianucci et al. 2018
Acer platanoides	26.2	15.67	planophile	Chianucci et al. 2018
Acer platanoides	21.77	14.57	planophile	Chianucci et al. 2018
Acer platanoides	32.38	16.56	planophile	Chianucci et al. 2018
Acer platanoides	22.3	14.9	planophile	Raabe et al. 2015
Acer pseudoplatanus	33.81	17.09	planophile	Chianucci et al. 2018
Aesculus hippocastanum	39.58	16.85	plagiophile	Chianucci et al. 2018
Aesculus hippocastanum	35.34	16.29	plagiophile	Chianucci et al. 2018
Aesculus hippocastanum	29.64	14.93	planophile	Chianucci et al. 2018
Aesculus hippocastanum	38.1	15.99	plagiophile	Chianucci et al. 2018
Ailanthus altissima	20.01	14.86	planophile	Chianucci et al. 2018
Alnus glutinosa	51.26	20.6	spherical	Chianucci et al. 2018
Alnus glutinosa	51.1	21.1	spherical	Pisek et al. 2013
Alnus incana	35.09	20.03	planophile	Chianucci et al. 2018
Alnus incana	22.94	15.85	planophile	Chianucci et al. 2018
Alnus incana	31.47	20.19	planophile	Chianucci et al. 2018
Alnus incana	27.03	19.47	planophile	Chianucci et al. 2018
Alnus incana	24.2	19.23	planophile	Chianucci et al. 2018
Alnus incana	23.5	12.7	planophile	McNeil et al. 2016
Betula pendula	63.29	16.69	erectophile	Chianucci et al. 2018
Betula pendula	48.08	22.92	uniform	Chianucci et al. 2018
Betula pendula	60.05	17.53	erectophile	Chianucci et al. 2018
Betula pendula	32.31	21.2	planophile	Chianucci et al. 2018
Betula pendula	54.83	17.36	spherical	Chianucci et al. 2018
Betula pendula	60.05	16.18	erectophile	Chianucci et al. 2018
Betula pendula	50.19	21.28	spherical	Chianucci et al. 2018
Betula pendula	56.3	18.7	spherical	McNeil et al. 2016
Betula pubescens	15.8	11.7	planophile	Pisek (unpublished data)
Carpinus betulus	12.9	9.69	planophile	Chianucci et al. 2018
Carpinus betulus	32	16.8	planophile	Pisek (unpublished data)
Castanea sativa	34.4	20.59	planophile	Chianucci et al. 2018
Castanea sativa	34.4	21.7	planophile	Pisek et al. 2013
Fagus sylvatica	18.08	15.09	planophile	Chianucci et al. 2018
Fagus sylvatica	26.9	18.7	planophile	Pisek (unpublished data)

Fagus sylvatica	25.4	15.5	planophile	Fleck 2002
Fraxinus angustifolia	35.55	21.34	planophile	Chianucci et al. 2018
Fraxinus ornus	21.69	14.22	planophile	Chianucci et al. 2018
Juglans regia	30.08	16.71	planophile	Chianucci et al. 2018
Laurus nobilis	34.2	18.68	planophile	Chianucci et al. 2018
Laurus nobilis	43.8	26	uniform	Pisek (unpublished data)
Olea europaea var. frantoio	53.88	23.98	spherical	Chianucci et al. 2018
Olea europea	54.4	20.8	spherical	Raabe et al. 2015
Paulownia tomentosa	45.32	19.16	plagiophile	Chianucci et al. 2018
Picea abies	34	7	planophile	Malenovskýet al. 2008
Picea sitchensis			spherical	Norman et al. 1974
Pinus halepensis			spherical	Sprintsin et al. 2011
Pinus silvestris			spherical	Niinemets et al. 2002
Populus alba	38.6	24.08	uniform	Chianucci et al. 2018
Populus nigra	43.75	19.6	plagiophile	Chianucci et al. 2018
Populus tremula	31.51	20.86	planophile	Chianucci et al. 2018
Populus tremula	39.3	22.28	uniform	Chianucci et al. 2018
Populus tremula	41.06	22.96	uniform	Chianucci et al. 2018
Populus tremula	39.18	22.15	uniform	Chianucci et al. 2018
Populus tremula	35.83	21.29	planophile	Chianucci et al. 2018
Populus tremula	39.6	39.6	uniform	Raabe et al. 2015
Quercus cerris	25.68	18.13	planophile	Chianucci et al. 2018
Quercus cerris	38	3	planophile	Chianucci et al. 2015
Quercus ilex	36.01	20.16	planophile	Chianucci et al. 2018
Quercus ilex	29. 2	18.6	planophile	Pisek (unpublished data)
Quercus petraea	28.46	19.63	planophile	Chianucci et al. 2018
Quercus petraea			planophile	Farque et al. 2001
Quercus pubescens	31.09	21.34	planophile	Chianucci et al. 2018
Quercus robur	34.79	19.29	planophile	Chianucci et al. 2018
Quercus robur	25.2	17.7	planophile	Pisek et al. 2011
Quercus rubra	27.59	16.86	planophile	Chianucci et al. 2018
Quercus rubra	26.24	15.32	planophile	Chianucci et al. 2018
Quercus rubra	43.16	17.63	plagiophile	Chianucci et al. 2018
Quercus rubra	22.72	13.97	planophile	Chianucci et al. 2018
Quercus rubra	21.73	13.52	planophile	Chianucci et al. 2018
Quercus rubra	23.31	16.3	planophile	Chianucci et al. 2018
Quercus suber	31.42	22.01	planophile	Chianucci et al. 2018
Robinia pseudoacacia	15.49	10.99	planophile	Chianucci et al. 2018
Salix alba	31.3	19.35	planophile	Chianucci et al. 2018
Salix caprea	32.01	17.65	planophile	Chianucci et al. 2018
Sorbus aria	30.64	18.99	planophile	Chianucci et al. 2018
Sorbus domestica	27.96	18.98	planophile	Chianucci et al. 2018
Sorbus hybrida	40.69	19.77	plagiophile	Chianucci et al. 2018
Sorbus torminalis	37.94	19.22	plagiophile	Chianucci et al. 2018
Ulmus minor	34.31	18	planophile	Chianucci et al. 2018

Annex IV – Minor changes after 2020

Date	Minor change to latest published version in 2020	Affected sections of this document