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Original Research

Use of Remote Sensing for Investigating Riparian Shrub Structures

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Abstract

Our paper presents a comparison of remote-sensing methods for evaluation of riparian shrub structures. Investigation involved three methods: leaf area index measurements (LAI-2000), hemispheric photography, and terrestrial laser scanning. Direct measurements using a digital slide caliper were chosen as a reference method. This paper firstly reviews the methodology of laboratory and field research. Additionally, an original method of calculating the volume and surface area of plants on the basis of laser scanning data has been proposed. The second part of paper concentrates on the comparison of plant structure coefficients determined with all investigated devices. In the case of the LAI Ring 5 index from LAI-2000 measurement as well as canopy openness of shrub (P), obtained on the basis of hemispheric photos, high linear dependence between them and cross-section covering coefficient ϖ_p from direct investigation were obtained. Volume and surface area of plants calculated on the basis of laser scanning in micro- and macrostructural approach were also compared to the analogous parameters obtained from direct measurements. In this case, the results strongly depend on the modeling parameters, but the proposed method seems to be prospective in this task.

Keywords: riparian scrubs, remote sensing, terrestrial laser scanning, hemispheric photography

Introduction

One of the factors that determines flood flow conditions is the structure of vegetation in flooded areas [1, 2]. Methods that are currently in use, based on empirical, tabulated roughness coefficients (e.g. Manning's method), are commonly criticized for their subjectivity, dimensional form and non-dependence on filling [3]. Following the approach proposed by Pasche [4], the DVWK Guidelines [5] link the computation of drag coefficient due to vegetation λv to the macro- or micro-structural parameters of vegetation: diameter of plant or branch dp and the average span between them ax. An alternative estimate of drag coefficient due to shrubs has been proposed by Kaiser [6]. This method eliminates laborious determination of micro-structural geometrical parameters of plants. The structure of vegetation is overall characterized by the cross-section covering coefficient ϖ_p. This coefficient is the ratio of the plant cross-sectional surface area divided by its volume. The basic method for determination of this index is by direct measurements of the structure of shrubs [7]. However, because of the laboriousness of such research, remote sensing methods, which rely on integrated optical analysis, have been developed over the past several years [8, 9]. Advanced optical technologies have a good chance of providing more reliable and more accurate techniques for measurement of biomass and vegetative parameters that are useable in hydraulic calculations [10].

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Biomass serves as an important biophysical parameter appropriate for assessing a diversity of natural characteristics and determine flood flow conditions [11]. The biomass quantification or estimation methods have been developed long before from ground-based destructive weighting [12], space-borne optical remote sensing [13], to airborne laser scanning [14]. As a state-of-the-art technology, airborne laser scanning (ALS), often termed as light detection and ranging (LiDAR), has been adopted as an attractive measure for biomass detection due to its capability to directly measure canopy structures and stand attributes [14-17]. The relatively low density of current ALS systems cannot reflect canopy structure comprehensively. Therefore, ALS has been utilized mostly for stand- or regional-wise estimations of tree characteristics [18]. ALS-based biomass estimation at individual tree level was also validated [19] not long before.

Terrestrial laser scanning (TLS) occurs as an effective and low-cost means for biomass investigation of individual trees, as its fine spatial resolution and small beam size allow the inner parts of crowns to be measured with detailed information [20]. This makes it possible to estimate biomass accurately, and the performances of TLS apparatuses have been steadily increasing [21]. With these favourable factors, the appearances of TLS in tree inventory tasks have also been increasing, and the relevant applications include measuring e.g. canopy structure [22] and leaf area index (LAI) [23]. These works can help biomass estimation indirectly, and direct biomass estimation has also been conducted with a primarily verified result for a tree, not for shrub structures.

Our paper presents a comparison of three methods for evaluation of shrub structures, required to determine the hydraulic characteristics of flooded areas. The methods under study are based on LAI-2000 measurements, hemispheric photography, and terrestrial laser scanning. Additionally, the methodology for determination of shrubs' geometric parameters based on laser scanning data is also proposed. Research was carried out using the data obtained in laboratory measurements of artificially prepared vegetation. Direct geometry measurements of the plants under study were also carried out as a reference.

This methodology was subsequently used to investigate the structure of natural shrubs. Willows that were studied were located on the banks of the Barycz River. This enabled the authors to present the perspectives of using terrestrial laser scanning and hemispheric photography for collecting data required to calculate the parameters of flow drag due to vegetation on banks and in flooded areas.

Methodology

Direct Measurements

Laboratory research was carried out in the Civil Engineering Department at the Poznań University of Life Sciences. The object of investigation was artificial models of willow branches. Shrubs were built of individual willow branches. Standard shrub parameters were assumed based on field measurements of shrubs that cover the flooded areas of the Warta River. Assumed research variants reflected the variability of shrub structures. A sample of 30 young willow branches was thoroughly measured. The length of each section between forks of branches was measured. Measurements of the upper and the lower diameters were done with a digital slide calliper. Five variants with different numbers of branches were investigated in the research: A – 30 items, B – 25 items, C – 20 items, D – 15 items, and E – 10 items. Additionally, the volume of shrubs was scalable and two volume variants were considered. Volume W1 corresponded to the natural shrub's volume (freely arranged branches). Volume W2 was obtained by increasing the density of branches with a thin line. This led to a total of 10 different density variants. From this data densities of shrubs were derived in terms of the cross-section covering coefficient values ϖ_p:

Table 1. Alternative variants of shrubs' volume.

No.	Shrub volume	Number of branches	ϖ_p [$m^2 \cdot m^{-3}$]
1.	W1	A	0.211
2.	W2	A	0.276
3.	W1	B	0.180
4.	W2	B	0.235
5.	W1	C	0.150
6.	W2	C	0.196
7.	W1	D	0.111
8.	W2	D	0.145
9.	W1	E	0.074
10.	W2	E	0.096

$$\varpi_p = \frac{A_p}{V_p} \qquad (1)$$

...where: A_p – cross-sectional surface area of the plant $A_p = \Sigma(dpi \cdot li)$ [m^2], V_p – shrubs' volume [m^3], d_p – branch diameter [m], l – branch length [m].

Table 1 summarizes the cross-section covering coefficient values ϖ_p for all research variants. The maximum coefficient value was 0.28 m^2/m^3 for the variant W2A, whereas the minimum value 0.07 m^2/m^3 was obtained for the W1E variant.

LAI-2000 Measurements

Automated measurement of vegetative structure can be carried out using, among others, the LAI-2000 analyzer manufactured by LI-COR [9, 24]. This device quickly and easily determines the LAI and LAD values of a plant canopy. The leaf area index (LAI) is defined as the ratio of total one-sided leaf surface of vegetation divided by the surface area of the land on which the vegetation grows [m^2/m^2]. The leaf area density (LAD) is the coefficient of density of leaves defined as the ratio of total leaf surface of vegetation divided by the volume of vegetation [m^2/m^3]. For vegetation with no leaves, LAD can be interpreted as the cross-sectional area of all the shrub's branches divided by shrub volume, which coincides with the cross-section covering coefficient.

The LAI-2000 principle of operation relies on estimation of the intensity with which dispersed blue light penetrates the plan canopy. In order to measure the LAD of a shrub, a series of a dozen or so measurements was carried out. The first measurement of light was performed outside the plant, so that the sensor's field of view contained only the sky. Subsequent measurements were carried out in the plant canopy at a height of 50 cm. Experiments were performed in a special laboratory tent with dispersed fluorescent light instead of sunlight.

Hemispheric Photography

The easiest way to measure the structure of vegetation is by hemispheric photos [25]. Since a hemispheric photo is a typical example of point measurement, a stand with the camera is placed in the middle of the surface being investigated. The analysis, which is based on hemispheric photos, allows for the determination of parameters such as the absolute amount of light registered [9] at various measurement levels, openness, shrub's structure, spatial variability of leaves, and leaf area index (LAI).

The hemispheric photos were taken using a single-lens reflex Canon EOS 5D (12 MP matrix) with a Sigma 8 mm f/3.5 DG EX FISHEYE lens. This set allows the user to produce hemispheric images (vertical registration angle – 180º). In order to eliminate the influence of the external environment, pictures were taken in a specially arranged tent made of white linen. The tent was set out in a hall that was illuminated with dispersed fluorescent light. The camera was installed on a stand and then leveled. The upper edge of the lens was approximately 50 cm above the trunk in which willow bars were mounted. Throughout the measurements the stand with the camera remained in the same position. Analysis of hemispheric photos was carried out using a Gap Light Analyzer v. 2.0 software.

Terrestrial Laser Scanning

One of the devices that enable automatic measurement of the structure of vegetation is the terrestrial scanner FARO LS 880 [15]. Data derived from the use of terrestrial lidar can be applied for determination of shrub properties (e.g. shrub volume and height) and construction of models that in turn allow for more detailed information on the shrub to be obtained (e.g. 3D models of a shrub's structure) [26]. Therefore, compared to conventional terrestrial measurements, the potential set of data that can be obtained on a sample surface by means of a laser scanner provides far greater possibilities for determining shrub properties and analyzing their structure [27]. In our research we used the LS 880 HE80 laser scanner manufactured by FARO. This scanner has a wide scanning range – 360º horizontally and 320º vertically. The technology used allows for this scanner to represent up to 250,000 points per second, with a linear error of ±3 mm per 25 m.

We used standard scanner settings, i.e. ¼ of the resolution, which provided an impressive 50,000,000 measurement points from a single measurement stand. For this resolution, the time of a single turn of the scanner is approximately 7 minutes (without the option of using a digital camera for taking photos). Points obtained from one stand provide information on the location of objects and of their dimensions. These data refer, however, to only one side of a given object. Additionally, problems may occur when one object shadows another. Therefore, to obtain full 3D models of a spatial object it is necessary to move the scanner and scan from various sides of the shrub [28]. Lastly, the obtained points are put together.

In order to determine the geometry of the vegetation in the microstructure, the shape of the individual branches should be determined. To do that authors proposed cylinders as models of branch sections with width dz. This method assumes that the plant is divided along the z axis into segments of a given width. Within each segment data is projected onto the plane and measurement points are split into groups, which potentially form the one branch. Next, each group is matched with a cylinder. Its radius depends on group size and its height is that of the segment. Procedure parameters are as follows:

- maximum branch width – segmentation is based on a non-supervised classification method that does not require the number of classes to be fixed
- segment width – chosen empirically in the macro-structural approach, where the plant is considered to be a compact solid impermeable for the flow of water, it is important to choose those measurement points that represent the surfaces of the plant. In cases when the solid is convex, the task is reduced to finding a 3D convex hull

A convex polyhedron is a natural generalization of a convex, closed polygon. The solid is made of three kinds of geometrical objects: vertexes, edges (segments), and convex polygons. The algorithm for the convex hull in a multidimensional space is highly complex. Implementation details can be found in the literature, e.g. O'Rourke [29]. However, in this approach, when the plant shape is represented as a convex hull generated in the one-stage construction procedure, the shape of the model differs considerably from the original plant solid. Therefore, to achieve better matching to non-convex parts of the hull, we propose using a multi-stage solid generation procedure in which points are divided into segments with common edges. Each segment is generated as a separate convex hull, but the solid obtained from putting all separate segments together is non-convex. Points are divided by planes parallel to the XY plane. The method requires an initial parameter, namely the segment width (distance between two division planes). To ensure that surfaces of individual segments match each other, the modeling procedure for a single segment consists of the following steps:

- points from one segment are projected onto the division plane
- a 2D convex hull is generated for all the points in the segment; this procedure is based on Graham's algorithm [29]
- the bottom part of a segment's 3D convex hull is made of the points selected in the previous step, complete with a height coordinate
- the 3D convex hull is created: its upper part is made of the points selected according to the above procedure for the next segment

Results and Discussion

Laboratory Research

Hemispheric photos were studied using the LAI_{Ring5} (result calculated for the space between the zenith angle 0 and 75º). Another parameter was the 2D space filling with willow bars, i.e. canopy openness P. Openness corresponds to the percentage index calculated as the ratio of surface area free of vegetation divided by the total surface area of the hemispheric image. Openness of shrubs under study ranged from 68% – W2A to 80% – W1E. LAI_{Ring5} values ranged from 0.10 – W1E to 0.29 – W2A.

By comparing the densities of test shrubs derived from direct investigation and those resulting from processing of hemispheric photos, correlation relationships between them were sought. Fig. 1 shows the relationship between the cross-section covering coefficient and the LAI_{Ring5} index. In this case a strictly linear dependence between those two values is obtained. The correlation coefficient R is 0.949 for the LAI (p=0.00002). Dependence between the cross-section covering coefficient and openness of shrubs (P) was also analyzed (Fig. 2). In that case, as expected, increase in openness coincided with a decrease in the cross-section covering coefficient. Also, in this case a strictly power function between these values is obtained. The correlation coefficient R is 0.957 for the P (p=0.00004).

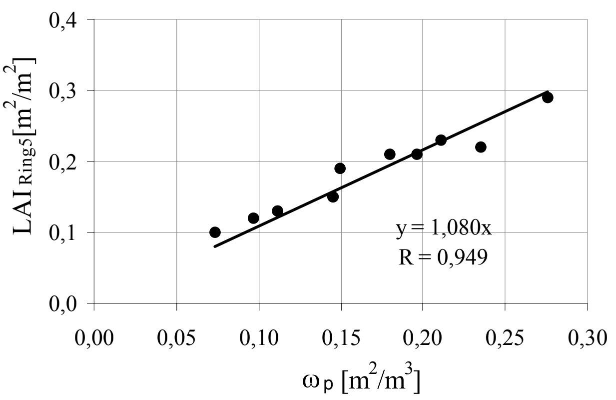

Fig. 1. Relationship between the cross-section covering coefficient ϖ_p and the value of LAI_{Ring5}.

Results of all the measurements were used to test the methods that rely on terrestrial scanner measurements. Before commencing, the analyses data was preselected. Erroneous points were discarded using selected cleaning filters. This produced visualizations of each shrub variant.

In a micro-structural approach, selection of an appropriate thickness of the segment has a significant impact on the result. Selection of the best segment width was carried out empirically, so as to achieve a compromise between the accuracy of a model and the possibilities of identification of

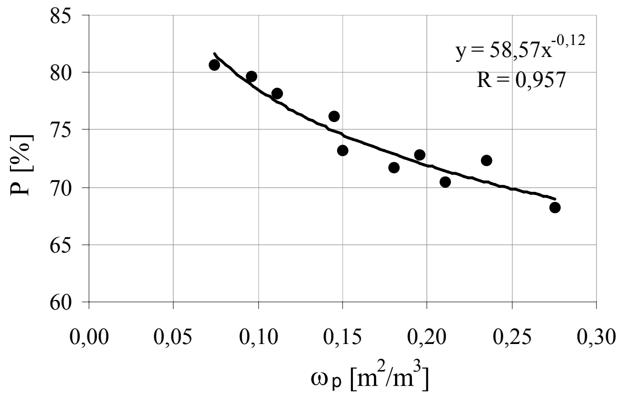

Fig. 2. Relationship between the cross-section covering coefficient ϖ_p and shrubs' openness P.

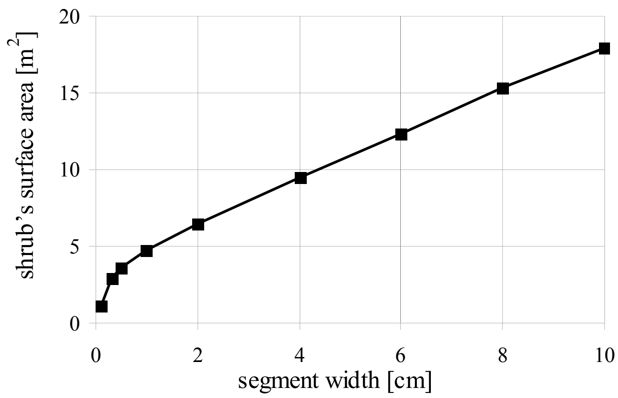

Fig. 3. Surface area of shrub model from variant W1C versus segment width in the micro-structural model.

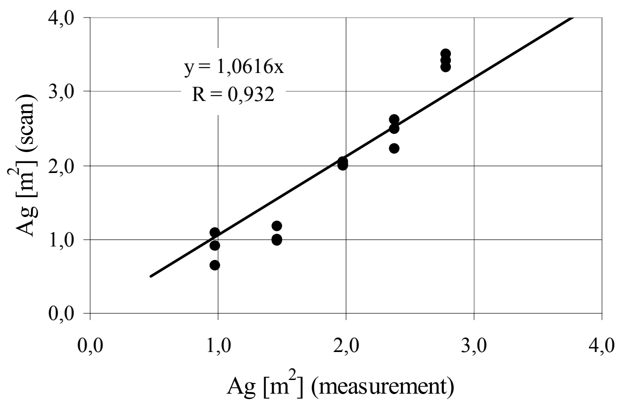

Fig. 4. Total surface area of branches calculated based on cylinder models with 3 mm segment width compared to that from direct measurements.

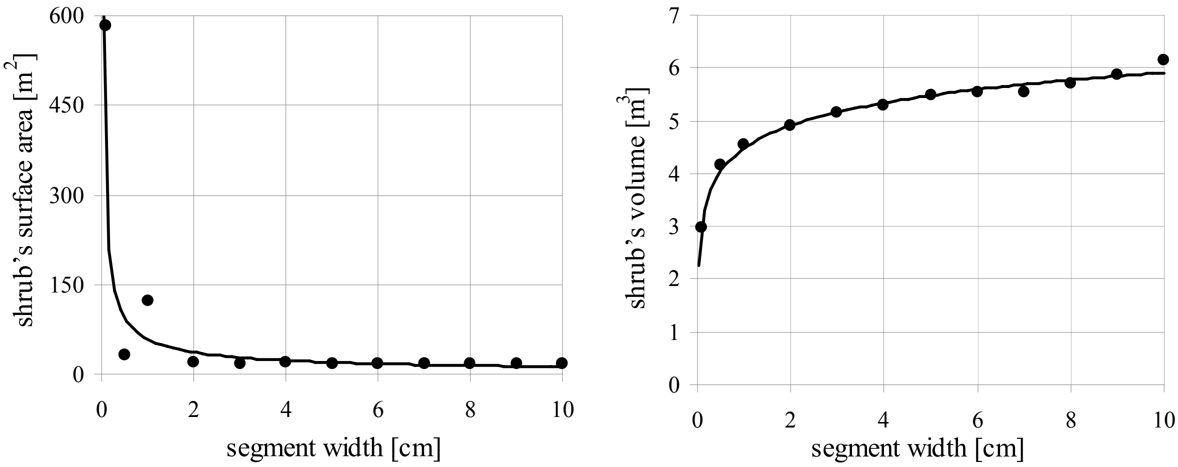

Fig. 5. Variant W1C: shrub model surface area and volume vs. distance between segment limits in the macro-structural model.

points, that depend on scanning resolution. Fig. 3 shows the dependence of segment width from the estimated surface area for variant W1C.

In order to verify the accuracy of our method the total surface area of branches Ag calculated based on cylinder models for individual variants was compared with the total surface area derived from direct measurements (Fig. 4). Although the values obtained from scanning are slightly too high, the obtained correlation nonetheless proves the analysis to be correct and indicates that the proposed method may be recommended as the right one for micro-structural analyses. Correlation coefficient R is 0.932 for the A_g (p=0.003).

In the multistage macro-structural approach the whole modeling process also heavily relies on the choice of optimal segment width. Plots shown in Fig. 5 represent the dependence of the estimated shrub's volume and surface area (variant W1C) from the distance between segment limits. It can be seen that for too small segment width values the calculated surface area soars beyond reasonable levels, which is because there are too few points in some segments and problems with continuity of solid's geometry arise. The best match with the volume measured directly was obtained for segments with width of approximately 0.5 cm, but the surface area obtained for this value is already far too high. Fig. 6 shows the visualizations of shrub solid for variant W2D for segments with width of respectively 2 cm and 10 cm.

Shrub volumes obtained from the analysis of scans were compared with direct measurements (Fig. 7). Volumes obtained based on the TLS are averages over five branch variants. Analysis of results shows that for the shrub models under study the one-stage convex hull generation (3D method) leads to a solid that differs significantly from the real one (correlation coefficient R=0.504 and p=0.159). Use of the multi-stage shrub solid generation (2D – 3D convex hull method) seems therefore more advantageous (correlation coefficient R=0.875 and p=0.085). Differences between direct measurements and scanner data can result from errors in estimation of a shrub's solid in direct measurements, where the volume was calculated based on measurements at three standard heights.

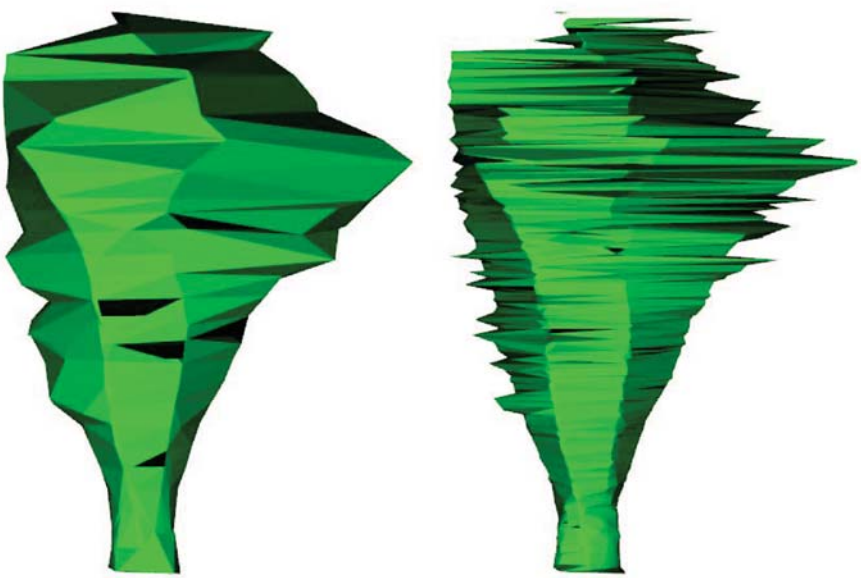
Fig. 6. Variant W2D: solid shrub visualization, using segment widths of 10 cm and 2 cm.

Field Research

The methodology developed for investigating shrub structures was used in field research. The object of study was willows. Field research was carried out in the Barycz River valley near Sułów village. This research location was chosen because of the valley's width and the presence of shrubs, but also because aerial laser scanning had been previously done for this area (Milicz Forest District). The authors intend to compare the results of their terrestrial studies with lidar analyses, which is from where their interest in this area stemmed.

Research covered 8 shrubs of rosemary willow (*Salix eleagnos* SCOP.) of varied density and height. Measurements were taken on July 14 and 15, 2008, i.e. at the peak of the vegetation season when branches were covered in leaves. Selected shrubs were those that provided easy access with the FARO LS 880 scanner (those directly over the water were rejected) and those that were not shadowed by neighboring trees or bushes. This was required by the methodology of LAI-2000 measurements and hemispheric photos. Each shrub was carefully measured. Height measurements were carried out with a measuring staff. Perimeters at various heights were measured with a measuring tape, assuming measurement planes every 50 cm, i.e. at the height of 0.5 m, 1.0 m, 1.5 m and so forth. LAI-2000 measurements and hemispheric photos were taken at the height of 0.5 m and 1.5 m. Scanning each shrub required the scanner to be set out in at least three positions. For each shrub its location was determined using GPS. Detailed photographic documentation of research was also made.

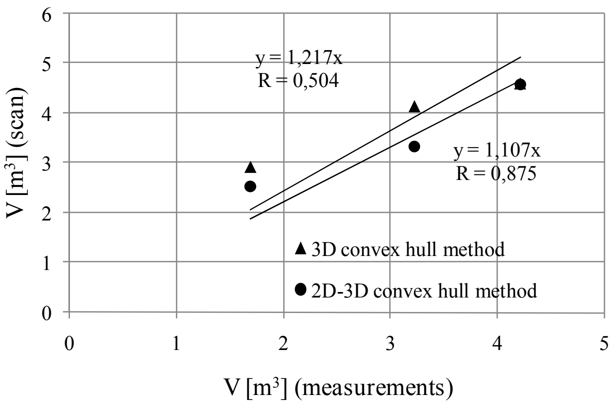

Fig. 7. Shrub volumes derived from scan analysis compared to direct measurements.

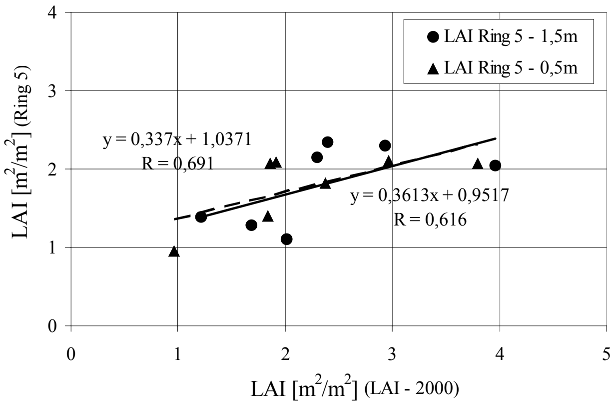

Fig. 8. LAI_{Ring5} based on hemispheric photos *vs*. LAI derived from LAI-2000 for different measurement heights.

In the analysis of hemispheric photos both the LAI_{Ring5} and openness were used. Results of LAI_{Ring5} measurements, based on hemispheric photos, ranged from 0.96 (k3) to 2.11 (k7) at a height of 0.5 m and from 1.1 (k5) to 2.3 (k7) at a height of 1.5 m. Openness: 15.57% (k7) – 36.88% (k3) at 0.5 m and 12.38% (k7) – 31.98% (k5) at 1.5 m. Next, the relationship was determined between the LAI_{Ring5} based on hemispheric photos and the leaf area index LAI calculated using the LAI-2000 analyzer for measurements at 0.5 m and 1.5 m (Fig. 8). The LAI coefficient calculated with the LAI-2000 ranged from 0.96 (k3) to 3.8 (k6) at a height of 0.5 m and from 1.21 (k3) to 3.96 (k7) at a height of 1.5 m.

The relationship between LAI derived from hemispheric photos and the values measured with LAI-2000 was also analyzed. Correlation coefficient R=0.691 (p=0.086) for measurements at the height of 0.5 m and R=0.616 (p=0.141) for 1.5 m indicate strong correlation dependence. This is particularly visible for a height of 0.5 m. Comparison study of leaf area index of forests were also pursued by [30]. Leaf area index (LAI) measurements made at 17 forest sites of the Fluxnet Canada Research Network Comparison of LAI measurements based on hemispheric photos and LAI-2000 for all available points from all sites. In field measurements we took LAI-2000 data every 10 m, while photographs were generally taken every 50 m because it was more time consuming. It is encouraging to see that, overall, DHP (digital hemispherical photography) agreed very well with LAI-2000 in terms of the effective LAI (correlation coefficient R=0.93). The DHP camera was normally mounted at 1 m above the ground while LAI-2000 was put at about 0.5 m above the ground. This good agreement between these two techniques is found because LAI-2000 was reliable when operated properly and strict procedures were followed for DHP exposure setting and image processing. Jonckheere et al. [9] emphasize that the DHP exposure setting is critical for correct determination of LAI. If the automatic exposure inside the stand was used (as done in many other studies), the LAI from DHP would have been underestimated by over 40% in comparison with LAI-2000 [31].

A similar study was performed for openness values for shrubs obtained from hemispheric photos and the LAI values calculated with LAI-2000 (Fig. 9). Strong correlation R = 0.942 (p=0.0016) for the measurement height of 0.5 m and R=0.998 (p=00003) for measurements at 1.5 m were obtained under the assumption of exponential relationship. In this case the measurement height is basically irrelevant. However, Sang et al. [32], a similar relation between LAI and canopy openness, was found for the three forest communities: canopy openness varied inversely with LAI. The relation is exponential and significant. Therefore, canopy openness is a good indicator of LAI in forests. This result can be used to test the validity of the LAI based on remote sensing and to provide a reference for the study of canopy heterogeneity and its effect.

Since shrubs were scanned during the vegetation period, in this case it was necessary to use only the macro-structural approach. Using the experience from previous laboratory measurements, micro-structural models for natural shrubs from the Barycz River valley were developed. Segment width assumed in calculations was 10 cm. Estimates of geometrical parameters derived from the analysis of scan images were compared with reference results. Fig. 10 shows the relationship between a shrub's volume measured directly and the values obtained from the 2D – 3D convex hull method. Correlation coefficient R=0.859 (p=0.013) for these data confirms that the proposed method leads to a correct rendering of shrub's geometry.

Using a mobile terrestrial LIDAR to measure fuel properties, longleaf pine woodland were also pursued by [33]. Data were collected using a mobile terrestrial LIDAR unit at sub-cm scale for individual fuel types (shrubs) and heterogeneous fuelbed plots. Spatially explicit point-intercept fuel sampling also measured fuelbed heights and volume, while leaf area and biomass measurements of whole and sectioned shrubs were determined from destructive sampling. Volumes obtained by LIDAR and traditional methods showed significant discrepancies.

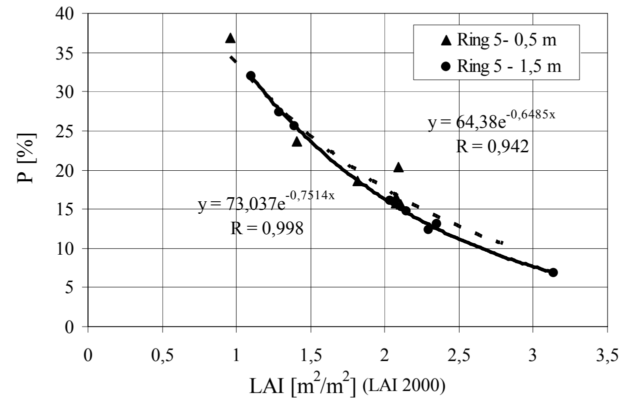

Fig. 9. Openness P for Ring 5 based on hemispheric photos *vs.* LAI from LAI-2000 for different measurement heights.

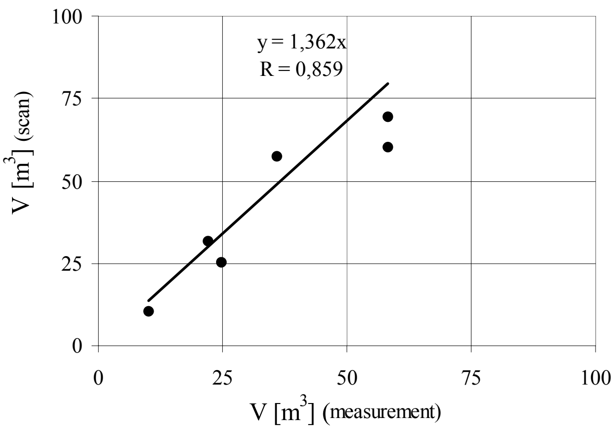

Fig. 10. Shrub volumes measured directly *vs.* results based on analysis of scans.

Conclusions

Results presented in this paper show the possibility of using new measurement tools based on novel geomatic techniques for investigation of flow conditions in flooded areas. Use of integrated optical analysis for investigation of shrubs can lead to a breakthrough in estimation of macro- and micro-structural conditions of drag due to vegetation in high water channels. Results of shrub density measurements were used to test the methods based on analysis of hemispheric photos and measurement with the LAI-2000 analyzer.

The methods for estimation of shrub vegetative structure required us to determine the hydraulic characteristics of flooded areas based on data derived from terrestrial laser scanning. Geometry of shrubs as impermeable elements (the macro-structural approach) was determined. Results were used to calculate the volume and surface area of the solid that constituted the convex hull of the shrub. Attempts were made to estimate the geometry of individual branches that constitute the shrub (the micro-structural approach). Apart from estimation of surface area and volume of branches, this approach allows for estimation of the surface area of the cross-section covering due to vegetation.

Test measurements of natural shrubs and comparison with the artificial ones led us to the following observations and remarks:

- Hemispheric photos can be applied for estimation of the cross-section covering coefficient, based on correlation with the LAI_{Ring5} index and openness P. The relation is exponential and significant. The method can be considered correct and useful for estimation of the structure of vegetation.
- In the case of micro-structural studies a method was used that assumes that plants are divided along the axis into segments of a given width. Comparison of surface values obtained from scanning with those derived from direct measurements confirmed that the analysis was correct and pointed at the possibility of recommending the proposed method for micro-structural analyses. In terms of computation, the micro-structural approach is somewhat more problematic. High scanning resolution, vegetation depth, possible leaves, and terrain conditions (plants moving due to wind) can lead to reflections that have to be accounted for as noise. In this case before the geometric model is generated, data must be filtered.
- Analysis of shrub macro-structure proved that one-stage generation of convex hull (3D method) can lead to solids that differ significantly, in terms of geometry, from that of real shrubs. However, the multi-dimensional method (2D-3D convex hull method) seems to be appropriate. In modeling a shrub's solid based on TLS data, also the selection of segment width for the partition of a shrub is crucial. Too small segments can lead to dramatic increase of calculated surface area, which is because there are too few points in some segments and problems with the continuity of a solid's geometry arise.

Acknowledgements

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