FURTHER DEVELOPMENT AND IMPLEMENTATION OF AN EU-LEVEL FOREST MONITORING SYSTEM
- FUTMON-

ACTION: C1: *TREE HEALTH*
IN COOPERATION WITH THE
INTERNATIONAL COOPERATIVE
PROGRAMME ON ASSESSMENT AND
MONITORING OF AIR POLLUTION
EFFECTS ON FORESTS (ICP FORESTS)

Action C1-tree-30 (NWD)

Manual for LAI-assessments

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1. Definition of LAI

Leaf area is relevant for different processes in a slightly different way, leading to two general classes of LAI-definitions: Those that are based on light interception and those that are based on the exchange surface of leaves.
Actually, at least two different definitions exist for the light interception-based LAI and a third one represents the exchange surface-oriented definition (Jonckheere et al. 2004):

Definition #1: LAI = Maximum projected leaf area per ground area
Projected leaf area has been used as LAI definition in studies based on radiometer measurements as a measure for light attenuation in canopies (Bolstad and Gower 1990). Since projected leaf area depends on the projection angle, Myneni et al. (1997) defined LAI as the maximum projected leaf area per ground area.

Definition #2: LAI = Half the total interception area of leaves per ground area
The total interception area of a leaf is its shape approximated by a convex hull (Chen and Black 1992). Chen and Black (1992) evaluated the concept of projected leaf area as a measure for radiation interception and found out that the total interception area is a more adequate quantity with regard to light interception of needles, bent, and wrinkled leaves than their projected area, using a projection angle of 45°.

Definition #3: LAI = Half the total leaf area per ground area
Lang (1991) and Chen and Black (1991) took the original definition of Watson (1947): "Total one-sided leaf area per ground area", which is only valid for flat leaves, and extended it to needles and convex objects, which are not flat. The total leaf area is the area of the whole leaf surface (all-sided) and is divided by 2 in order to conform to the original definition.

1.1 *Purposes of different LAI definitions*

The purpose of definitions #1 and #2 is to quantify light interception of leaves arranged in a canopy. The light-induced energy uptake makes this definition relevant for processes like photosynthesis (due to photochemical light use) and transpiration (due to leaf temperature). But also other processes are driven by vectors that linearly penetrate the canopy: Wind is such a vector and the calculation of wind loads and wind-dependent boundary layers around leaves may be adequately described based on these definitions, given the adequate projection angle.

The purpose of definition #3 is to quantify the exchange surface of leaves as the total amount of leaf area in the canopy. This surface is available for processes like gas-exchange through stomata or deposition of elements and interception of rain. Since photosynthesis and transpiration depend on the gas-exchange through stomata, definition #3 is also relevant for these processes.

1.2 *Measurement methods for different LAI definitions*

The measurement of the projection area after definition #1 is most easily achieved by radiation measurements above and below the canopy or gap fraction assessments with different devices. The dependence on the projection angle requires measurements at different angles or the use of hemispherical lenses integrating over all projection angles. Since the measurements are usually performed from below the canopy, the horizontal movement of a vector through the canopy (light at dawn or dusk, wind movement) is not well represented in the practically applied measurement methods, so that the relevance of these measurements at least for wind movements is questionable.

LAI after definition #2 is determined with the same methods as definition #1, but it considers the bent, hemicylindrical and wrinkled surface of leaves or needles by correction factors that need to be established for each species (Chen and Black 1992). The underrepresentation of horizontal projection angles is the same as for definition #1 and these measurements are, therefore, most relevant for light interception.

LAI after definition #3 is most accurately assessed by direct measurements, such as biomass harvests or leaf litter collections with subsequent determination of the leaf area of samples. The area measurements on non-flat leaves or needles are based on the projection area of scanned foliage, which is corrected with species-specific form factors to derive the total surface area. An alternative is the use of stand-specific allometric relationships between branch and stem cross-sectional area and appending leaf area that have been established beforehand. While this group of direct measurements is considered most accurate, it does not permit to assess short-term fluctuations in LAI due to seasonal influences, insect damages or other forms of reduced vitality.
Also, gap fraction measurements can be used to derive LAI after definition #3: The optically measured “effective LAI” (Chen 1996) then needs to be corrected for the non-random distribution of leaves in the canopy, since the non-random distribution (“leaf clumping”) leads to increased gap fractions relative to the random distribution that is needed for a derivation of total surface area of all canopy elements (so-called “total plant area index”(Chen 1996)). Another correction is applied for the contribution of non-green tissues to the measured gap fraction, which is mostly due to woody elements. The effect of woody elements needs, therefore, to be assessed in the leafless stage in winter for deciduous trees or to be estimated from allometric relationships.

1.3 *Used definition in this manual*

The definition that best conforms to the objectives of ICP-Forests is definition # 3. The objective of the measurements is to assess the interannual variability of the maximum LAI value reached during the year rather than phenological changes.

2. Applied measurement methods

LAI may be measured with direct contact methods (biomass harvest and leaf litter collection) or with indirect methods, where LAI is derived from the optically sensed gap fraction of the canopy.

2.1 *Direct measurement methods*

The direct measurement methods comprise leaf litter collections and destructive leaf biomass harvests. While they are considered most accurate, they are also laborious and partly destructive. Destructive methods can not regularly be applied on a permanent monitoring plot, but they can provide the basis for allometric relationships if they are executed on trees neighbouring the monitoring plot.

2.1.1 Quantities needed

- Dry weight of leaves
- Leaf mass per area (LMA) representative for the plot
- Half the total surface area of leaf or needle samples
- Species-specific conversion factors between projected area and total surface area
- For allometry: trunk or branch diameters

Since it is impossible to measure the area of all leaves collected or needles harvested, the amount of foliage is assessed by dry weight determination of the leaves or needles. The conversion to leaf area is achieved by LMA determination on leaf or needle samples. For LMA-calculation, half the total leaf surface area needs to be determined with a planimeter. Here, species-specific correction factors are required to convert from projected area to surface area in the case of non-flat foliage (see Appendix). Since LMA is highly variable in a forest stand, mainly due to the light distribution, the amount of samples for LMA determination must be high enough to cope with the variability.

2.1.2 Biomass harvest

Biomass harvests may be executed on trees in the proximity of the monitoring plot and require the use of stand- and species-specific allometric relationships. Allometric relationships between foliage area and trunk or branch cross-sectional area are based on the pipe model and, thus, depend on the efficiency of vessels in the sapwood. Since this parameter varies between sites and eventually between years with different climate conditions, allometric relationships need to be established from trees on the plot or in close proximity to the monitoring plot and at least every 10 years.

The establishment of allometric relationships also has to consider the dependence on tree size and needs to be performed on at least 3 trees per species on even-aged stands (Jonckheere et al. 2004) and 10 trees per species on uneven-aged stands. The trees must represent the size distribution of trees on the monitoring plot. Principally all leaves or needles of the selected trees have to be harvested and weighed and their LMA needs to be assessed on samples with a standard error of the mean below 5%. A reduction of the amount of foliage harvested is possible based on the allometric relationship to branch basal area that need to be established on at least 10 representative main branches and their appending branches per tree.

2.1.3 Leaf litter collection

A detailed description is found in the field protocol on litterfall. Two points need to be added for the purpose of LAI determination:

- In order to avoid litter decomposition, litter traps have to be emptied at least every two weeks during that part of the year, where 75% of the leaves fall. Longer intervals up to 3 weeks may only be adequate in periods of continuous drought.
- The amount of sampled leaves taken for LMA determination of a batch of leaves needs to be high enough to be representative. This means that the standard error of the mean LMA of these samples needs to be lower than 5%.

2.2 *Indirect measurement methods*

The indirect assessment of LAI is based on the measurement or simulation of the canopy gap fraction with different devices.

2.2.1 Passive optical measurements

Passive optical measurements include differential measurements of radiation above and below the canopy (e.g. Plant Canopy Analyzer LAI-2000, AccuPAR Ceptometer, SunScan Ceptometer) and measurements of penetrating radiation from below (e.g. hemispherical photography, Demon, TRAC). Some methods depend on diffuse light conditions (Plant Canopy Analyzer LAI-2000, hemispherical photography) whereas other methods use direct sun light (TRAC, ceptometers, Demon)

2.2.1.1 **Quantities needed**

- Canopy gap fraction
- Canopy gap size distribution
- Foliage element width
- Needle-to-shoot area ratio (optional)
- Woody-to-total plant area ratio

Canopy gap fraction can either be assessed by differential light measurements above and below the canopy, by measurements of the sunfleck proportion on the ground, or by determination of obscured and non-obscured sky proportions. While projected leaf area may be derived from gap fractions via the Lambert-Beer equation (Monsi and Saeki 1953), the total surface area of leaves can only be derived, when corrections for the non-random distribution of leaves (leaf clumping) and the contribution of woody elements to the measured gap fraction are applied. The canopy gap size distribution is derived from hemispherical photographs or the TRAC instrument and permits to calculate the degree of between-shoot clumping. The calculation is based on the width of foliage elements. The needle-to-shoot area ratio describes the clumping of needles inside a shoot. The contribution of woody canopy elements to the gap fraction measurement is given by the woody-to-total plant area ratio.

2.2.1.2 **Theory of Plant Canopy Analyzer (PCA) measurements**

The summarizing equation for the derivation of LAI from LAI-2000-measurements and other passive optical measurements is given by Chen (1996):

$$L = (1-\alpha)L_e \gamma / \Omega$$

Here, α denotes the proportion of woody surfaces relative to the whole plant area, L_e is the effective leaf area index (the uncorrected instrument output), γ stands for the needle-to-shoot area ratio, and Ω is the foliage element clumping index. Foliage elements, for which between-shoot-clumping is considered are either leaves or shoots of needles.

The effective leaf area index L_e is the raw instrument output calculated from the measured gap fraction under the assumption of a spatially random leaf distribution. Since leaves and needles are arranged along woody axes, their distribution is usually not random, but clumped around these axes so that the amount of gaps is higher than expected from the assumed random distribution.
Therefore, corrections with respect to the leaf spatial distribution pattern are required. For conifer stands, where needles are densely clumped in shoots that often do not allow light penetration, shoots are considered as foliage elements and the correction for this grouping effect is performed with the needle-to-shoot area ratio γ. For broad-leaved forest stands, individual leaves are considered as foliage elements and γ is set to 1, therefore. On a larger spatial scale, foliage elements are further grouped along branches and tree crowns. The effect of this large scale clumping is considered with the element clumping index Ω, which is based on measurements of the gap size distribution of the canopy. These measurements can either be performed with the TRAC instrument or with hemispherical photographs (see below).
In passive optical gap size or gap fraction measurements, LAI derivation is based on all canopy elements including woody organs. Since only green leaves contribute to the true LAI, this effect is removed by the woody-to-total plant area ratio α (standard values for different forest types are given in the appendix).

2.2.1.3 Guidelines for PCA measurements

(1) Spatial arrangement

The effective leaf area index measurements shall be representative for the whole monitoring plot. A regular grid of 16 or 25 measurement positions covering the whole plot is appropriate to ensure the representativeness on most plots, provided that the standard error of the mean L_e stays below 5% under these conditions. For plots with higher variability (standard error of the mean >5%), a 7 x 7 grid of measurement positions is required. In the case that grid positions are too close to stems or branches obscuring the view of the sensor, an alternative position in up to 2 m distance needs to be established.

(2) Measurement height

The measurement height is 2m above the floor. This permits to see the bubble level from below when mounted on the underside of the sensor, so that the use of viewcaps in order to hide the operator of the instrument is not necessary. In case of sloping terrain, viewcaps may anyway be necessary to block readings from the upper side of the plot.

(3) Light conditions

PCA measurements must be made under uniformly overcast sky or diffuse light. The best time to find the appropriate conditions is immediately pre-dawn and immediately post-sunset, an alternative are cloudy days. The light conditions may be judged based on the visibility of shadows on the ground or sunlit foliage: Both indicate direct light and prohibit accurate PCA-measurements. Shadows on the ground may e.g. be visible, though clouds seem to cover the sky and sunlit foliage may still be visible for a while after the sun disappeared.

Next to diffuse light conditions, the measurement requires a minimum amount of light to distinguish obscured sky from gaps. The minimum condition can be checked by placing the hand above the PCA sensor and checking if the displayed value on the datalogger screen significantly reacts. As a general rule, the sky is too dark, when the operator cannot distinguish single needles or leaves in the canopy by eye.

(4) Placement of the above canopy sensor

The above canopy sensor needs to be placed in a nearby clearing with the same sky conditions as the monitoring plot. 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 a clinometer in order to ensure that the vegetation is less than 16 degrees (or 32 or 47 degrees, depending on the sky bands) off the horizon. In very narrow clearings it might be appropriate to use viewcaps on both sensors so that the above canopy sensor may be placed close to the edge of a clearing.

(5) Below canopy measurements

Further details are given in the field protocol for LAI-assessments and the PCA-manual.

2.2.1.4 **Guidelines for TRAC-measurements**

The clumping index **Ω** for between shoot clumping may be assessed by hemispherical photography (see field protocol on radiation measurements and LAI) or by the TRAC instrument (Chen and Cihlar 1995, Chen et al. 1997, Law et al. 2001a, 2001b).

(1) Spatial arrangement

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.

(2) Light conditions

Measurements should best be taken when the solar zenith angle is near 60°. The range between 35° and 60° is acceptable.

(3) Preparations

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.

(4) Gap Size distribution measurements

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.

(5) Data inspection

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.

(6) Data evaluation

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.

2.2.2 Active optical measurements

Active optical measurements evaluate the backscatter of emitted radiation from the canopy: Airborne LIDAR derives the LAI from the relative amount of backscatter from the ground surface below the canopy, while terrestrial LIDAR builds a complete 3D-model of the canopy that permits to derive gap fractions. The LIDAR-based methods will be subject to a later version of this manual.

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