RECONSTRUCTIONS OF TREE STRUCTURE FROM LASER-SCANS AND THEIR USE TO PREDICT PHYSIOLOGICAL PROPERTIES AND PROCESSES IN CANOPIES

S. Fleck [a, *], D. van der Zande [b], M.Schmidt[c], P. Coppin [b]

[a] Am Lindenberg 19, 37133 Friedland, Germany - stefan.fleck@gmx.de
[b] Laboratory for Forest, Nature, and Landscape Research, Katholieke Universiteit Leuven, Belgium - (dimitry.vanderzande, pol.coppin)@agr.kuleuven.ac.be
[c] Chair of Plant Ecology, University of Bayreuth - markus.schmidt@uni-bayreuth.de

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ABSTRACT:

Two ways of tree structure reconstruction from laser-measurements are comparatively presented with respect to their suitability for functional interpretation of tree structures. A concept for physiological evaluation of the data is tested that comprises three steps: 1. The automated evaluation of terrestrial laser-scanner data, 2. application of a fine-scaled 3D-light model, and 3. a nitrogen dependent photosynthesis model. The automated evaluation procedure for laser-scanner data based on the 3D-Hough transformation could correctly identify the point-to-point connections of the main branch system of apple trees. Based on 3D-structure measurements, the 3D-light model STANDFLUX-SECTORS predicted maximum leaf mass per area (LMA_{max}) of branches with a root mean square error of 10.3 g/m². Vc_{max} and J_{max} of beech and oak leaves were shown to be derivable from LMA. The comparison between daily courses of modelled light and branch sapflow showed similarities, but also dissimilarities that can only be explained with fine-scaled 3D-structure.

1. INTRODUCTION

The advances in terrestrial laser-scanning of trees during the last few years resulted in a variety of tree structure reconstructions that are based on the evaluation of three-dimensional clouds of points (e.g. Persson et al. 2003, Watt et al. 2003, Erikson and Vestlund 2003, Fleck et al. 2004a, Haala et al. 2004, Parker et al. 2004). Different algorithms are proposed to extract accurate structure information out of the automated measurement of range images (Simonse et al. 2003, Abmayr et al. 2004), but a concept for functional interpretation of tree structure data is still not fully developed. However, such a concept could give important hints to the sort of structure information that is most valuable for models that are built on tree structure.

This paper presents two examples of tree structure reconstruction from laser-measurements in horticulture and forest ecology in combination with the validated application of physiological models to the yielded structure description. The proposed physiological evaluation concept is generic in that sense that it would be applicable to all tree species due to the consideration of universally valid mechanisms, i.e. the dependence of leaf photosynthesis rates on incident light and that of incident light on 3D-canopy structure.

In horticulture, the relevance of fruit tree structure for amount and quality of harvested fruits is since long a matter of research (Palmer et al. 1989, Lakso and Corelli Grappadelli 1992, Wagenmakers and Callesen 1995, Wünsche et al. 1995), but its scientific analysis is up to now still based on empirical investigations, because canopy structures and their functional implications are seen as too complex to assess and model them for whole trees in detail. In forest ecology, the latter is even more relevant because ecophysiological research of forests is mainly oriented to CO_2- and water exchange of large areas. 3D-laser-scanning may give fundamentally new impulses to these disciplines, when the physiological mechanisms that link structure with function at a certain scale are identified and structure reconstructions are given in the appropriate format.

2. MATERIALS AND METHODS

2.1 Laser measurements

5 rows of *Malus × domestica* 'Jonagold' trees of different pruning systems at the Royal Research Station of Gorsem, Belgium, were investigated in the leafless state in spring with a Sick LMS-200 laser-scanning system (Sick, Waldkirch, Germany). The laser-scanner scanned in an angular resolution of 1° along a vertical range of 100° and was moved on a tractor orthogonal to the scan lines and with constant speed through the rows. The scanner had a frequency of 1515 Hz and maximum distance to the scanned objects was 4m.The resulting 3D-point clouds had a resolution of about 3cm in direction of motion and were evaluated with a 3D-Hough transform algorithm: All possible point-to-point connections from the same tree were characterized by their azimuth angle, elevation angle, and distance of their straight line to the origin. This facilitates to identify points on a common axis based on angular criteria. The evaluation comprised these steps:

1. Segmentation of the whole 3D-point cloud into sub-clouds (one per tree)
2. Determination of the neighbourhood-points of each point
3. Determination of azimuth, elevation, and distance to the origin for all lines connecting the central point with neighbouring points in each neighbourhood

* Corresponding author.

4. Grouping of those lines with only small deviation from each other in azimuth, elevation angle, and distance to the origin (i.e. those that lie on the same axis)
5. Elimination of redundant lines and points from the axes
6. Selection of the longest axes
7. Sorting points of each axis along axis direction
8. Checking axes for gaps and mean distances between points
9. Removing axes with too large gaps
10. Deleting remote single points from axes
11. Repeating steps 2 to 10 for different sizes of neighbourhoods and with differently strict application of selection criteria
12. Connecting not selected points to their nearest neighbour point

Single-point laser measurements:
3D-structure of a large 25m high beech tree and an oak tree in the Steigerwald, Germany, as well as two other mature beech trees in the Fichtelgebirge was assessed by single-point measurements with an infrared-laser aiming at a reflector that was positioned by hand from a jacklift to defined positions in the canopy. 10 points per branch were localized in order to describe the branch leaf mass with leaf cloud enveloping polyhedrons (Fig.1). Leaf area of each leaf cloud was estimated using allometric relationships to branch diameter from the same tree. The total tree structure was approximately described based on 300 to 700 point measurements per tree.

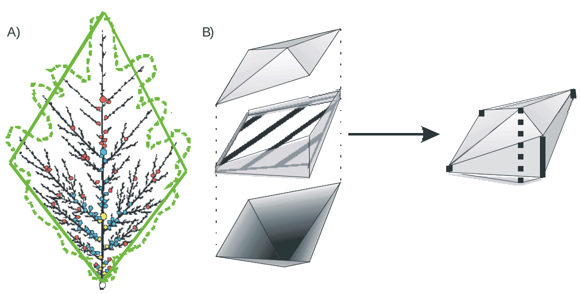

Figure 1: A) beech branch with maximum planar extension of its leaf cloud (dotted line), which may be approximated by four laser-localized points of a quadrangle. B) Leaf cloud enveloping polyhedrons were constructed based on such quadrangles (hatched area).

2.2 3D-Light Modeling

The 3D-light model STANDFLUX-SECTORS is based on the STANDFLUX model (Ryel et al. 1993) that was developed based on the light model of Duncan (1967). While STANDFLUX divides tree canopies along height layers and cylinder jackets, STANDLFUX-SECTORS sub-divides these sections further into sectors and radial sections of them that are allowed to differ in height extension. Direct and diffuse irradiation are then calculated for a 3-dimensional grid of matrix points treating the sections as turbid media with a certain leaf area density. Relative irradiance is the integrated ratio of total irradiation at matrix points to total irradiation above the stand.
The model was applied in this study to the mature beech tree in the Steigerwald. 6 branches of this tree were used for sapflow measurements and fully harvested at the end of the season and their leaf area and leaf mass per area (LMA) was determined (compare Fleck et al. 2004b).

Hemispherical photos were taken exactly at the position of single leaves of the two beech trees in the Fichtelgebirge in order to determine relative irradiance based on light measurements close by (compare Fleck 2002). LMA of these leaves and leaf nitrogen content were determined.

2.3 Nitrogen-dependent photosynthesis model

The biochemical leaf model of Farquhar (1982) contains maximum carboxylation velocity (Vc_{max}) and maximum electron transport rate (J_{max}) as its most sensitive parameters.
The relationship between these parameters and leaf nitrogen was investigated using the model version of Harley and Tenhunen (1991) to derive Vc_{max} and J_{max} at T=298K from

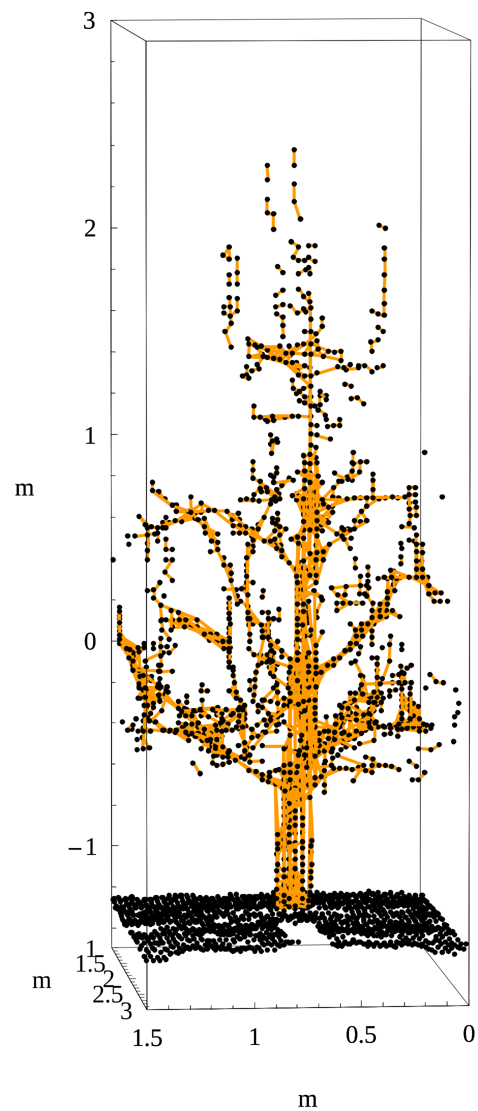

Figure 2: 3D-point cloud of an apple tree (1352 points) with detected branch segments

A/C_i-curves of leaves of the 25m high beech tree and its neighbouring oak tree. The leaves were grouped to 7 (beech) and 13 (oak) nitrogen classes. A/Ci-curves were measured at three temperatures per leaf with the Li-6400 system.

3. RESULTS AND DISCUSSION

The laser-scans yielded 3D-point clouds of 1000 to 2500 points per tree (Fig. 2). Even very thin structures were deteted, e.g. a branch fixing wire in the plantation. The first evaluation cycle (maximum distance for neighbourhood determination = 0.3m, axis deviations of maximum 1° and 10cm) yielded mainly the stem segments of the trees, while subsequent cycles with 0.25m and 0.2m neighbourhood distance and larger axis deviation could detect segments of most main branches. About 10% of the points were after the evaluation only linked to one other point. These points were mainly located at the distal part of branches, where stronger ramification induces shorter axes, or in the uppermost part of the canopy, where the distance between points of the same axis is larger due to the measurement set-up (long distance to the scanner and acute angles). The data provide a good basis for the derivation of the whole main branch system via connection of the identified branch segments. But the relatively low resolution of the laser-scanner data does not yet permit to estimate branch diameters in an accuracy that would be needed for subsequent application of allometric relationships. Merging multiple scans from both sides of the tree row, higher angular resolution, and lower driving speed would probably be sufficient to reach this goal with the presented measurement set-up, but alternative measurement set-ups with a 3D-laser-scanner would probably be more efficient.

Allometric relationships between branch diameter and appending leaf area provide a test method for tree structure reconstructions due to their low variability throughout the canopy. They could be used to identify those parts of a scanned tree, where not the full amount of leaf area could be detected or extracted from the measurements and provide the opportunity to fill leaf cloud enveloping polyhedrons in the proximity of identified branches with the appropriate leaf area. Given that allometric relationships between branch diameter and branch leaf area are applicable to the scanned structure, a 3D-light model like STANDFLUX-SECTORS could be automatically parameterized with such data (Fig. 3).

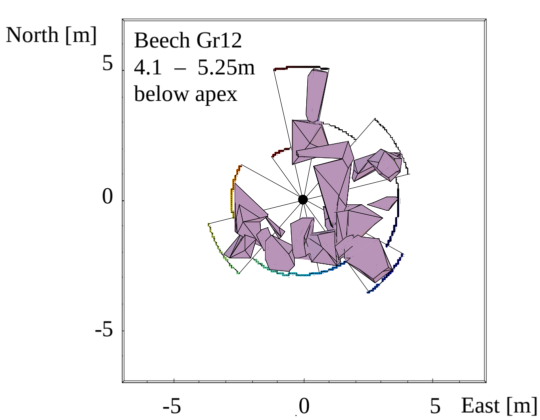

Fig. 3: Parameterization of a height layer of the Steigerwald-beech in STANDFLUX-SECTORS. Leaf area density of sectors is derived from leaf cloud volumes. The branch system is not represented.

STANDFLUX-SECTORS was applied to a 25m high beech in its stand to calculate relative irradiance in matrix point layers above 5 branches of this tree (3 shade branches, 2 sun branches). The relationship between simulated relative irradiance and measured maximum LMA of these branches corresponds well with the measured relationship of 45 leaves from two other beech trees (Fig. 4).

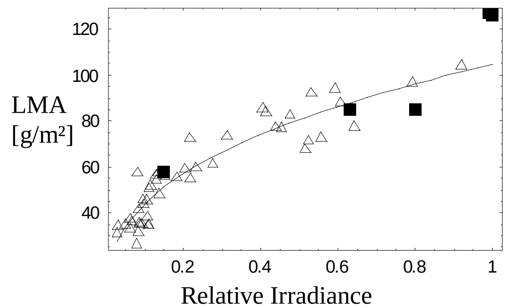

Fig.4: Max. LMA of 5 beech leaf clouds (■) vs. simulated irradiance above them and single leaf measurements with hemispherical photos (△).

Using this measured relationship to calculate LMA of the branches only based on the rough 3D-structure description would, thus, result in a root mean square error of 10.3 g/m^2 (Fleck 2002), showing that even the single-point measurements describe tree structure accurately enough to derive branch-specific light acclimation of leaves throughout the canopy. LMA-values of the investigated beech trees ranged between 23 and 128 g/m^2.

LMA and Nitrogen per area of leaves were strongly correlated (r^2=0.92 for beech and 0.89 for oak, data not shown). A tight relationship was also found between leaf nitrogen and Vc_{max} of leaves of both trees (Fig. 5).

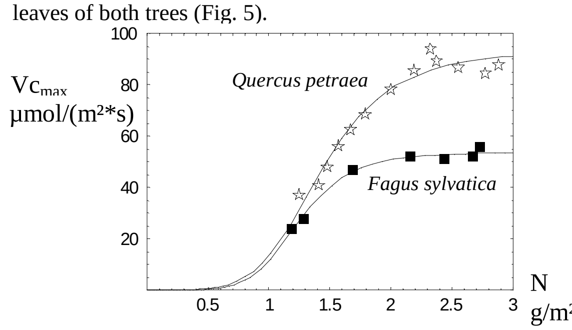

Fig. 5: Dependence of photosynthesis parameter Vc_{max} on leaf nitrogen.

Vc_{max} of both species increased with increasing leaf nitrogen, but saturated at a threshold value of about 2.2 g/m^2 (beech) and 2.3 g/m^2 (oak). The same was similarly true for J_{max}. The relationships were, therefore, approximated with a saturating function of the type $y = ax^b/(x^b+c)$, which yielded r^2-values of 0.99 (beech) and 0.96 (oak) - (J_{max}: 0.99 and 0.99). This result and the dependence of other parameters of the Harley/Tenhunen model on nitrogen may be used for a description of leaf photosynthesis that is directly based on LMA or nitrogen per area and microclimatological drivers (Fleck 2002).

The comparison of light calculations of STANDFLUX-SECTORS with sapflow measurements of the 5 beech branches shows a largely parallel development in both daily courses (Fig. 6), indicating the strong influence of light on branch transpiration. However, the time course of both variables was

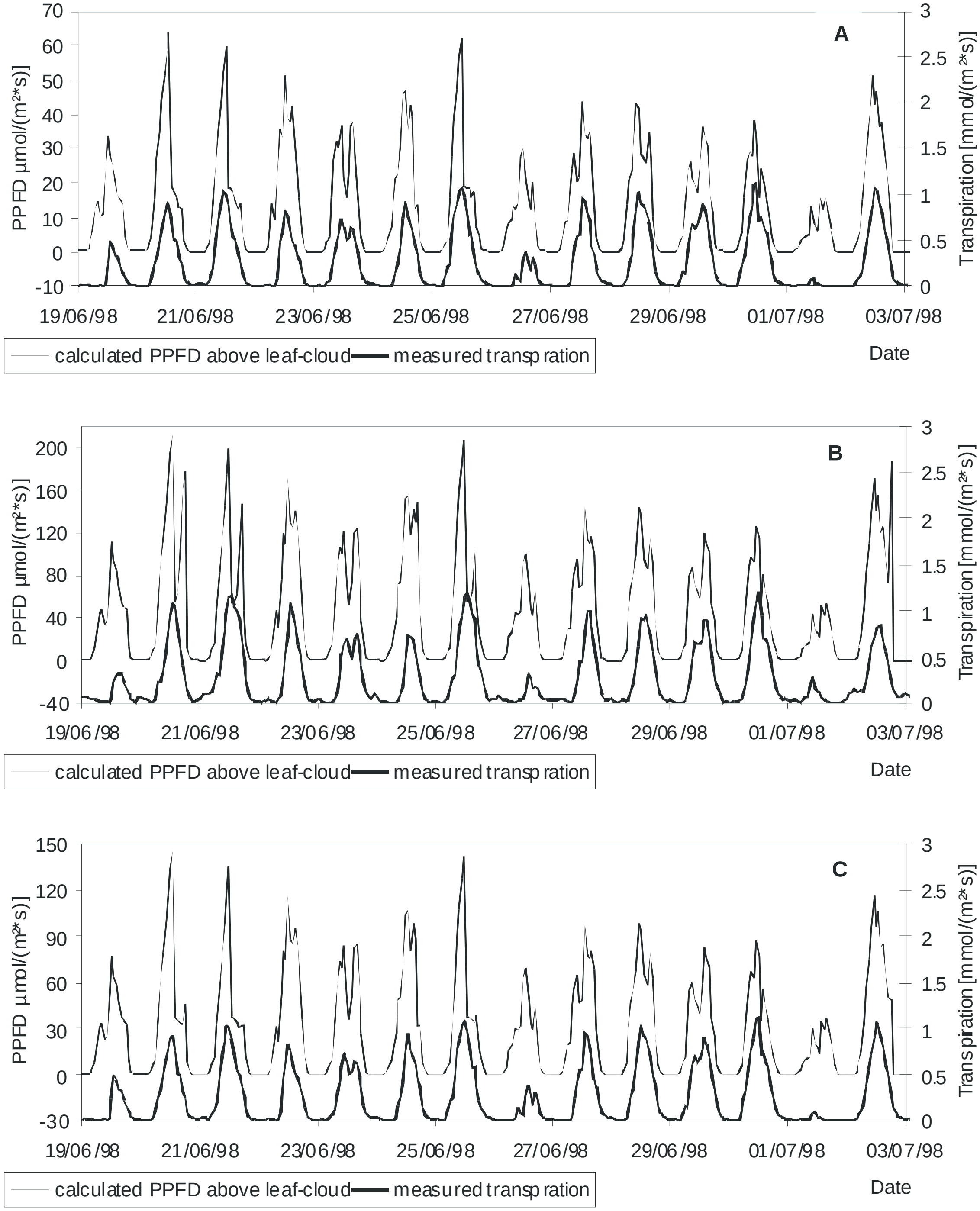

Fig. 6: Time course of measured transpiration rates and average of calculated PPFD directly above the investigated shade leaf clouds A, B, and C during the investigation period.

often parallel, but not strictly and not on every day. The occurring dissimilarities are difficult to explain as a phenomenon on the branch scale. If leaf gas-exchange is mechanistically coupled to light acclimation of leaves and micro-meteorological conditions (and that's what the results from oak and beech leaves suggest), such dissimilarities are likely to be the result of 3D-structure and variable conditions inside a leaf cloud volume.

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