Vegetation Density Measurements using Parallel Photography and Terrestrial Laser Scanning

A Pilot Study in the Duursche en Gamerensche Waard

Jord Warmink
Department of Physical Geography
Faculty of Geosciences
Utrecht University

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Preface

This thesis was made in the scope of my final examination before receiving my Master’s degree in Physical Geography at the Faculty of Geosciences at the Utrecht University. My specialization is: Coastal and River Morphodynamics, with an accent on rivers. This report is the presentation of the final research, covering a fieldwork preparation, literature review and individual research. The field study was carried out in two floodplain sections along the branches of the lower river Rhine in The Netherlands. The terrestrial laser scanning part was done in cooperation with the Technical University Delft (TUDelft).

I want to thank everyone who helped me during the research. Loura Warmink and Willemijn Perdijk were a great help in the field and I was very glad to have some company during the field days. I would like to thank Michiel Schaap for his assistance on image processing, which appeared to be an important part of this research. Our discussions have resulted in an improved quality of the research. Furthermore, I want to thank Jaap Rouwenhorst, from Staatsbosbeheer, for permission to measure in the nature reserve, Duursche Waarden.

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Summary

Hydrodynamic vegetation density, the sum of the projected plant area per unit volume, is an important parameter for floodplain flow models. Currently, no objective and accurate measurement method is available to measure aggregated vegetation density in the field as reference data. The current field methods to obtain reference data assume cylindrical stems or lack spatial support. Therefore, the aim of this research was to determine the aggregated hydrodynamic vegetation density using two new methods, the parallel projected photographic method (PP) and the terrestrial laser scanning method (TLS) on floodplain vegetation.

Both methods were validated on reference data, the PP method was subsequently applied to more complex vegetation types. Field reference data consisted of (1) a stem map, describing the position and diameter of 650 trees in a single forest patch and (2) 17 manually measured plots of forest floodplain vegetation. PP consists of a series of digital photographic images of vegetation against a contrasting background. The centre columns of all images were merged into a single composite parallel image. This mosaic was thresholded to determine the fractional coverage of the vegetation, which was converted to vegetation density using the optical point quadrat method. TLS was carried out using a Leica HDS3000 time of flight laser scanner. Data processing of TLS data consisted of slicing the points around breast height. In a polar grid the vegetation density was predicted, using two models: (1) the Percentage Index (PI) and (2) the Vegetation Area Index (VAI), based on the optical point quadrat method.

It is shown that the PP method predicts the vegetation density very well ($R^2 = 0.996$) up to vegetation densities of $0.12 \text{ m}^{-1}$, which is dense forest. The PP method needed no calibration, because the regression line did not significantly differ from the line of identity at the 99.9 confidence interval. The method is also flexible as support is easily changed by increasing the distance to the screen, and the length of the guide rail for the camera. The sensitivity analysis showed that PP was sensitive to the resolution of the raw images, and the estimate of the plot length. Hue transformation of the composite images showed that a background of a dark blue or purple hue would be most appropriate for future studies instead of white or red.

The $PI$ and $VAI$ model were applied to the TLS data. The $VAI$ method, corrected for missing points and the assumption that the trees were randomly distributed, performed slightly less than the PP method ($R^2 = 0.77$) up to vegetation densities of $0.19 \text{ m}^{-1}$. The $VAI$ showed a small overestimation, probably due to leaves. $PI$ showed bad results ($R^2 = 0.27$), because no correction for occlusion was included in the model. The TLS method using the $VAI$, has the advantage that: (1) it does not require calibration, (2) it results in a spatial distribution of vegetation density, (3) is easily extended to 3D, and (4) the support has a variable size. The PP method is more efficient to collect reference data with respect to costs and time. This research has shown that TLS and PP are two complementary techniques that show high accuracies for field measurements of vegetation density.
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Chapter 1

Introduction

The 1993 and 1995 peak discharges of the rivers Rhine and Meuse led to an emergency situation in the Dutch river region. After the 1993 and 1995 floods, the Dutch government accepted a new policy to prevent future flooding of the lowland rivers (Middelkoop et al., 2004; Baptist, 2005; Van Stokkom et al., 2005). In this policy, raising the dikes is no longer an option. Instead creation of space for the river is preferred to reduce peak water levels (Baptist et al., 2004; Anonymous, 2004; Van Stokkom et al., 2005).

The floodplains in the Netherlands are part of the main ecological structure and are important nature development areas, which allows natural succession (Nienhuis et al., 2002; Baptist, 2005). Compared to agricultural land use, natural succession of floodplain vegetation increases the vegetation density and height of the floodplain. Vegetation causes flow friction, which slows down the water flow during inundation and increases the water levels, thereby increasing the flood risk. Therefore the Cyclic Floodplain Rejuvenation strategy was developed (Nienhuis et al., 2002; Baptist et al., 2004). This strategy aims at mimicking the effect of channel migration by anthropogenic removal of vegetation, lowering floodplains and reconstructing secondary channels. These measures are applied recursively, if due to succession and sedimentation the water flow over the floodplain is limiting the flood safety (Smits et al., 2000; Duel et al., 2001; Baptist et al., 2004). The Cyclic Floodplain Rejuvenation strategy can increase flood safety and ecological biodiversity, but requires adequate monitoring of the discharge capacity of floodplain areas.

The “Flood Protection Act” ("Wet op de Waterkering") lay down that the expected peak water levels must be checked every 5 years (Anonymous, 1995). To test if the dikes are safe enough to withstand a large flood, the water levels in the Dutch rivers are computed using hydrodynamic models (Anonymous, 1995; Van Velzen et al., 2003b). The water level depends on the resistance exerted by the floodplain surface and vegetation present in the floodplain area (Nepf, 1999; Shi and Hughes, 2002; Järvelä, 2002; Baptist, 2005; Van Stokkom et al., 2005; Straatsma and Middelkoop, 2006). Vegetation is an important factor in the determination of the roughness of floodplain areas and has a large influence on the resulting water levels. Accurate and spatially variable data on the vegetation structure is needed as input for the models (Mason et al., 2003; Straatsma, 2005). Height and density of submerged vegetation and density of emergent vegetation are the key characteristics from which roughness parameters in hydraulic models are derived (Straatsma and Middelkoop, 2006). Vegetation height can be easily measured in the field, for example by directly measuring the length of stems and shoots. Therefore, this study will focus on the determination of hydrodynamic vegetation density, which is defined as the sum of the projected plant area per unit volume (Petryk and Bosmajian, 1975).
1.1 Airborne vegetation mapping techniques

The Ministry of Transport, Public works and Water management determines the hydrodynamic roughness of the floodplains by visually mapping the ecotopes in the floodplains from aerial photographs (Jansen and Backx, 1998) and assign a roughness value to each ecotope using a lookup table (Van Velzen et al., 2003a; Jesse, 2004). Ecotopes are defined by Rademakers and Wolfert (1994) as “spatial landscape units that are homogeneous as to vegetation structure, succession stage and the main abiotic factors that are relevant to plant growth”. This method, however, may become inadequate to monitor the spatial and temporal changes in vegetation roughness, since the procedures are time consuming and no within-ecotope variance of the vegetation roughness is recorded (Straatsma and Middelkoop, 2006). There is a need for a more automated approach to assess hydrodynamic roughness of floodplain vegetation (Mason et al., 2003; Straatsma and Middelkoop, 2006). Successful attempts have been reported to map wetland vegetation using spectral remote sensing data (Van der Sande et al., 2003) and spectral remote sensing data in combination with a digital surface model (Ehlers et al., 2003). To document spatial variability in floodplain vegetation, airborne laser scanning (ALS) was used in previous studies. The ALS method was applied in forestry to determine forest canopy height profiles (Lefsky et al., 2002), single tree detection and species recognition (Brandtberg et al., 2003; Holmgren & Persson, 2004 in: Straatsma and Middelkoop, 2006). ALS was used to map topography (Marks and Bates, 2000) and vegetation (Cobby et al., 2001; Mason et al., 2003) in lowland floodplains as input for hydrodynamic models. Straatsma and Middelkoop (2006) give an overview of ALS methods to map vegetation height and density of floodplain vegetation. They concluded that ALS is a promising tool to map vegetation density of forests. However, field reference data remains necessary to (1) relate remotely sensed data to vegetation classes, (2) to quantitatively convert these data to structural characteristics and (3) to obtain an accuracy assessment of the results.

1.2 Field measurement techniques of vegetation density

Over the past decades, various quantitative methods have been established to measure vegetation density in the field. Assuming that vegetation can be considered as vertical cylinders, the density would be readily determined by manually measuring the diameter of all stems within the area of interest. The vegetation density is then the product of number of stems per unit area (N) and the average diameter of the stems (d). However, this approach becomes inaccurate in complex vegetation types, due to the presence of side branches, complex stem shapes and leaves. Therefore, alternative methods using point frames have been employed (Zehm et al., 2003). Since these manual methods are laborious and usually provide density estimates only for small plots, photographic methods have been proposed in which photographs of vegetation are taken against a contrasting background. Vegetation density is then estimated from the vegetation cover on the digitized image (Ritzen and Straatsma, 2002; Zehm et al., 2003). Vegetation density can be derived from the Leaf Area Index (LAI), which is traditionally determined in vertical direction for canopy coverage (Aber, 1979; Jonckheere et al., 2004), but can also be determined in a horizontal direction. Current photographic methods still provide biased estimates of vegetation density. Firstly, they disregard the effects of the central projection of the photograph images: consequently, vegetation elements close to the camera take a larger space than the same element at a larger distance due to the opening angle of the camera. This may lead to an overestimation of the fractional coverage of the vegetation, which depends on the distance to and the size of the first vegetation element. Furthermore, these photographic methods do not generate information on three-dimensional distribution of vegetation density.
1.3 Objectives

A measurement tool, which seems promising to map 3D vegetation structure by acquiring extremely dense point clouds (Lichti et al., 2002) is terrestrial laser scanning (TLS). TLS uses laser pulses to measure the distance to a reflecting object. The reflected laser pulses are recorded and result in a point cloud. Currently TLS is used in forestry for (1) characterizing trees using shape fitting (Thies et al., 2004), (2) filter operations in the 3D raster domain (Gorte and Winterhalder, 2004; Aschoff et al., 2004) and diameter–height profiles (Bienert et al., 2006). These studies focussed at detecting individual tree shapes, which is still problematic for complex vegetation that are dominant in Dutch floodplains. The determination of hydrodynamic density, however, does not require to identify each individual stem or vegetation element. But aims at the average density of the vegetation over a certain volume. The performance of TLS for this purpose has still remained unexplored.

The existing methods to measure vegetation structure have limitations for the determination of hydrodynamic vegetation density of complex vegetation types. They assume cylindrical stems, have a high degree of subjectivity or lack in spatial support. The photographic method, currently, is the most objective and accurate measurement method, but the central projection causes uncertainties. TLS seems promising to map 3D vegetation structure. Improving the photographic methods and TLS can result in valuable data to use as calibration data for more automated methods, as input data for lookup tables or to give a better insight in vegetation structure parameters of floodplain vegetation, in general.

1.3 Objectives

The aim of this research was to test parallel photography (PP) and terrestrial laser scanning (TLS) as measurement tools to determine the aggregated hydrodynamic vegetation density of floodplain vegetation and assess the accuracy and objectivity of the two methods.

- Develop an unbiased photographic method with a parallel projection to determine the vegetation density of forest and herbaceous floodplain vegetation under summer and winter conditions.
- Assess the accuracy of the PP method for aggregated vegetation density measurements.
- Develop a method to determine the vegetation density from TLS data.
- Assess the accuracy of TLS for aggregated vegetation density measurements on plot level.
- Compare parallel photography and TLS with respect to accuracy, time required in the field, costs and objectivity.

1.4 General approach

In this report, first some background information is presented on water flow hydraulics and roughness (chapter 2), previous studies on vegetation structure measurements (chapter 3) and the study area (chapter 4). Subsequently the methods, used to measure vegetation density using PP are presented (chapter 5). To test the improved photographic method, different vegetation plots were measured using the PP method. The PP method was validated on plots with simple vegetation structure and, subsequently, the method was applied to complex vegetation to test the applicability for other vegetation types. The results are presented in chapter 6.

Thirdly, the TLS method was tested in a forest in the Gamerensche Waard. The Percentage Index (P) and the Vegetation Area Index (VAI) (Straatsma, 2005) were used to predict the vegetation density of the forest (chapter 8). A stem map was measured in the forest as reference data to validate the two models and the results are presented in chapter 9. The accuracies, uncertainties and sensitivity of
the PP and the TLS methods are discussed in respectively chapter 7 and 10. The applicability of the
PP and TLS method for vegetation density measurements are discussed in chapter 11. Finally, some
conclusions and recommendations are given in chapter 12.
Chapter 2

Hydrodynamic roughness of floodplain vegetation

Water flowing over a floodplain experiences a resistance from the bed and vegetation in the floodplain area. The shape of the bed forms and the grain size determines the degree of resistance exerted by the bed. Also artificial objects and vegetation on the floodplain cause obstruction of the flow. The degree of obstruction can be expresses as a resistance value. Resistance causes a decrease of the flow velocity. This results in a rise of the water levels, thereby increasing the risk of flooding.

2.1 Water flow through and over vegetation

The resistance of vegetation elements can be expressed using a roughness value. The roughness of vegetation results in a change of the logarithmic flow profile (figure 2.1). The water flow can be described for two different layers: the flow through and over vegetation (Baptist, 2005). Therefore, different roughness equations are used for submerged and non-submerged vegetation. Research is done about the hydrodynamic roughness of vegetation. Besides the differences in submergence, different equations are formulated for flexible (Niklas and Moon, 1988; Fathi-Maghadam and Kouwen, 1997; Kouwen and Fathi-Moghadam, 2000; Järvelä, 2004) and rigid vegetation (Petryk and Bosmajian, 1975; Klopstra et al., 1997; Baptist, 2005).

2.2 Roughness descriptions of non–submerged vegetation

Kouwen and Fathi-Moghadam (2000) estimated the roughness of vegetation for flexible, non–submerged vegetation types. They used an equation based on the species specific vegetation index: $\xi$, which was derived by Niklas and Moon (1988); Fathi-Maghadam and Kouwen (1997); Kouwen and Fathi-Moghadam (2000). The vegetation index ($\xi$) accounts for flexibility, shape and biomass of the vegetation, which are the most important parameters for vegetation roughness calculation. This equation was tested on coniferous trees (Kouwen and Fathi-Moghadam, 2000) and on leafless and leafy bushes and trees (Järvelä, 2004). The vegetation index is species specific, which limits the applicability in Dutch floodplains where the vegetation consists of many different species.
2.3 Roughness descriptions of submerged vegetation

Figure 2.1: Velocity profiles of different vegetation structures. Left: submerged vegetation, centre and right non–submerged vegetation (modified after Fishenich (1996))

Petryk and Bosmajian (1975) used an approach assuming rigid vegetation, which was verified by Baptist (2005). The following equation was presented for the roughness of non–submerged vegetation:

\[
C_r = \sqrt{\frac{1}{C_b^2} + \frac{1}{2gC_DN\bar{d}h}} \quad \text{for} \ h \leq k
\]  

(2.1)

where \(C_r\) is the representative Chézy value (\(m^{1/2}s^{-1}\)) of the vegetated floodplain, \(C_b\) is the roughness of the bed, \(g\) is the acceleration of gravity (\(ms^{-2}\)), \(N\) is the stem density per unit area (\(m^{-2}\)), \(\bar{d}\) is the average diameter of the stems (\(m\)), \(h\) is the water depth (\(m\)), \(k\) is the vegetation height (\(m\)), and \(C_D\) is the drag coefficient (\(\sim\)). The drag coefficient includes the shape of the elements, the water density and the flow velocity (Bridge, 2003).

This equation is more appropriate than the equation described by Kouwen and Fathi-Moghadam (2000) to describe the roughness of Dutch floodplain vegetation, because it is independent of the vegetation type. Furthermore, it is not based on an empirical relation, so no calibration is needed.

2.3 Roughness descriptions of submerged vegetation

For the determination of the hydrodynamic roughness of submerged vegetation, an approach for flexible and stiff vegetation were developed. Kouwen and Li (1980) empirically related the flexural rigidity to vegetation height for growing and dormant grasses up to 0.9 m (Järvelä, 2004). The advantage of this method was that the vegetation height was the only parameter needed to determine in the field. This approach was used by Mason et al. (2003) to estimate the vegetation roughness of floodplain vegetation as a function of the vegetation height. The vegetation height is relatively easy to determine in the field, and the flexibility was estimated using the empirical relationships, from Kouwen and Li (1980). The disadvantage of this method was that the empirical relation was only valid for natural grasses up to 0.9 m. An empirical relation for the Dutch floodplain vegetation is complicated to set–up, due to the
2.4 Hydrodynamic vegetation density

heterogeneity of the vegetation. Furthermore, Van Velzen et al. (2003a) stated that the flow velocities over Dutch floodplains are low and bending of the vegetation is not an important parameter in roughness calculations.

A more appropriate approach to determine the hydrodynamic vegetation density, was derived and used in flume studies by Klopstra et al. (1997) and verified by Klopstra et al. (1997) and Baptist (2005). In this approach the velocity profile of submerged vegetation is treated separately for the vegetation layer and the surface layer. The two profiles are smoothly matched through boundary conditions at the interface. This led to a relatively difficult numerical equation, which was simplified by Baptist (2005) to:

\[ C_r = \sqrt{1 + \frac{1}{2gC_DN_d} + \frac{\sqrt{g}}{\kappa} \ln \frac{h}{k}} \quad \text{for } h > k \]  

(2.2)

where \( \kappa \) is the Von Kármán’s constant (0.4) and \( N_d \) represents the hydrodynamic vegetation density \((m^{-1})\). The first term of the equation is equal to the equation for non–submerged vegetation (equation 2.1) and the second term is similar to the logarithmic velocity profile, which is superimposed on top of the vegetation layer (figure 2.1).

\[ C_r = \sqrt{1 + \frac{1}{2gC_DN_d} + \frac{\sqrt{g}}{\kappa} \ln \frac{h}{k}} \]

Figure 2.2: Definition of hydrodynamic vegetation density

2.4 Hydrodynamic vegetation density

Equations 2.1 and 2.2 proved to be a good approximation for the hydrodynamic vegetation roughness for Dutch floodplain vegetation and are valid for a wide range of vegetation properties and flow conditions (Baptist, 2005). These equations were tested on different types of Dutch floodplain vegetation and performed well. The main parameter to be determined in the field is the vegetation density, represented by \( N_d \) in the equations.

Hydrodynamic vegetation density \((Dv)\) is defined as the sum of the frontal areas of all plant elements \((A)\) in the direction of the water flow \((F)\) per unit volume (figure 2.2). The equation for
hydrodynamic vegetation density is:

\[ D_v = \frac{\sum A_i}{AL} \]  \hspace{1cm} (2.3)

where \( A_i \) is the projected area of a vegetation element \((m^2)\), \( A \) is the surface area of the plot in side view \((m^2)\) and \( L \) is the length of the plot in the flow direction \((m)\). The unit is \( m^2 \), which reduces to \( m^{-1} \). Under the assumption that vegetation consists of cylindrical elements, vegetation density can be calculated as the product of the number stems per square meter \((N)\) and the average diameter \((\bar{d})\), with a unit of \( m^{-1} \):

\[ D_v = \frac{\sum A_i}{AL} = N \cdot \bar{d} \]  \hspace{1cm} (2.4)
Chapter 3

Review of vegetation density measurement methods

Parameters related to $D_v$ are important in forestry (Chasmer et al., 2004; Gorte and Winterhalder, 2004; Thies et al., 2004) and ecology (MacArthur and MacArthur, 1961; MacArthur and Horn, 1969; Aber, 1979; Roebertsen et al., 1988; Dudley et al., 1998; Zehm et al., 2003). Different methods to measure $D_v$ have been proposed and are discussed on this chapter.

3.1 Point frame method

The point frame method was originally proposed by Levy and Madden (1933). The horizontal point frame method consists of a frame with three parallel diagonal rails with holes punched at regular intervals. Estimates of vegetation density were obtained by pushing pins through each hole, and the number of hits with the vegetation ($N_{hits}$) was recorded for each position (Dudley et al., 1998). The vegetation density was calculated by:

$$D_v = \frac{1}{L_p} \cdot \frac{N_{hits}}{N_{holes}}$$

(3.1)

where $L_p$ is the pin length (m), and $N_{holes}$ is the total number of holes. Bonham (1989, in Dudley et al., 1998) stated that the point frame method is one of the most objective methods of measuring vegetation density. Previous research has shown the point frame method to be accurate, efficient and reliable (Dudley et al., 1998). Dudley et al. (1998) adapted the point frame method to measure vegetation density by constructing a horizontal point frame to support horizontal pins. The length of the pin and the height of the frame limited the volume that can be measured at a single location. Another disadvantage was the uncertainty introduced by moving vegetation during the measurement.

3.2 Cover board method

MacArthur and MacArthur (1961) used the cover board method to relate the foliage structure to bird species. A white board, marked with a grid was used, which was held in the vegetation. The board was horizontally moved away from an observer and the distance ($L$) was recorded, where 50% of the grid points was covered by vegetation from the point of the observer. Assuming a random distribution of the
3.3 Optical point quadrat method

The cover board method had the advantage that it was rapid, required minimal equipment and provided estimates over large distances in sparse vegetation. However, the board method relies on subjective estimates of fractional coverage by the observer, which may cause substantial error (Dudley et al., 1998). Spatial support is limited to the size of the board.

3.3 Optical point quadrat method

The cover board method was adapted by MacArthur and Horn (1969) and Aber (1979) to measure canopy–height profiles in forests. They used a camera with a grid superimposed on the focusing screen. The lens is pointed straight up and used as a range finder. The height to the lowest leaf covering each grid point was determined by focusing the lens on that leaf and reading the distance \(d\), off the lens mount. The canopy–height profile is defined as the “surface area of all canopy material, woody and foliage, as a function of height”. The data on the distribution of leaves with height can be transformed to the Leaf Area Index (LAI) (Aber, 1979):

\[
LAI = \ln \frac{N_{d1}}{N_{d2}} \quad (3.4)
\]

where \(N_{d1}, N_{d2}\) are the number of points sighted above distances \(d1\) and \(d2\) to the camera. In this method only the first hit was recorded, so leaves higher in the canopy were hidden from the camera (Aber, 1979). This hiding effect, or occlusion, was corrected by taking the natural logarithm. The camera method appears to be an objective procedure that provided estimates over large horizontal and vertical distances in sparse vegetation. However, it has the disadvantage that it requires special photographic equipment (Dudley et al., 1998). The method relies on a random distribution of the vegetational elements (MacArthur and Horn, 1969; Aber, 1979).

Parker et al. (2004) used the optical point quadrat method with a laser profiler to estimate the foliage–height profile and the LAI. The authors used a single laser beam directing upwards to measure the distance to the nearest leaf for multiple transects in the forest. The advantage of this method was that it was less subjective and faster than the camera method. The method has some practical limitations and small vegetation elements were not recognized by a single laser beam (Parker et al., 2004).

3.4 Photographic method

Greame and Dunkerley (1993) estimated the vegetation density of Eucalyptus trees in ephemeral desert streams using a photographic method. Photographs were taken from the vegetation in a horizontal direction, with the camera axis in downstream direction. These photographs were projected as colored slides onto a digitizing tablet and all trees and trunks were digitized. The fractional coverage of the vegetation was summed up to yield \(\sum A_i\) (equation 2.3). Greame and Dunkerley (1993) used the manual method \((N \cdot \bar{d})\) as reference data, where the number of stems per unit area were multiplied by the average diameter (equation 2.4). They concluded that the data from the photographs matched quite well with the reference data when tested on trunks with a simple geometry.
3.4. Photographic method

The digitization process was time consuming. Therefore, the method was improved by Ritzen and Straatsma (2002) and Zehm et al. (2003), using digital photography and a white screen as background. The method was applied by Zehm et al. (2003) on low (< 80 cm) vegetation, while Ritzen and Straatsma (2002) measured forest, shrub, and herb vegetation in floodplains. Subsequently, Ritzen and Straatsma (2002) took 8 digital photographs from the vegetation in front of the centre of the screen. Each picture was taken from a slightly different position. Zehm et al. (2003) used a single digital photograph for each measured plot. The distance from the camera to the screen was measured using a measuring ruler. The distance was chosen in such a way that the fractional coverage of the screen was around 50 percent, with a maximum distance of 10 meter.

The fractional coverage of the screen by vegetation was determined by applying a threshold value. Pixels with an intensity value below the threshold were classified as vegetation (black) and above the threshold as screen (white). To increase the contrast between vegetation and background, Wijma (2005) used a red screen, and Zehm et al. (2003) suggested to use a black screen, for light colored vegetation. The fractional coverage of the screen was calculated by the percentage of black pixels compared to the total number of pixels in the photograph. The vegetation density was calculated using equation 3.7. Ritzen and Straatsma (2002) and Wijma (2005) applied the threshold and calculated the fractional coverage of every photograph. The fractional coverages were averaged for the 8 photographs of every plot to yield $D_v$. Zehm et al. (2003) developed the program S\textit{\textsc{view}} to extract various parameters from the thresholded photograph, amongst others, the vegetation density. In a later study, S\textit{\textsc{view}} was extended with an automatic thresholding algorithm (Nobis and Hunziker, 2005). Ritzen and Straatsma (2002) applied the photographic method on floodplain vegetation in the Duursche Waarden and Wijma (2005) measured the vegetation density of floodplain vegetation along the Alli\`er (France) and the Volga river (Russia). Representative values for the vegetation density using different measurement tools are summarized in table 3.1.

Table 3.1: Vegetation density values from previous research, using different measurement methods

<table>
<thead>
<tr>
<th>Reference</th>
<th>$D_v$ value ($m^{-1}$)</th>
<th>Measurement method</th>
</tr>
</thead>
<tbody>
<tr>
<td>MacArthur and Horn (1969)</td>
<td>0.13 – 1.95 (LAI)</td>
<td>optical point quadrat</td>
</tr>
<tr>
<td>Aber (1979)</td>
<td>3 – 7 (LAI)</td>
<td>camera and litter fall</td>
</tr>
<tr>
<td>Bonham (1988, in Dudley et al., 1998)</td>
<td>0.005 – 0.082</td>
<td>$Nd$ (tree trunks)</td>
</tr>
<tr>
<td>Greame and Dunkerley (1993)</td>
<td>0.004 – 0.024</td>
<td>photographic</td>
</tr>
<tr>
<td>Ritzen and Straatsma (2002)</td>
<td>0.015 – 0.05</td>
<td>airborne laser scanning</td>
</tr>
<tr>
<td>Wijma (2005)</td>
<td>0.02 – 0.16</td>
<td>photographic</td>
</tr>
<tr>
<td>Straatsma and Middelkoop (2006)</td>
<td>0.005 – 0.38 (VAI)</td>
<td>airborne laser scanning</td>
</tr>
</tbody>
</table>

3.4.1 Occlusion

In the methods described above, occlusion (i.e. trees being hidden behind other trees) plays an important role. Occlusion can be visualized by the extinction of the light in a semi transparent medium Straatsma (2005). Under the assumption that the trees in a forest are randomly distributed, the decrease of light through the forest can be calculated by:

$$i = i_0 \cdot e^{D_v L}$$

so

$$D_v = -\frac{1}{L} \ln \frac{i}{i_0}$$
3.4. Photographic method

where \( i_0 \) is the initial amount of light, \( i \) is the amount of light at distance \( L \) (m) and \( D_v \) is the density of the vegetation. This equation is similar to the equation used by Aber (1979) (equation 3.4).

Ritzen and Straatsma (2002) and Wijma (2005) used the following equation to correct for occlusion:

\[
D_v = \frac{1 - (1 - A_{tot})^{S/L}}{S}
\]

(3.7)

where \( A_{tot} \) is the fractional coverage of the screen (–), \( L \) is the length of the plot (m) and \( S \) is the spacing factor (m), which is defined as the average distance between the trees. The spacing factor is a measure for the occlusion and depends on the density of the vegetation. It can be estimated by \( \sqrt{1/N} \), where \( N \) is the number of trees per square meter. The spacing factor had to be measured manually in the field, which introduced subjectivity in the method.

Figure 3.1: Uncertainties of the centrally projected photographic method: stems are not recorded (tree 1 and 2), the projected size \( (A_{i,p}) \) of the trees is larger than the actual size \( (A_i) \) (tree 3 and 4), and occlusion is enhanced, because a large tree (5) is hidden by a smaller tree (3) (modified from Ritzen and Straatsma, 2002)

3.4.2 Bias in the photographic method

The photographic method had some uncertainties, which were caused by the central projection of the photographs. The uncertainties are visualized in figure 3.1 and result from:

1. Not all stems in the plot were photographed: in figure 3.1 can be seen that tree (1) and (2) are not in front of the camera, but they contribute to the density of the plot. This results in an underestimation of \( D_v \). This effect can be corrected using the half plot length.
2. The projection of the trees is larger than the actual diameter of the trees \( (A_{i,p} > A_i) \). This effect is larger when the trees are closer to the camera (tree (3) and (4) in figure 3.1) and results in an overestimation of the \( D_v \). This effect was reduced in the studies of Ritzen and Straatsma (2002) and Wijma (2005) by photographing from a location where no trees were close (20 cm) to the camera.
3. The central projection results in enhanced occlusion. This effect is visualized by tree (5), which is fully occluded by a smaller tree (3). In case of normal occlusion (section 3.4.1), assuming parallel projection, tree (5) is occluded only partly by tree (3).

Even though these uncertainties average out to some extent by taking a series of photographs, subjectivity remains. The subjectivity can be decreased, using a parallel projected photograph, thereby
3.5 Terrestrial laser scanning

Terrestrial laser scanning (TLS) is increasingly being appreciated as an efficient tool for fast and reliable 3D point cloud data acquisition. It has a wide range of application fields like, 3D visualization of industrial structures, infrastructure and architecture (Lemmens and van den Heuvel, 2001; figure 3.2). TLS measures distances using a laser range finder. Laser scanners generate a 3D point cloud representing the surface of objects. The quality of the 3D point clouds generated by laser scanners and the automation potential make TLS also an interesting tool for forest inventory (Bienert et al., 2006).

Figure 3.2: Examples of application of TLS in digitization of industrial structures (left) and infrastructure (right) (from: www.delfttech.nl)

3.5.1 Technical specifications of terrestrial laser scanners

Laser scanners that are currently on the market can be categorized by different criteria:

- Field of View: laser scanners generally have a panoramic field of view of 360° horizontally and a one–side vertical field of view between 80° and 135° (Bienert et al., 2006).
- Range measurement principle: time of flight or phase–modulation based (Fröhlich and Mettenleiter, 2004).

Today, the most popular measurement system is the time of flight principle, which allows up to several hundred of meters. Laser scanners using the time of flight principle fire discrete laser pulses. The distance is calculated from the pulse travel time between emission and return of the pulse (Straatsma and Middelkoop, 2006). Besides the time of flight principle, the phase based measurement principle is another common technique. The phase–modulation laser scanners determine the distance to the target from the phase difference of the return pulse of a continuously emitted laser signal (Straatsma and Middelkoop, 2006). This type of scanner has smaller ranges, limited to 100 m, but a higher accuracy level. The specifications of three different scanners are presented in table 3.2 (Fröhlich and Mettenleiter, 2004).
3.5. Terrestrial laser scanning

Other parameters are: (1) Scanning speed. In general the time of flight based scanners are slow compared to phase based scanners. (2) Spatial resolution i.e. the number of points scanned in the field of view. The spatial resolution determines the point density. (3) Accuracy and range of the instrument. An instrument with a large range will generally have lower accuracy (table 3.3). (4) The combination with other devices mounted on the laser scanner. Some scanners are equipped with a built–in GPS instrument or a digital camera, for the acquisition of high resolution surface texture and the fusion of point cloud and image data processing (Bienert et al., 2006). Forest inventories need a high sampling rate of at least 10 kHz (Bienert et al., 2006) and a large field of view.

When multiple echoes return from a single pulse, ghost points are created. Ghost point are points which have an erroneous distance, because the distance is calculated from the average of the travel times of the two returned pulses. As a consequence, the location of the ghost point in the point cloud is erroneous. Ghost points are produced when some twigs partly occlude each other and have to be considered in the development of data processing schemes (Bienert et al., 2006).

3.5.2 Application of terrestrial laser scanning in forestry

Previous research focussed on object extraction of individual trees using TLS, which could be converted to vegetation density. The first step in this process is the generation of a Digital Terrain Model (DTM) from the laser scan data.

DTM generation

A simple approach to DTM generation was used by Aschoff et al. (2004). The authors laid a grid over the scanned plot and selected the point with the lowest z value in each grid cell to be the ground point, excluding the points above a certain threshold. Subsequently, all points with similar z values, were classified as a ground point or a vegetation point. Afterwards, a filter was applied to remove misclassified points from the ground point data set. The final steps in DEM generation were the visual removal of misclassified ground points and the creation of a continuous surface using interpolation (Aschoff et al., 2004). This simple approach gave satisfactory results in this study, but more sophisticated methods have been employed Kraus and Rieger (1999).

Geometrical shape fitting

3D terrestrial laser scanning has been used to map forest stands and to digitize individual trees by geometrical shape fitting (Thies et al., 2004) (figure 3.3). For the digitization of trees the points classified

Table 3.2: Examples of the technical specifications of TLS systems (Fröhlich and Mettenleiter, 2004).

<table>
<thead>
<tr>
<th>System</th>
<th>Scanner type</th>
<th>Meas. principle</th>
<th>Freq.</th>
<th>Range</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leica HDS3000</td>
<td>Panoramic</td>
<td>Pulse</td>
<td>1 kHz</td>
<td>&gt; 100 m</td>
<td>6mm @ 50m</td>
</tr>
<tr>
<td>Optech ILRIS–3D</td>
<td>Camera (small hor.</td>
<td>Pulse</td>
<td>8 kHz</td>
<td>800 m</td>
<td>3mm &lt; 100m and 1–3cm &gt; 100m</td>
</tr>
<tr>
<td></td>
<td>field of view)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zoller &amp; Fröhlich IMAGER 5003</td>
<td>Panoramic</td>
<td>Phase</td>
<td>500 kHz</td>
<td>52 m</td>
<td>–</td>
</tr>
</tbody>
</table>

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as vegetation are used for shape fitting. The primary interest in the shape fitting process lies in the diameter and the growing direction of the tree. Therefore, Thies et al. (2004) used an approach, where a cylinder model was fitted to a segment of the point cloud. After successful fitting in one segment, the next cylinder was fitted to a new selection of points, to describe the stem in the next section. This resulted in an overlapping sequence of cylinders describing the radius and orientation of the stem as it changes with height.

Bienert et al. (2006) proposed a technique for point cloud segmentation to detect diameters at breast height and diameter–height profiles. Diameter–height profiles proved valuable to vegetation roughness calculation (Baptist, 2005). The diameter at breast height was determined by cutting a slice at 1.3 meter above ground level. An adjusting circle was fitted into the 2D projection of the points of the slice. Proceeding with this technique stem diameters at every height can be determined.

![Image](a) The reflection intensity decreases with distance (Thies et al., 2004)  
(b) Single tree scanned from 4 directions for detailed digitization (Gorte and Winterhalder, 2004)  
(c) Diameter–height profile (Bienert et al., 2006)

Figure 3.3: Examples of terrestrial laser scanning applications on forest stands

Table 3.3: Classification of scanners on the range measurement principle (Fröhlich and Mettenleiter, 2004)

<table>
<thead>
<tr>
<th>Range principle</th>
<th>Range (m)</th>
<th>Acc. (mm)</th>
<th>Manufacturers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time of flight</td>
<td>&lt; 100</td>
<td>&lt; 10</td>
<td>Callidus, Leica, Mensi, Optech, Riegle</td>
</tr>
<tr>
<td></td>
<td>&lt; 1000</td>
<td>&lt; 20</td>
<td>Optech, Riegle</td>
</tr>
<tr>
<td>Phase modulation</td>
<td>&lt; 100</td>
<td>&lt; 10</td>
<td>IQSun, Leica, VisImage, Zoller &amp; Fröhlich</td>
</tr>
</tbody>
</table>

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Utrecht University
The voxel approach

Gorte and Winterhalder (2004) used a different approach, where they first converted the 3D point cloud into the 3D grid domain. The cells in a 3D grid were small cubes called voxels (volume elements as opposed to pixels in 2D). The grid size of the cells determined the resolution of the 3D grid. During the conversion of a point cloud to a 3D grid, the \textit{xyz} position of a point, together with the chosen resolution, determined the position of the corresponding voxel. The voxels were given the value of the number of laser hits in a voxel. After the conversion to voxels, they used 3D raster processing techniques instead of point calculations to create a voxel representation of a single tree, including topology, such as stem, branches and twigs.

Chasmer et al. (2004) applied the voxel technique on a larger scale, to compare the ALS and TLS methods, for vegetation mapping purposes in a forested area. They concluded that the airborne method will likely underestimate the leafy biomass within the canopy, and may influence measures of \textit{LAI}, due to the hiding of lower leaves by the overlying canopy. The TLS method underestimates the tree height due to the same effect. The voxel approach made it possible to quantify the difference between the airborne and terrestrial methods in 3D space. The study illustrated that, due to occlusion, substantial parts of the understory and canopy are excluded from ALS and TLS respectively.

TLS methods for vegetation density mapping

From these studies, it can be concluded that the TLS method is promising for determining the vegetation density of forests. In combination with automatic data processing tools, the gap between conventional inventory techniques and laser scanning may be bridged (Bienert et al., 2006). The advantage of the TLS method is that 3D images of vegetation density can be generated, which may be valuable for comparison with ALS.
Chapter 4

Study areas

This study was carried out in two floodplains along the rivers Rhine and IJssel in The Netherlands: the Gamerensche Waard (GW) and the Duursche Waarden & Fortmond (DW).

Figure 4.1: Location of the Gamerensche Waard (GW) and the Duursche Waarden (DW) floodplain

4.1 The Gamerensche Waard

The Gamerensche Waard floodplain is located at the left bank of the river Waal, the main branch of the Rhine river distributaries (figure 4.1). The floodplain is located west of the city of Zaltbommel, in an outer bend of the river. The geomorphology consists of levee deposits and three artificial side channels. The floodplain area is flooded, annually, over a large area at high discharges. The area of the old brick factory (appendix A.1) is the highest point of the floodplain and is rarely flooded (figure 4.3(b)). The size of the floodplain is about 73 hectares and it is developed as a nature area. In 1996, three side
4.2. The Duursche Waarden & Fortmond

channels were constructed, one perennial and two channels close to the main channel, ephemeral. The ruin of the brick factory was removed in the same period (figure 4.2).

Since 1996, an intensive vegetation monitoring program exists for the Gamerensche Waard. Throughout the year, the whole floodplain is grazed by horses, in the growing season also cows are present. The dominant vegetation consists of softwood willow forest (Salix alba, Salix viminalis) and grassland with creeping thistle (Cirsium arvense) and stinging nettle (Urtica dioica) patches (Jesse, 2004). Several ecotope maps were made of the area during the monitoring of the development of the side channels (Jans, 2004). Information on the temporary development of the vegetation classes is, therefore, available (Van Velzen et al., 2003b; Jesse, 2004). The area of natural grassland has decreased since 1996 and is replaced by dry herb vegetation or softwood forest.

![Figure 4.2: Aerial photograph of the GW floodplain area, with the TLS forest upper left](image)

Measurement locations in the GW

In the Gamerensche Waard, TLS was carried out in a willow forest patch. The forest was 80 meter wide and 120 meter long (figure 4.3(c) and 4.3(d)). The edges of the forest were dense and the central parts had a more open structure. The elevation differences inside the forest area were small, with a maximum of 0.5 meter. Little undergrowth was present, only some patches of stinging nettle. The horses and cows, which were present in the floodplain area, had removed most undergrowth (figure 4.5(c)). Besides the TLS measurements, 12 forest plots were measured in the forest using the photographic method. Additionally, 10 plots of dry herb vegetation and dense softwood forest were measured, elsewhere in the floodplain area. The measurement locations are shown in appendix A.2.

4.2. The Duursche Waarden & Fortmond

The Duursche Waarden & Fortmond floodplain is located at the right bank of the river IJssel, a side branch of the river Rhine. It is located 10 km north of the city of Deventer (figure 4.1). The Duursche Waarden area is a nature reserve, while the area around Fortmond is dominated by cultural land and forest (figure 4.4; appendix A.1). The geomorphology consists of a point bar with a side channel.
connected at the downstream end, and a river dune. The dead arm and a sand pit were connected in 1989 to the main channel. The area is grazed by horses and cows with 0.8 animals per hectare (Jesse, 2004). This resulted in extensively grazed vegetation, consisting of natural grasslands with patches of shrubs and herb vegetation and forest in various stages of development (e.g. softwood willow (Salix alba, Salix viminalis), poplar (Populus nigra, Polpulus x canadensis) and ash (Fraxinus excelsior)). The typical inundation depth of these floodplains is 3 m, but water depths may rise to 5 m in case of extreme floods.

The Fortmond area is characterized by several houses and farms, which are located along the road (figure 4.4; appendix A.1). This area is used for agriculture and the vegetation is dominated by production grassland and agricultural crops. The area around the old brick factory is high and accessible in winter and open for recreational use. A camping site is present along the IJssel, in the southern part of the floodplain. The forest near Fortmond is more than 40 years old and consists of oak (Quercus robur), beech (Betula pendula) and a small mature pine stand (Pinus sylvestris). The centre part of the forest lies between 4 and 8 m above sea level and is rarely flooded. The western part of the forest is lower and flooded regularly. The nature reserve area is flooded during a large part of the winter.

In 1989, the DW was the first floodplain that was subjected to landscaping measures by the Ministry of Transport, Public Works and Water management (Jesse, 2004). Ever since, this area is a
4.2. The Duursche Waarden & Fortmond

Figure 4.4: Aerial photograph of the DW floodplain area, with the Fortmond area in the western part of the floodplain and the nature reserve in the north (from: www.googleearth.com)

nature reserve, and the vegetation is intensively monitored. The vegetation is dominated by natural grassland, herb vegetation and softwood forest. The area covered with grasslands is reduced since 1989, while the areas with dry herb vegetation, thorn shrubs and softwood forest have increased. Small softwood forest stands were present between the fields. The high area around the old brick factory consists of herb vegetation, with isolated trees and shrubs. Several small fields of reed are present along the river. On the river dune, the only hardwood forest vegetation in the study areas is located. In this thesis, the name Duursche Waarden (DW) will be used for the combined area of the nature reserve and the area around Fortmond.

Measurement locations in the DW

In the DW floodplain, 51 vegetation plots were measured. The photographic method was used to determine the vegetation density in different vegetation types. The measurement locations are presented in appendix A.2. Five herbaceous plots were measured again under winter conditions. In winter, however, most areas of the floodplain were flooded (figure 4.5(d)), due to a high river discharge. Therefore, not all vegetation types could be duplex measured under winter conditions. The locations, measured in summer in the nature reserve area were flooded (figure 4.5(b)). So the duplex measurements were carried out near the old brick factory, which was the only location with herbaceous vegetation, which was not flooded. The locations of the duplex measured plots are shown in appendix A.2.
4.3 Plot selection

In the floodplain areas of the Duursche– and Gamerensche Waard the measurement plots were selected, initially, based on the DTB-river maps that show topographical descriptions of the vegetation (appendix A.2). During the measurements, the vegetation type of the measured plot was recorded. The vegetation types are based on the vegetation mapping studies by Van Velzen et al. (2003a) and Jesse (2004). In each vegetation type with natural vegetation, if possible, at least 5 plot locations were measured. Agricultural vegetation types were not measured, due to time limit actions. The measured vegetation types are:

- **a** hardwood forest with oak (*Quercus robur*) and ash (*Fraxinus excelsior*),
- **b** softwood willow forest (*Salix alba, Salix viminalis*),
- **c** shrub vegetation consisting of hawthorn (*Crataegus laevigata*),
- **d** natural grassland consisting mainly of grass (*Lolium perenne*) and clover (*Trifolium repens*),
- **e** herbaceous vegetation with dominant creeping thistle (*Cirsium arvense*), grass, stinging nettle and dewberry (*Rubus caesius*),
- **f** herbaceous vegetation with dominant stinging nettle (*Urtica dioica*), dewberry, creeping thistle and grass,
- **g** herbaceous vegetation, with high species diversity, consisting of stinging nettle, grass, great bind

Figure 4.5: Flooding of the measurement area (a,b) and impression of the study areas (c,d).
weed (*Calystegia sepium*), dewberry and the great willow herb (*Epilobium hirsutum*) and reed marshes (*Phragmites australis*).

Representative plots were selected for each class. The fractions of high and low vegetation in the area were reflected in the measurement plot. This fraction was estimated visually in the field. The plot size of the herbaceous plots was about 2 m wide and 0.5 m long and forest plots were 5 meter wide and between 5 and 10 meter long. The forest plots were delimited in a rectangle, and no trees were intersecting the edges of the plot. A single plot of hawthorn brushwood was measured. The measurement locations including the mapped vegetation types are presented in appendix A.2.
Chapter 5

Vegetation density measurements method using parallel photography

The centrally projected, photographic method has several limitations. Therefore, I propose a new method to measure vegetation density in the field: the parallel photographic method (PP). A parallel image mosaic was created, by merging multiple photographs, taken along a parallel transect. The method was validated on simple vegetation structures and applied to more complex vegetation types.

5.1 Reference data collection

In the Gamerensche Waard and Duursche Waarden floodplain sections, 68 measurements were carried out using the PP method. The vegetation type and the parameters, like the camera setting and the plot setup, which influenced the PP, were recorded on the field form (appendix C.1). The coordinates of the plot centre were measured using GPS with an accuracy of 5 meter. Furthermore, the weather at the time of the measurement was recorded. The ground height at the location of the plot was estimated based on a height map.

5.1.1 Manual vegetation density measurements

The reference data for forest plots was collected by measuring the circumference of all trees in a plot at breast height, which was defined as 1.3 m above the ground surface. The diameter was calculated from the circumference by division through $\pi$. Multiplying the average diameter of all trees in the plot by the number of trees per square meter, yielded an estimation for the vegetation density ($D_{v N_d}$; equation 2.4).

The reference data of the herbaceous plots was measured similarly, with the exception that not all stems in each plot were measured, but 30 stems were randomly selected at the half vegetation height (the height where the photographs were taken). The diameter was measured using a sliding gauge, with an accuracy of 0.1 mm. When the stems were not cylindrical, the average diameter was estimated. Subsequently the total number of stems was counted in the plot and divided by the measured surface area of the plot. For the first 14 herb plots the $D_{v N_d}$ value was measured at 15 cm above ground level instead of at the photo height, leading to an overestimation of $D_v$.

This measurement method was based on the assumption that all vegetation elements were cylin-
5.2. The parallel photographic method

5.1.2 Vegetation height measurements

Additionally, the vegetation height of all herb plots was determined by measuring the length of the same 30 stems used for the density calculation. The length of these 30 stems was measured from the top to the ground surface using a folding rule. Furthermore, the length of the highest stem in the plot \( (H_{v_{\text{max}}}) \) and the highest representative stem \( (H_{v_{\text{rep}}}) \) are recorded. The highest representative height is defined as the highest leaf or when leaves are absent, the height of the layer of highest stem (figure 5.1).

The selection of 30 stems at the photo height resulted in an overestimation of the average vegetation height, because vegetation lower than the photo height was not included in the height determination. For some plots, a separate height measurement was taken, where the stems were randomly selected at 15 cm above the ground surface, instead of the photo height. The 30 stems were selected just above the ground surface. This gives a better representation of the average vegetation height. The vegetation height measurement data is needed for the calculation of vegetation roughness in future studies. It is, however, not part of this research. The results are presented in appendix C.2.

![Figure 5.1: Definition of maximum vegetation height \( (H_{v_{\text{max}}}) \), representative maximum vegetation height \( (H_{v_{\text{rep}}}) \) and the average vegetation height \( (H_{v_{\text{average}}}) \).](image)

5.2 The parallel photographic method

The PP consists of taking multiple photographs of the vegetation against a contrasting background along a line, parallel to the screen. From these photographs, the centre columns were clipped and merged to produce a single parallel projected photo mosaic for each measurement plot.
5.2. The parallel photographic method

The parallel photographic method (PP method) required a contrasting background screen, digital camera, measuring tape, a 6 m long guide rail (divided into two parts of 3 m), 3 tripods to support the rail, an 80 cm and a 5 cm long level, a surveyors beacon, clips to fixate the rail to the tripod and a laptop. The plot was selected as described in section 4.3. In herbaceous vegetation a plot was prepared in a vegetation stand by selecting a 2 m wide and about 50 cm long area. A red screen of 2 m high and 2.5 m wide was placed behind the vegetation, with a backward angle to reduce shadows. The plot was created by removing or flattening the vegetation in front of the plot. The length of the plot was determined, so the screen was covered for 50% (figure 5.2). The guide rail was set up parallel to the screen. The guide rail of 3 m was used in herbaceous plots and the 6 m long rail in forest plots. The rail was levelled, in front view, using the long level, by adjusting the height of the tripods, and in side view by changing the forward angle on the tripods. The camera was fixed on the rail, so only sideward movement was possible. The digital camera was moved along a guide rail and at small intervals (1 cm in forest plots and 5 cm in herbaceous plots) a photograph was taken. In this research a Canon PowerShot 520A was used, where the exposure could be set manually. The photographs of the forest plots were slightly underexposed, because the shutter time had to be larger than \( \frac{1}{15} \) to ensure sharp images. The herb plots were set at a good exposure. The aperture was set as large as possible, to maximize the depth of view.

The shutter time and aperture were set manually, so all photographs had equal exposure. Three calibration photographs were made of the surveyors beacon: left, right and in the centre of the plot.
5.2. The parallel photographic method

to calculate the number of pixels represented by the sliding distance. The parallel photographs were
taken by sliding the camera over the rail from left to right, with fixed intervals: every 5 cm for forest
plots and 1 cm for herbaceous plots. The forward tilt was checked at each photograph using the small
level and corrected if necessary. Most plots were measured with the camera at a small opening angle
(±12° i.e. fully zoomed in). The resolution was set at 2272x1704 pixels. To study the effect of the
resolution, some plots were also measured with a larger opening angle (±46° i.e. zoomed out), and
different resolutions were applied. For every forest plots about 100 pictures were taken, for herbaceous
plots about 200. The photographs were transferred to the laptop, after each plot, to avoid remounting
the camera during the measurement.

For comparison, the centrally projected method (Ritzen and Straatsma, 2002), was also applied
to plots (section 3.4). The same field setup, without the guide rail was used and 8 photographs were
taken at the same distance and height as the PP method. The zoom was fixed and the whole plot was
visible at each photograph.

5.2.2 Creation of a parallel photo mosaic

The centre columns of the plot photographs were merged, to create a parallel projected photo mosaic
of the plot. This was done by calculating the number of columns (w) in pixels representing the sliding
interval over the guide rail (figure 5.3). The equation used to calculate the width value is:

\[ w = \frac{ppm \cdot d}{x_{res}} \]  
(5.1)

where \( ppm = \frac{x_{res}}{2D_p \cdot \tan \frac{1}{2} \alpha} \)  
(5.2)

and \( \alpha = 2 \arctan \frac{\frac{1}{2} ccd}{f} \)  
(5.3)

where \( ppm \) is the number of pixels per meter (pix \cdot m^{-1}), \( d \) is the horizontal sliding distance (m), \( x_{res} \)
is the resolution along the x–axis of the photograph (2272), \( D_p \) is the distance from the camera to the
screen (m), \( \alpha \) is the opening angle, which depended on the zoom, \( ccd \) is the horizontal size of the sensor
recording the picture (5.69 mm) and \( f \) is the focal length of the lens (23.2 mm, with zoom and 5.8 mm
without zoom). These values were derived from the manual of the camera.

This calculation assumes that a pixel in the centre of the picture represents an equally large
surface area as a pixel at the side of the photograph. Because only the centre columns of the photographs
were taken, overestimation of the surface area is avoided. Furthermore, the number of centre columns
depend on the zoom, resolution and sliding interval. The only parameter measured in the field in
this calculation is the distance from the camera to the screen. The calculated number of columns
were consistent with the measured number of columns using the surveyors beacon. For zoomed in
photographs, with a horizontal resolution of 2272 pixels, the number of pixels per meter ranged between
550 and 9850 pix \cdot m^{-1}. The resolution for the photographs with a large opening angle was lower,
between 365 and 1400 pix \cdot m^{-1}, depending on the plot length.

The calculated number of columns were clipped out of the original pictures and merged together.
This was done using a script, written in the Python programming language. The flowchart and the script
are presented in appendix B.1.
5.3 Data analysis

The vegetation density \(D_{vp} \) was calculated from the parallel photo mosaic by:

\[
D_{vp} = -\frac{1}{L} \cdot \ln (1 - A_{tot})
\]

(5.4)

where \( A_{tot} \) is the fractional coverage of the screen by vegetation and \( L \) is the plot length. This equation is similar to the description of vegetation density by MacArthur and MacArthur (1961) and Aber (1979) (equation 3.3 and 3.4). The term \( \frac{1}{L} \) was included to make \( D_{vp} \) independent of the plot length.

5.3.1 Intensity thresholding

To determine the fractional coverage of the screen by the vegetation a threshold operation was applied, based on the intensity histogram of the mosaic. The mosaic was converted from full color to a binary image, where vegetation pixels were set to black, and screen pixels were set to white. The threshold was set manually, based on the intensity histogram. Shadows on the screen and the effect of mixed pixels (partly screen and partly vegetation) caused overlap in intensity values between the two classes. The percentage of black pixels was calculated and yielded the fractional coverage. A GNU Image Manipulation Program The Gimp 2.2 (2006) (www.gimp.org) was used to perform the thresholding. The beginning of the second peak in the intensity histogram proved a visually correct threshold value (figure 5.4(a)).

5.3.2 Hue thresholding

For herb vegetation a red screen was used as background, to increase the contrast between screen and vegetation. However, the discrimination between screen and vegetation by intensity thresholding resulted in high uncertainties, because the red screen and green vegetation had similar intensities. Therefore, the RGB (Red, Green, Blue) picture was converted to HSV (Hue, Saturation, Value). The hue value represents the color type as a value between 0 and 360 degrees (figure 5.5), where red has a value of zero. Subsequently, the threshold was applied on the hue value. Shadow and light intensity have little influence on the discrimination (Lillesand et al., 2004). Besides that the hue value was a better discriminator for herb vegetation, another advantage was that the threshold value was equal for each plot because the screen had a fixed color. The threshold values were determined for a single plot and

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5.3. Data analysis

Figure 5.4: A histogram of the intensity of the mosaic of a forest plot and a hue histogram of the mosaic of a herbaceous plot. The threshold value was based on these histograms subsequently applied to all other plots. The histogram of the hue is presented in figure 5.4(b) and the threshold values are drawn in figure 5.5. The histogram and the HSV circle show that the screen area is set from 300° to 15°, where 15° is the border between red and orange.

Figure 5.5: Hue, saturation, value circle, where the hue (H) is presented as the circle from 0 to 360 degrees, the saturation (S) ranges from full color to gray and the value or intensity (V) ranges from black to white.

The medical image processing and visualization program MeVisLab (2006) was used to convert the RGB images to HSV and calculate the fractional coverage. A trial version can be downloaded from www.mevislab.de. This program has build-in modules for HSV conversion, thresholding and coverage calculation. In MeVisLab, the procedure can be automated. $D_{vpp}$ was computed using Excel, with the
5.3. Data analysis

coverage values from MeVisLab as described above. The flowchart of the procedure is presented in appendix B.1. Figure 5.2 shows the approach used for the PP method in an overview.

5.3.3 Comparison to the reference data

The vegetation densities, measured by the reference data \( (D_{vN}) \) were compared to \( D_{vPP} \) using scatter plots. In this study, regression analysis was used between the measurement methods. \( R^2 \) is a measure for the amount of explained variance, and expresses the strength of the relation acquired by regression analysis. Subsequently, a student’s t-test was applied to test if the slope of the regression line was significantly different from 1. To test if the within-subject variation depended on the vegetation density, the residuals (i.e. reference minus predictor) were plotted against the reference. Furthermore, the standard error (SE) of the residuals was calculated.
Chapter 6

Results of the photographic methods

In this chapter, the results from the field measurements using the parallel and centrally projected (CP) photographic methods are presented. At first instance, the methods were validated, subsequently, the PP method was applied to plots with different vegetation types, in summer and winter.

6.1 Validation of the photographic methods

6.1.1 Central projected method

Figure 6.1(a) shows the scatter plot of the selected validation plots, measured by the CP method. The reference values were plotted on the vertical axis and the $Dv_{CP}$ on the horizontal axis. Only 11 out of the 17 validation plots, were measured by the CP method. The $y = x$ line is shown in red, in the figure. The $Dv$ ranges from $0.014 \text{ m}^{-1}$ for open forest to $0.12 \text{ m}^{-1}$ for dense parts of the forest and the $Dv_{CP}$ increases linearly with the reference data. This figure shows that linear regression explained a reasonably large part of the variance ($R^2 = 0.87$). The regression equation and the standard error of the signed residuals to the $y = x$ line are presented in table 6.1.2.

The signed residuals of $Dv_{CP}$ to the line of identity are plotted in figure 6.1(b). The negative residuals in the scatter plot of the residuals show that the $Dv_{CP}$ was overestimated. The overestimation can be explained by the increased projection of the trees on the screen (figure 3.1). No relation was present between the errors of the $Dv_{CP}$ and the vegetation density. The $Dv_{CP}$ shows a reasonably large scatter, with a maximal deviation of $0.025 \text{ m}^{-1}$. Few measurements of dense forest, with $Dv_{Nd}$ values above $0.07 \text{ m}^{-1}$ are present. This can be explained by a, generally, increasing complexity with increasing density. Therefore, these plots could not be used for validation purposes.

6.1.2 Parallel projected method

The scatter plot of the validation of the PP method is presented in figure 6.2(a). The range of the $Dv_{PP}$ values was similar to the $Dv_{CP}$, and the $Dv_{PP}$ increased linearly with the manually measured data. The PP method proved well able to predict vegetation density of floodplain forest: the linear regression model with a zero intercept, explains 99.6 percent of the variance. The regression function is given by:

$$Dv_{Nd} = 1.0059 \cdot Dv_{PP} \quad (n = 17, R^2 = 0.996, SE = 3.7 \cdot 10^{-3})$$ (6.1)
6.1. Validation of the photographic methods

Figure 6.1: Scatter plots of the validation of the centrally projected photographic method

Figure 6.2(b) shows the residuals of the $Dv_{PP}$. The maximal absolute error was 0.008 m$^{-1}$, which was smaller than for the $Dv_{CP}$. The residual standard error decreased from 0.010 for the CP method to 0.0037 for the PP method. The residuals of the $Dv_{PP}$ are scattered around the $y = 0$ line, indicating that both methods are highly comparable. A Students t–test, on the regression line, proved that the slope of the regression model did not significantly differ from 1, at the 99.9 percent confidence interval.

To test the performance of the PP method, for 5 plots, the manually measured diameters at breast height of all the trees in a plot were compared to the diameters reconstructed from the parallel projected photo mosaic. This comparison was done for the validation plots where no occlusion occurred. Reconstructing the diameters of a measured tree was done by making a map of the plot in the field, numbering all individual trees and measuring their diameters. The numbered trees on the map were recognized on the photo mosaic, and the diameter, in pixels, was measured in an image manipulation program. Subsequently, the measured diameters were also converted to pixels using the width value (section 5.2.2).

The manually measured diameters were compared to the reconstructed values (figure 6.2(c)). It shows that the projected tree size agrees with the measured diameter of the trees. The linear regression model explained 97 percent of the variance. The figure of the signed residuals of the calculated diameters (figure 6.2(d)) shows a decreasing error with an increasing size of the trees in pixels. This is caused by uncertainties in the diameter reconstruction, due to mixed pixels and errors in the number of clipped centre columns. Mixed pixels occurred at the edges of the trees. When a mixed pixel was dominated by screen, the reconstructed diameter was smaller than the measured diameter. Similarly, when a mixed pixel was dominated by vegetation the diameter was overestimated. The effect of the error in the number of clipped centre columns was caused by rounding of the number of centre columns to a whole number. This also caused over– or underestimation. Both effects caused random errors in the reconstructed diameters. The errors were larger for smaller trees. These effects had a limited effect on the measurement method. The sensitivity of the clipped number of centre columns will be discussed further in chapter 7.

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6.1. Validation of the photographic methods

(a) Performance of the PP method in the validation plots

(b) Signed residuals of the PP method to the $y = x$ line

(c) Measured diameters versus the calculated diameters, based on the parallel projected photo mosaics in numbers of pixels

(d) Residuals of the measured and calculated diameters

Figure 6.2: Scatter plots of the validation of the PP method and the measured and calculated diameters

Table 6.1: Statistical expressions for the validation of the photographic methods, with the regression equations, explained variance ($R^2$) and residual standard error (SE)

<table>
<thead>
<tr>
<th>Regression equation</th>
<th>$R^2$</th>
<th>$SE$</th>
<th>sample size ($n$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP method</td>
<td>$D_{VNd} = 0.89 \cdot D_{VCP}$</td>
<td>0.871</td>
<td>$1.0 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>CP residuals</td>
<td>$Err_{CP} = 0.15 \cdot D_{VNd} - 0.014$</td>
<td>0.21</td>
<td>$9.1 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>PP method</td>
<td>$D_{VNd} = 1.0059 \cdot D_{VPP}$</td>
<td>0.996</td>
<td>$3.8 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>PP residuals</td>
<td>$Err_{PP} = 0.04 \cdot D_{VNd} - 0.002$</td>
<td>0.08</td>
<td>$3.7 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>diameters</td>
<td>$d_{measured} = 0.998 \cdot d_{calculated}$</td>
<td>0.97</td>
<td>1.1</td>
</tr>
</tbody>
</table>

6.1.3 Conclusions of the validation

It was proved that the PP predicted the vegetation density of the validation plots very well up to vegetation densities of 0.12 $m^{-1}$. The PP method was an improvement over the centrally projected photographic method. For forest plots without side branches, the PP method performs equally well as the manual method for cylindrical vegetation. The PP method, however, is independent of the assumptions underlying the manual method (section 2.4). Therefore, the PP method will be used as a measurement
6.2. Application of the parallel photographic method on complex vegetation

6.2 Application of the parallel photographic method on complex vegetation

To test the applicability of the PP method on more complex vegetation structures, the method was used to measure a wide range of vegetation types in the Gamerensche Waard and Duursche Waarden floodplains. Because the PP is a better estimator for the vegetation density of complex vegetation than the manual method, the $D_{v_{pp}}$ was considered as reference data. The results are presented in figure 6.3, where the $D_{v_{n,d}}$ is plotted on the horizontal axis and the $D_{v_{pp}}$ on the vertical axis. The regression equations and statistical coefficients are presented in table 6.2.2.

6.2.1 Variations in vegetation types and measurement technique

The results of the application of the PP method were categorized based on vegetation type and variations in the measurement method. The selected categories were: (1) forest and shrub plots with more than 10 side branches and leaves, (2) plots with herbaceous vegetation, measured with a small opening angle, (3) plots with herbaceous vegetation, where reference data was measured at 15 cm above ground level and (4) plots with herbaceous vegetation, measured with a large opening angle. Figure 6.3 shows the parallel photo mosaics and thresholded images of these measurements.

Leaved forest plots

The scatter plot of the forest plots, which were not appropriate for validation, because many side branches or leaves were present, are shown in figure 6.4(a). These plots were measured using the white screen as background and the photographs were taken at breast height. The range of $D_{v_{pp}}$ values was large, for these plots, compared to the validation plots, with $D_{v_{pp}}$ values up to 0.23 m$^{-1}$. The $D_{v_{n,d}}$ values, however, had the same range as the validation plots. The $R^2$ value decreased from 0.996, for the leafless validation plots to 0.62 for leaved forest plots. The residual standard error increased from $3.7 \cdot 10^{-3}$ to $3.8 \cdot 10^{-2}$, accordingly.

The $D_{v_{n,d}}$ of leaved forest plots shows an underestimation, compared to the $D_{v_{pp}}$ and a large scatter is visible in the figure. The underestimation was confirmed by the slope of the regression line of the residuals (figure 6.4(d)), which was significantly different from zero at the 99.8 confidence interval. The scatter plot of the residuals showed an increasing underestimation of the density as measured using the $D_{v_{n,d}}$. This was caused by the increasing presence of side branches and leaves with stem density. The side branches and leaves were not measured by the manual method, but were included in the $D_{v_{pp}}$ measurement.

Herbaceous vegetation plots

The second category of measurements consisted of the herbaceous plots, where the manual method was applied at the photo height (figure 5.2). Figure 6.4(c) shows the scatter plot of the resulting $D_{v_{pp}}$ values.
Figure 6.3: Categories of the applications of the PP method for different vegetation types and variations in the measurement technique. The parallel photo mosaics are shown at the right side, the thresholded images, on the left side. For the herbaceous vegetation, the pixels classified as background are shown in blue, for forest vegetation in white. From top to bottom: (a) forest plots used for validation, (c) forest plot with leaves, (e) herbaceous vegetation, measured with a small opening and (g) herbaceous vegetation, measured with a large opening angle.
The $D_{v_{pp}}$ of the herb plots was more than 15 times larger than for forest validation plots, ranging from 0.7 $m^{-1}$ to 2.0 $m^{-1}$. A considerable fraction of the coverage consisted of leaves (figure 6.3).

The comparison of the $D_{v_{pp}}$ and the $D_{v_{Nd}}$ (figure 6.4(c)), showed a bad correspondence with the $y = x$ line. When the residuals were taken into account, an average underestimation of 0.78 was visible. This underestimation was independent of the value of the $D_{v_{pp}}$. The residual standard error was quite large (0.14) for a sample size of 9 measurements. The underestimation was caused by the abundance of leaves and side branches in the plots.

### Lower layer of the herbaceous plots

Initially the $D_{v_{Nd}}$ method was measured at 15 $cm$ above ground level, instead of at the photo height. To compare the photographic results with the $D_{v_{Nd}}$, this layer was selected out of the parallel projected photo mosaic. The surveyor’s beacon, which is present on each photograph, was used to select layer at the correct height. The selected layer had a height of 20 $cm$ from 5 to 25 $cm$ above ground level.

These lower layers showed very large $D_{v_{pp}}$ values up to 6.2 $m^{-1}$. The coverages of the screen by vegetation were close to 100 percent. The scatter plot (figure 6.4(e)) shows a large deviation of the line of identity and a trend of increasing underestimation with increasing density. The regression line has a slope of 4.3, which means that the $D_{v_{Nd}}$ is at least 4 times larger than the $D_{v_{pp}}$.

### Plots measured with a large opening angle

The last variation in the measurement method contained the plots which were measured with the camera set at a large opening angle. This resulted in mosaics covering the vegetation from the ground surface to the top of the vegetation. Figure 6.3(g) shows that the range of the $D_{v_{pp}}$ values between the top of the vegetation and the lower layer is large. The $D_{v_{pp}}$ values calculated from these mosaics are averaged over the vegetation height. The averaged $D_{v_{pp}}$ values are compared to the $D_{v_{Nd}}$, measured at the half vegetation height. The $D_{v_{pp}}$ values are presented in figure 6.4(f). As expected, this resulted in a bad correspondence to the $y = x$ line and only 13 percent of the variance was explained by the regression line. The figure shows that the $D_{v_{Nd}}$ underestimated the vertically averaged $D_{v_{pp}}$ of the herbaceous plots.

### 6.2.2 Vegetation measured under winter conditions

To test the application of the PP method under winter conditions 5 plots were duplex measured. This small sample resulted from the flooding of the floodplains at high discharges, which occur frequently in winter and limited the area for research. During this fieldwork in the winter 90 % of the herb plots measured in the summer were flooded. Furthermore, parts of the floodplains were mowed, therefore, most plot measured in summer could not be measured again in winter. The 5 remaining plots were vegetation test areas in the DW, used for a different research, and were therefore not mowed. The duplex measured plots belong to the species rich herbaceous vegetation type. Under winter conditions the dewberry (Rubus caesius), was the dominant species in the plot.

The scatter plot of the winter measurements is presented in figure 6.5(a). It can be seen that the range of $D_{v_{pp}}$ values was smaller under winter conditions, with a maximum of 0.91 $m^{-1}$, than in summer, when the maximum $D_{v_{pp}}$ value was 2.9 $m^{-1}$ for the same plot. The explanation of the variance by the regression equation is 0.88, but it must be noted that this value is biased, because the sample size
Figure 6.4: Scatter plots of the application of PP on (a) leaved forest plots, (c) plots consisting of herbaceous vegetation, measured at the half vegetation height with a small opening angle, (e) herbaceous plots measured at 15 cm above ground level, with a small opening angle, and (f) herbaceous plots measured at the half vegetation height, with a large opening angle, resulting in vertically averaged \( D_{VPP} \) values.
is small. The point with the highest $D_{vpp}$ value shows an underestimation, while the other points are located closer to the line of identity. A possible explanation is that, generally, at higher vegetation densities, more side branches are present and, therefore, the underestimation of the $D_{vN}$ increases with increasing vegetation density. Only a single measurement of relative dense vegetation was done under winter conditions, so no trend can be seen.

The comparison between the $D_{vpp}$ measured under summer and winter conditions is presented in figure 6.5(b). It can be seen that the summer measurements show a large overestimation. Regression analysis showed no significant relation with the $y = x$ line, between summer and winter measurements ($p = 0.13$), but no conclusions can be deducted from these measurements, because of the low sample size.

Figure 6.5: Scatter plots of the application of the parallel photographic method on complex vegetation structures

Table 6.2: Statistical expressions for the application of the PP, with regression equations, explained variance ($R^2$) and the residual standard error ($S E$). The expression with a “⋆” were unreliable, because of the small sample size. They were strongly influenced by a single measurement (figure 6.5)

<table>
<thead>
<tr>
<th>Regression equation</th>
<th>$R^2$</th>
<th>$S E$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leaved forest</td>
<td>$D_{vPP,leaved} = 1.27 \cdot D_{vN} + 0.020$</td>
<td>0.64</td>
<td>$2.4 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>Leaved forest residuals</td>
<td>$Residual = 0.50 \cdot D_{vPP,leaved} - 0.017$</td>
<td>0.63</td>
<td>$3.8 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>Herbs</td>
<td>$D_{vPP,herbs} = 0.89 \cdot D_{vN} + 0.81$</td>
<td>0.83</td>
<td>0.15</td>
</tr>
<tr>
<td>Herbs residuals</td>
<td>$Residual = 0.064 \cdot D_{vPP,herbs} + 0.68$</td>
<td>0.02</td>
<td>0.14</td>
</tr>
<tr>
<td>Lower layer</td>
<td>$D_{vPP,lower} = 4.3 \cdot D_{vN} + 0.23$</td>
<td>0.77</td>
<td>0.19</td>
</tr>
<tr>
<td>Vertically averaged</td>
<td>$D_{vPP,vertical} = 1.5 \cdot D_{vN} + 0.54$</td>
<td>0.13</td>
<td>0.22</td>
</tr>
<tr>
<td>Winter conditions</td>
<td>$D_{vN} = 0.60 \cdot D_{vPP,winter} + 0.081$</td>
<td>0.98*</td>
<td>$3.7 \cdot 10^{-2}$*</td>
</tr>
<tr>
<td>Summer – winter</td>
<td>$D_{vPP,winter} = 0.46 \cdot D_{vPP,summer} - 0.53$</td>
<td>0.88*</td>
<td>0.16*</td>
</tr>
</tbody>
</table>
6.2.3 Time requirements

To assess the applicability of the PP in the field, the time required in the field is an important factor. Therefore, the time needed to measure a single plot was recorded (table 6.3). In the field, a screen and guide rail were placed in the vegetation, the photo camera was mounted on the rail and levelled and between 100 and 200 photographs were taken. For one person, it took about 20 minutes to measure a single plot, depending on the number of photographs and the processing speed of the camera and laptop. The conversion from the individual photographs to a parallel photograph took approximately 2 minutes using Python. Setting a threshold and calculating the vegetation density, took another 2 minutes for each parallel photograph. In future studies the data analysis can be fully automated, except the thresholding of the intensity value.

<table>
<thead>
<tr>
<th>Action</th>
<th>Time (minutes)</th>
<th>Depends on</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setup screen</td>
<td>5</td>
<td>weather</td>
</tr>
<tr>
<td>Setup frame</td>
<td>5</td>
<td>experience</td>
</tr>
<tr>
<td>Making photographs</td>
<td>5 – 15</td>
<td>number of photographs</td>
</tr>
<tr>
<td>Transfer photographs to laptop</td>
<td>5</td>
<td>processing speed</td>
</tr>
<tr>
<td>Data analysis</td>
<td>4</td>
<td>level of automation</td>
</tr>
<tr>
<td>Total</td>
<td>29</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.3: Field time required for the PP method
Chapter 7

Accuracy and objectivity of the parallel photographic method

The results indicate that the parallel photographic method is an improvement over the central photographic method and the manual method. The $D_{vPP}$ values matched the $D_{vN\bar{d}}$ values for the validation plots and showed consistent results on vegetation with a more complex structure. There are, however, several factors, which influence the prediction of the $D_{vPP}$ and determine the quality of the method. These will be discussed in this chapter.

7.1 Notes on the field technique

7.1.1 Quality of the reference data

The reference data for the validation of the PP method was collected using the manual method. The diameter was measured using a sliding gauge for thin stems. For thicker stems the circumference was measured using a measuring tape and the diameter was computed. These measurement instruments had a high accuracy. The assumption underlying the reference data was that the measured stems were cylindrical. Because the assumption of cylindrical stems was never strictly true, the decision of the height where the diameters were measured influenced the $D_{vN\bar{d}}$. The measurement height had a variation of 10 cm, because the breast height was estimated visually and small difference in ground elevation were present. The error in the height of the diameter measurement was random and averaged out over the plot. This can result in an uncertainty in the vegetation density of about 5 percent, when few trees are present in the plot.

For herb plots, the average diameter was measured from 30 randomly selected stems. The surveyor was always inclined to take the conspicuous stems and forget the very small grass blades. This behavior depends on the characteristics of the plot and caused large uncertainties in the $D_{vN\bar{d}}$. Because the results for a single plot are different for every surveyor, the effect is averaged out when more observers are conducting the measurements. In this research, 95% of the measurements were carried out by the same observer. The method, therefore, had a high degree of subjectivity and a low accuracy. The second error in the $D_{vN\bar{d}}$ measurement is caused by errors in the counted number of stems. Errors in the number of stems may cause substantial errors in the $D_{vN\bar{d}}$. To minimize the error of the number of stems, all stems above the photo height in the photographed area were counted. This area can be larger...
than \( \pm 1 \ m^2 \), containing several hundreds of stems. Therefore, errors in the counted number of stems easily occur. Finally, the error in the measured surface area introduced an error in the average stem density.

The mapping of the vegetation type for each plot was done visually, using the vegetation manual (Van Velzen et al., 2003a). The vegetation types, sort rich herb vegetation, creeping thistle, stinging nettle and natural grasslands are overlapping and the decision when a plant type was dominant was arbitrary and made this mapping subjective. The recorded vegetation types per plot are presented in appendix C.2.

### 7.1.2 Measurement time in the field

The time required in the field to measure a plot using the PP method was about 25 minutes, which is long compared to the time needed for the CP method, which can be carried out between 5 and 15 minutes (Ritzen and Straatsma, 2002). The time needed for the data analysis in this research (4 minutes), however, was less than the time indication mentioned by Ritzen and Straatsma (2002) (\( \pm 15 \) minutes, based on 8 photographs per plot), due to a high level of automation. The time needed to measure the vegetation density using the manual method depended on the complexity of the vegetation. Measuring the diameters of 30 stems using a sliding gauge took 5 minutes. Subsequently, the number of stems in the plot must be determined. For simple vegetation (< 30 stems) the value was known from the diameter measurement, but for grass vegetation this took up to 30 minutes.

Table 7.1: Time needed to measure the \( Dv \) using the PP method compared to the CP method and the manual method

<table>
<thead>
<tr>
<th>Action</th>
<th>PP time</th>
<th>CP time</th>
<th>( Nd ) time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setup screen</td>
<td>5 min</td>
<td>5 – 20 min</td>
<td>–</td>
</tr>
<tr>
<td>Setup frame</td>
<td>5 min</td>
<td>–</td>
<td>measuring ( \bar{d} ) of 30 stems: 5 min</td>
</tr>
<tr>
<td>Making photographs</td>
<td>5 – 15 min</td>
<td>( \pm 1 ) min</td>
<td>counting all stems in plot: 1 – 30 min</td>
</tr>
<tr>
<td>Transfer photographs to laptop</td>
<td>5 min</td>
<td>200 per 5 min</td>
<td>–</td>
</tr>
<tr>
<td>Data analysis</td>
<td>4</td>
<td>15</td>
<td>calc average diameter: 5 –15 min</td>
</tr>
<tr>
<td>Total</td>
<td>29 min</td>
<td>29 min</td>
<td>between 10 and 60 min</td>
</tr>
</tbody>
</table>

### 7.1.3 Field equipment

The amount of material needed in the field for the PP method was large compared to the CP and the manual method. At least two persons were needed to carry all equipment. The time needed for relocation between plot locations can, therefore, be significant. For that reason, a hand chart was used for transporting the equipment, but this reduced the accessibility in dense vegetation.

The levelling process of the guide rail was most important in the setup of the equipment in the field (section 5.2.1). The levelling consisted of (1) horizontal levelling of the guide rail, (2) tilt (i.e. the horizontal direction of the camera axis) and (3) rotation round the vertical axis (figure 7.1.3). Disturbances in the levelling can be constant during the measurement or variable.
7.1. Notes on the field technique

A constant error in the rotation or tilt of the camera results in a not perpendicular or horizontal camera axis. Both effects cause an overestimation of the plot length and, therefore, an overestimation of the \( D_{VPP} \). When a constant error in the horizontal level of the guide rail is present the mosaic shows skewed vegetation, but this has no effect on the \( D_{VPP} \). Errors in tilt and horizontal level, however, cause the \( D_{VPP} \) to be measured at a different height as the reference data. Variable errors in horizontal levelling, tilt and rotation cause disturbances of the resulting mosaic. The left side of figure 7.2(a) shows a distorted parallel photograph, while the parallel photograph on the right side has no distortions. These distortions cause a random error, because too much vegetation or screen is present on the mosaic. Therefore, variable errors in levelling of the guide rail probably have little influence on the accuracy of the \( D_{VPP} \).

\[ \text{Figure 7.1: Sources of errors in levelling of the guide rail} \]

The two tripods used to support the guide rail had a minimum height of 50 cm. This height was limiting, when measuring vegetation less than 1 m high. Two grass plots were measured using improvised support, the photographs were taken at 15 cm above ground level. Because the improvised support lacked stability, only two plots were measured. In future studies, extra support is needed or the tripods need to be adapted, when low vegetation is measured.

The white screen used as background must be clean. During the intensity thresholding, dirty spots are classified as vegetation. This causes an overestimation of the vegetation density. Measurements with the red screen were less sensitive to dirty spots, because the thresholding was done on hue instead of intensity. Very dark mud spots might influence the hue thresholding, but this did not occur during this research.

7.1.4 Influence of weather conditions

Besides the distortions caused by inaccurate levelling of the frame, considerable distortions of the mosaics were caused by moving of the stems due to wind. The movements had the result that the same stem was present or absent multiple times on the photo mosaic (figure 7.2(a)). The distortions by the wind had a random effect, which should not bias the \( D_{VPP} \).

Spatial differences in illumination

Spatial differences in illumination of the vegetation caused several problems. The first problem was caused by shadows of the vegetation on the screen, which have a lower intensity, than the screen.
7.1. Notes on the field technique

(a) A distorted photo mosaic due to wind or levelling errors. The arrows indicate the same leaf or stem shows up multiple times

(b) Example of a photo mosaic without distortions

(c) Hue image where the sun is shining through the screen

(d) Differences in illumination for each image

Figure 7.2: Example of distortions of the mosaic and differences in illumination

Shadows have the same effect as the above described dirty spots. To reduce the shadow effect and increase the contrast between vegetation and background the photographs were taken against the sun following Ritzen and Straatsma (2002). This problem can be solved by using a colored background for forest plots and apply the threshold on hue. In very dark forests, the hue calculation, however, can become problematic due to underexposure.

Secondly, in forests the leaves were partly illuminated, while the stems were in the shadow. This resulted in a decreased contrast between the leaves and the background and caused problems in the intensity thresholding. The illuminated leaves had an intensity value, between screen and vegetation. Consequently, the leaves were partly classified as screen and a partly as vegetation. This resulted in large uncertainties and an underestimation of the vegetation density. Furthermore, the intensity histogram was less bimodal, making it more difficult to visually determine the threshold.

The last problem occurred for herbaceous vegetation, when the sun was shining through the screen, resulting in overexposure. These highly overexposed areas on the mosaics caused problems in the hue thresholding (figure 7.2(c)). The bright, overexposed parts of the screen had a hue value representing a blue or purple color. This made thresholding using a fixed value unreliable, because only red parts were selected. A lightweight collapsible board can reduce over-illumination and will also reduce the shadow effect.
Temporal differences in illumination

During the measurements in dense forests, little light was available. The shutter time, however, must be larger than $\frac{1}{15}$ to prevent blurred photographs. This resulted in underexposure of the photographs, so only low intensity values were measured, thereby reducing the contrast. The influence on the resulting $Dv_{pp}$ was limited, because in most cases a good separation between screen and vegetation could be made. The accuracy, however, decreased, because the discriminating power was lower when the range of the available intensity values was reduced (figure 7.5(c)).

The pictures of the vegetation of a plot were taken over a 5 minute period, which caused differences in illumination between the different photographs of the mosaic (figure 7.2(d)). The aperture and shutter time of the camera were set manually, so these could not vary between the different photographs. The differences in illumination caused, however, severe under- and overexposure on the different slides. These differences caused difficulties on the intensity thresholding, but had no effect on the hue thresholding.

7.1.5 Disturbances of the vegetation

The creation of the plot was done by removing or flattening the vegetation in front of the plot and placing a screen behind it. The stems of the herbaceous vegetation were leaning onto each other and the removal of the vegetation caused adjacent stems to fall, and partly or not be recorded on the photographs. This distortion resulted in an underestimation of the $Dv_{pp}$ and had a large influence on small plots, and in dense vegetation. The disturbances were enhanced by plants like the great bind weed (Calystegia sepium), which was braided through the vegetation. A possible solution is to use a frame to delineate the vegetation plot.

7.2 Notes on the data analysis

7.2.1 Number of clipped centre columns

The number of centre columns ($w$) was used for creating the photo mosaic. $w$ was determined by the camera type, the resolution of the photograph, the opening angle of the camera and the distance from the camera to the screen.

The sensitivity of the $Dv_{pp}$ for an error in $w$, resulting from a 5 cm error in the measured distance to the screen, is presented in figure 7.3(a). This simulation was done to study the effect of the error in the measured distance from camera to screen, which was used to calculate the width value. Figure 7.3(a) shows that the relative error in the $Dv_{pp}$, resulting from a 5 cm error in the measured distance to the screen, increased exponentially with decreasing distance to the screen. The error was below 1 percent, for distances longer than 2 m. With a small opening angle, the error was smaller than 0.1 percent for distances larger than 0.5 m. Most plots were measured with a distance larger than 2 m and the influence on $Dv_{pp}$ are, therefore, limited. For plots with low vegetation, the distance from camera to the screen was about 1 m. In this case, a 5 cm error in the distance between camera and screen results in an error of 1.5 percent on $Dv_{pp}$, when a large opening angle is used. Therefore, this error is only of interest for the measurement of low vegetation, measured from very close range, with a large opening angle.

The sensitivity of the $Dv_{pp}$ for $w$ was tested for one plot with shrub vegetation. $w$ was varied
7.2 Notes on the data analysis

(a) Relative error of $D_{vPP}$ for an error in $w$, resulting from an error of 5 cm in the distance between camera and screen.

(b) Sensitivity of the fractional coverage to variations in $w$

Figure 7.3: Scatter plots of the sensitivity of $D_{vPP}$ to the number of centre columns ($w$)

between 6 and 48 pixels, with a correct value of 12 pixels. Three examples are shown in figure 7.4. Figure 7.3(b) shows the results of this test. The horizontal axis shows the variation in width values and the vertical axis shows the resulting variation in $D_{vPP}$ values. The accuracy of the measurements decreases when the $w$ is overestimated. The effect was random, but causes scatter. The error in the $D_{vPP}$ was smaller than 3 percent, resulting from the errors in the fractional coverage. This can be explained by the fact that increasing deviations of the correct $w$ resulted in increasing overlapping areas. Because the centre columns are overlapping, the same tree was included multiple times in the coverage calculation. This effect is visible in figure 7.4 (c), the vague image results from showing every branch multiple times next to each other. When branches show up multiple times the resulting fractional coverage will be overestimated. On the contrary, in the same way, screen parts were included multiple times, causing underestimation. Overestimation and underestimation occurred randomly, because the ratio between branches or screen areas varied. Due to the random behavior and the small error, the $D_{vPP}$ was not sensitive to a correct number of centre columns, but large errors in $w$ may cause uncertainties. Furthermore, when the $w$ value becomes too large, the problems of the central projection will occur. In this test, four times the correct $w$ did not result in significant overestimation of the $D_{vPP}$.

7.2.2 Thresholding

The crucial step in the calculation of the vegetation density was the process of thresholding (section 5.3). For forest plots this was done based on the intensity value of the pixels, for herb plots the hue value was used. The intensity value depended on the exposure of the photographs and was different for each measurement. Therefore, the thresholding was a manual procedure, which caused the method to have a certain degree of subjectivity. The decision of the threshold value was based on the shape of the histogram (figure 7.5). The error of the thresholding depended on the contrast of the parallel photograph and, therefore, on the quality of the original pictures. The error lies approximately between 0.5 % for strongly bimodal pictures and ±10 % for weakly bimodal pictures. Figure 7.5 shows the intensity histograms of a plot with high contrast between screen and vegetation, a plot with illuminated leaves and stems, resulting in little contrast and an underexposed picture.

The thresholding of the hue value was not sensitive to the intensity of the image. When the in-
7.3 Parameters determining the accuracy of the vegetation density

The vegetation density was calculated using equation 5.4. Besides the fractional coverage of the screen, the length of the plot was the other parameter in this calculation.

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7.3. Parameters determining the accuracy of the vegetation density

Figure 7.5: Three intensity histograms, where the shaded parts are classified as vegetation. The intensity is shown along the horizontal axis ranging between 0 and 255. The number of pixels are shown along the vertical axis.

7.3.1 Plot length

The length of the plot was measured in the field and had an error of about 2 cm for small herb plots and 10 cm for forest plots. Figure 7.6(a) shows the results of the sensitivity analysis of the $D_{vpp}$ value for errors in the plot length of 2, 5 and 10 cm. The absolute plot length is shown on the horizontal axis and the resulting relative error in the $D_{vpp}$ value on the vertical axis. For forest plots, the plot length was more than 5 m, resulting in an maximal error in the $D_{vpp}$ of 1 percent. For herb plots the plot length was smaller (0.5 m), but the measurement error of the plot length was about 2 cm, resulting in an error of 2 percent in $D_{vpp}$. Errors of 2, 5 or 10 cm in the measured distance of the plot length, result in increasingly large errors in the estimate of $D_{vpp}$. Figure 7.6(a) shows that the measurement error for small plot lengths is an important parameter. When the error in $D_{vpp}$ was expressed as a percentage of the plot length, then it appears that a a 12 percent error in plot length resulted in a 10 percent error in $D_{vpp}$.

Besides the measurement error, the error in the plot length was caused by the definition of the begin of the plot. The stems were not strictly aligned and the distance between the outer stems differs with the height, so a choice had to be made, where to delineate the plot. This introduced a minor degree of subjectivity in the method. This can be solved, using a frame to delineate the plot. Measuring the distance from the guide rail to the end of the frame, will reduce the error in the plot length and the subjectivity.

7.3.2 Number of photographs needed to create the mosaic

In this research the intervals between the different photographs were 5 cm for forest plots and 1 cm for herb plots, which resulted between 80 and 240 photographs for each plot. The reduction of the number of photographs taken per plot will reduce the amount of data and field time.

To study the effect of the number of photographs, $D_{vpp}$ was calculated with the photo mosaic created from different intervals between the photographs, with appropriate $w$ values. The threshold value was kept constant. Figure 7.6(b) shows the results of this simulation, where the interval between the individual photographs is plotted on the horizontal axis and the resulting $D_{vpp}$ is plotted on the vertical axis.

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7.3. Parameters determining the accuracy of the vegetation density

vertical axis. The figure shows that for herbaceous plots, the largest deviation occurred also at the largest spacings, but some variation remained at the smaller spacings. For forest plots, $D_{vPP}$ estimates become unreliable when the spacing becomes larger than 20 cm. This is the result of the more centrally projected photograph, which may cause some stems to be projected larger, and other to be missed (figure 3.1). For these plots the optimal spacing was 0.1 m for the herbaceous plot and 0.2 m for the forest plot. More photographs did not improve the accuracy. The spacing in this research of 1, and 5 cm, respectively, gave accurate results.

![Figure 7.6](image)

(a) Sensitivity for errors in plot length  
(b) Variation in the spacing (the x–axis has a log scale)

Figure 7.6: Results of the sensitivity analysis of the $D_{vPP}$ value for errors in the plot length (left) and the influence of the number of photographs and the resulting spacing on the vegetation density. The variation in the $D_{vPP}$ increased with increasing spacing.

![Figure 7.7](image)

Figure 7.7: Influence of the resolution of the original photographs on the vegetation density value.

7.3.3 Resolution of the photographs

The influence of the resolution of the photographs was studied on a single herbaceous plot. The results are presented in figure 7.7, and are based on 3 different resolutions and 2 opening angles of the camera. The simulation was done for a large and a small opening angle ($\alpha$). The photo mosaic was created from photographs of the same plot with equal intervals between the pictures. The resolutions were set at 2272x1704, 1600x1200 and 1024x768 pixels for a small $\alpha$, and 2272x1704 and 1024x768 for a large...
7.3. Parameters determining the accuracy of the vegetation density

This resulted in \( w \) values of 33, 23 and 15 pixels, for the small \( \alpha \), and 8 and 4 pixels for a large \( \alpha \). Because only 3 measurements were done with the small \( \alpha \), the resolution of the photo mosaics was reduced stepwise between the actual measurements, prior to determining the fractional coverage. The downscaling was done using a linear interpolation. This resulted in 12 extra resolutions.

Figure 7.7 shows a decrease of the vegetation density with increasing resolution. This can be explained by the effect of mixed pixels. The pixels which partly contain screen were mostly classified as vegetation. The effect of mixed pixels decreases with increasing resolution and gives a more accurate prediction of the vegetation density. Generally, the resolution has to be set at a value where the smallest, distinguishable stem must be at least 5 pixels thick. For the studied plot, a higher resolution than the maximum used resolution is recommended to acquire a better approximation of \( D_{vpp} \). Because the distance from the camera to the screen was large for this particular plot. Generally the maximum camera resolution of 2272 pixels in horizontal direction appeared sufficient in the applied sample configurations in forests and most herbaceous vegetation.
Chapter 8

Vegetation density measurement method using terrestrial laser scanning

The parallel photographic method proved to be an accurate and objective method to measure the vegetation density in the field, but lacked spatial variability. Therefore, terrestrial laser scanning (TLS) was used to test the ability to map $Dv$ of floodplain vegetation. This chapter describes the methods used to collect reference and laser data, and to extract the vegetation density from the TLS data.

8.1 Field reference data collection

The research was conducted in a forest patch in the Gamerensche Waard (section 4.1; figure 4.2). This forest was chosen for several reasons:

1. The vegetation consisted of intermediately aged, willows ($Salix alba$), with high, straight stems, which enabled the collection of reference data, using the manual method.
2. Little undergrowth and side branches were present in the forest, which could influence the predicted $Dv$. The remaining undergrowth, larger than 25 cm above ground level was removed. The absence of undergrowth and side branches made it possible to compare the TLS results with the reference data.
3. A wide range of $Dv$ values was present. The edges of the forest were dense, with $Dv$ values of 0.12 $m^{-1}$ and the centre part was more open ($Dv = 0.01 m^{-1}$).
4. The differences in the surface elevation in the forest were small, with a maximal difference of 50 cm. Therefore, a correction for ground level was not needed for every reference plot.

8.1.1 Measurement method of reference data

To register the TLS and reference data to ordnance datum, 27 wooden poles were placed around the forest (figure 8.1). The centres of these poles were marked and the coordinates were measured using differential GPS. The coordinates were measured relative to ordnance datum (RD–NAP). Georeferencing of the GPS base failed, which reduced the accuracy to 5 m. Precision was not influenced and was 2 cm.

Field reference data were collected simultaneously with the TLS data and consisted of a stem
map, containing 650 trees and covered a third of the surface area of the forest (figure 8.1). The tacheometer, Trimble 5600, with a Geodimeter System 600 control unit, was used to measure the locations of the trees. The tacheometer measured the horizontal angle, the vertical angle and the distance to a reflector using a laser beam. These values could be separately recorded. The laser beam must be aimed manually at the reflector. The location of the tacheometer was georeferenced by measuring the coordinates of at least three nearby poles. For the creation of the stem map, the tacheometer had to be set at 6 different locations, to cover all trees. Subsequently, the coordinates of the centres of all visible trees were measured. The centre of a tree was reconstructed by placing a reflector, firstly in front of the tree to measure the direction, and secondly next to the centre of the tree, to record the distance. The diameter was measured separately at breast height, using a measuring tape. The results of the tacheometer and the diameters were linked by an identification number given by the tacheometer. The stem map was created by recalculating the directions and distances from the tacheometer to coordinates. The accuracy of the locations of the trees on the stem map is 10 cm, caused by the manual estimation of the centre of the tree and the error in the uncertainty of the location of the tacheometer. The accuracy was determined by measuring the same tree twice from different tacheometer locations. The vegetation density was computed for 23 plots based on the stem map plus the number of side branches for each stem. The $D_v$ of these plots was computed, using the manual method. The plots based on the stem map, were used as reference data to validate the TLS method.

Figure 8.1: Data collection for TLS, with dGPS poles (5 of 24 are shown), scanner positions, stem locations, and polygons outlining the field plots and stem based plots.
8.2 Laser data collection

8.2.1 The laser scanner

The laser scan data was collected in August 2005 using the Leica HDS3000 laser scanner (Table 8.2), a time of flight scanner, which was chosen for its large effective range (100 m). The disadvantage of this type of scanner was that it is slow compared to a phase based scanner (Section 3.5.1). A full round scan with a horizontal angle of 360° and a vertical angle of 270°, takes approximately 90 minutes per scan with a resolution of 2 cm at 20 m distance. Before each scan a hemispheric mosaic was made by the onboard digital camera. The RGB color on the mosaic, in the direction of each pulse was assigned to each point. The specifications of the scanner are presented in Table 8.1.

![Figure 8.2: The Leica HDS3000 Laser scanner (Leica Geosystems, 2006)](image)

Table 8.1: Specifications of Leica HDS3000 (Leica Geosystems, 2006)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field of View</td>
<td>360° x 270°</td>
</tr>
<tr>
<td>Spot size</td>
<td>&lt; 6mm @ 50m distance</td>
</tr>
<tr>
<td>Positional accuracy</td>
<td>6mm @ 50m distance</td>
</tr>
<tr>
<td>Min. angle increment (horiz. &amp; vert.)</td>
<td>60 micro-radians</td>
</tr>
<tr>
<td>Optimal effective range</td>
<td>1 – 100m</td>
</tr>
</tbody>
</table>

8.2.2 Laser scanning

Nine laser scans were made, together covering about 75% of the forest (Appendix A.2). Scans 2 and 3 were made from the same position, resulting in 8 point clouds, each consisted of 1.7 to 4.8 million points. The scanner was positioned about 2 m above the forest floor on relatively open places in the forest. The effective penetration depth of the scanner proved to be about 25 m effectively, due to
8.2. Laser data collection

occlusion. At larger distances, very few points were recorded. The laser scans were made from inside the forest, because few points could penetrate the dense edges of the forest. After the first scan, the decision was made for the next scan location. Because the penetrating capacity of the scanner was less than expected the scans had to be made close together. The distance between the scan positions was about 15 meters, to create overlap. The scans were overlapping, at least 10 meters, and one third of the area of the forest was scanned by more than one scan. The resolution was set constant for each scan position, therefore, the number of emitted pulses was equal for each angle increment. The scan resolutions were set manually for each scan (table 8.2). For the scans the field of view was set at 360° horizontally. The vertical range was limited to 45° below horizontal and 35° above horizontal. The scans took between 30 and 90 minutes to complete, depending on the resolution.

Table 8.2: Scan resolutions per scan position in cm at 20 m distance to the scanner and number of points in millions

<table>
<thead>
<tr>
<th>Scan</th>
<th>Horizontal Res.</th>
<th>Vertical Res.</th>
<th>Number of points</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.9</td>
<td>3.0</td>
<td>3.5 million</td>
</tr>
<tr>
<td>2</td>
<td>4.8</td>
<td>2.0</td>
<td>4.3</td>
</tr>
<tr>
<td>3</td>
<td>4.5</td>
<td>2.0</td>
<td>4.3</td>
</tr>
<tr>
<td>4</td>
<td>9.2</td>
<td>2.0</td>
<td>2.3</td>
</tr>
<tr>
<td>5</td>
<td>4.0</td>
<td>2.4</td>
<td>4.8</td>
</tr>
<tr>
<td>6</td>
<td>3.3</td>
<td>2.2</td>
<td>2.4</td>
</tr>
<tr>
<td>7</td>
<td>3.4</td>
<td>3.0</td>
<td>4.5</td>
</tr>
<tr>
<td>8</td>
<td>4.1</td>
<td>3.0</td>
<td>2.6</td>
</tr>
<tr>
<td>9</td>
<td>5.5</td>
<td>5.3</td>
<td>1.8</td>
</tr>
</tbody>
</table>

8.2.3 Georeferencing of the scan data

A wooden pole was placed below the scanner, during each scan. The coordinates of these poles were measured using the tacheometer. These coordinates were used for georeferencing the scan positions. Furthermore, detailed high-resolution scans of several georeferenced poles near the scan positions were made. A pole was fitted in the point cloud from the detailed scans. The centre of the top of the fitted pole was determined and was assigned the coordinate of the pole. This data was used for initial georeferencing of the generated point clouds. To merge the 9 point clouds, the Iterative Closest Point algorithm was used (Besl and McKay, 1992). The laser scanning was carried out and georeferenced by Delfttech (www.delfttech.nl), a company specialized in 3D laser scanning projects. The accuracy of the location of the scan positions was 10 cm, the accuracy of the location of the tacheometer. The data was delivered as ascn files of the separate scans and contained the x, y and z coordinates for each point in the local coordinate system. The size of the files was between 80 and 225 Mb, depending on the number of points, and 1.1 Gb in total.
8.3 TLS data analysis methods

8.3.1 Preprocessing of the TLS data

The first step in processing of the laser data was to determine a Digital Terrain Model by selecting the scan point with the minimum height for each cell of 0.5x0.5 meter. The ground elevation at the scan location was determined by the average elevation of the cells in the scan area (25 m around the scanner). Subsequently, the points in a horizontal slice of 1 meter thick around breast height were selected, thereby eliminating the ground points. Breast height was defined as 1.3 m above the ground elevation of the Digital Terrain Model. At 25 m distance to the scanner a threshold was applied, because few points have penetrated the forest at larger distances. The slice approach was chosen to reduce the amount of data and for comparison with the reference data. Thirdly, the coordinates of the points in the slice were converted from x, y and z values, in the national grid, to a polar coordinate system, around the scanner. The horizontal angle compared to the scanner (α), vertical angle (β) and distance to the scanner (d) were calculated as new coordinates. Finally, a polar grid was created with cell sizes of 4° horizontally (α), and 0.5 m (d), with a maximum distance of 25 m. An example of the polar grid is shown in figure 8.3.

8.3.2 Prediction models

The vegetation density was predicted using two models. The first model was the Percentage Index (PI) and computed the percentage of laser points in each cell, using the following equation (Straatsma, 2005):

\[ Dv_{PI,d1-d2} = \frac{1}{d2 - d1} \cdot \frac{N_{d1-d2}}{N_{tot}} \]  

(8.1)

where \( N_{d1-d2} \) is the number of points per cell between distances \( d1 \) and \( d2 \) to the scanner (\( d2 > d1 \)) and \( N_{tot} \) is the total number of points in each wedge (horizontal angle increment of 4°). \( N_{tot} \) was determined by sampling the total number of points in the wedge, horizontally and in the triangle through \( b_{min} \) and \( b_{max} \) of the distal cell boundary vertically (figure 8.3). \( N_{d1-d2} \) was determined by sampling the number of points in the volume delineated by the triangle, the curved proximal and distal cell boundaries and the wedge. The polar grid had curved cells and the height of the slice was set to 1 m. The vertical angular boundaries of the cells (β), therefore, declined with distance to the scanner (d; figure 8.3). The first term of the equation was added to make the model independent of the cell length.

The second model is based on the LAI, developed by MacArthur and Horn (1969) and verified by Aber (1979). This model is based on the extinction model (section 3.4.1) or the inverted gap fraction model (Jonckheere et al., 2004), which corrects for the decreased probability of hitting a tree at larger distances from the scanner, due to occlusion. The model assumes a random distribution of the trees (Aber, 1979). Straatsma (2005) assumed that leafless trees show the same way of occlusion as trees in leaf–on conditions and used the Vegetation Area Index (VAI) as a predictor for the vegetation density of floodplain forests measured by airborne laser scanning. In this research the VAI model was applied to predict the \( Dv \) using terrestrial laser scanning data and had to be used horizontally:

\[ Dv_{VAI,d1-d2} = \frac{1}{d2 - d1} \cdot \ln \frac{N_{d1}}{N_{d2}} \]  

(8.2)

where \( N_{d1} \) and \( N_{d2} \) are the number of points behind distances \( d1 \) and \( d2 \). The \( \frac{N_{d1}}{N_{d2}} \) factor is the ratio of the number of points behind the proximal and distal cell boundary (figure 8.3).
8.3. TLS data analysis methods

Figure 8.3: Schematic representation of the polar grid (a) with polar coordinates around the scanner (abd), and in side view (b) of the cell structure to compute the PI and VAI prediction models.

8.3.3 Assumptions of the models

Three assumptions underlie the PI– and VAI–method:

1. The laser pulses travel parallel through the forest
2. All emitted laser pulses have returned
3. The trees are randomly distributed

Assumption (1) can be accepted, when small cells are used, but is strictly speaking not true. The assumptions (2) and (3), underlying the two prediction models must be corrected for.

Correction for missing points

Not all emitted laser pulses had been reflected. The pulse energy can be absorbed by an object, scattered or the pulse may have hit no objects. The data showed that about 5 percent of the emitted points had not returned. Therefore, these pulses must be reconstructed.

The total number of pulses that potentially passed through each cell was reconstructed. Missing points were taken into account by computing the total number of emitted laser pulses that passed through a cell in case no obstruction was present ($N_{\text{tot},i}$):

$$N_{\text{tot},i} = ppr_h \cdot (\alpha_{\text{max},i} - \alpha_{\text{min},i}) \cdot ppr_v \cdot (\beta_{\text{max},i} - \beta_{\text{min},i})$$  \hspace{1cm} (8.3)

where $\alpha$ is the horizontal angle of the wedge (rad), $ppr_h$ and $ppr_v$ are the point density horizontally and vertically (points/\text{rad}) and $\beta$ is the vertical angle (rad) (figure 8.3).

For the PI, the total number of points in each wedge ($N_{\text{tot}}$) was replaced by the theoretical number of points ($N_{\text{tot},i}$), that passed through each cell. The number of points per cell ($N_{d1-d2}$) was calculated.

J. Warmink, 2007

Utrecht University
by subtracting the points before the proximal cell boundary \( (N_{d0-d1,i}) \) from the number of points before the distal cell boundary \( (N_{d0-d2,i}) \). The equation for the PI becomes:

\[
D_{\text{VPI},i} = \frac{1}{d_{2,i} - d_{1,i}} \cdot \frac{N_{d0-d2,i} - N_{d0-d1,i}}{N_{\text{tot},i}} \quad (8.4)
\]

The VAI model depended on the number of points behind the proximal and distal cell boundary. The number of points behind the proximal and distal cell boundaries were reconstructed by subtracting the number of points before the proximal and distal cell boundary from the theoretical number of pulses that passed through each cell. The final equation to predict the vegetation density per cell becomes \((i)\):

\[
D_{\text{VAI},i} = \frac{1}{d_{2,i} - d_{1,i}} \cdot \ln \left( \frac{N_{\text{tot},i} - N_{d0-d1,i}}{N_{\text{tot},i} - N_{d0-d2,i}} \right) \quad (8.5)
\]

When less than 20 points were recorded after the distal cell boundary, the cell was not taken into account.

Figure 8.4: Plan view of \( D_{\text{VAI}} \) values per polar cell, tree locations (trees are sized with diameter, but not to scale), and outline of a field plot (from Straatsma et al., submitted)

**Comparison with the reference data**

The radial cells were, subsequently, transformed back to the Dutch ordnance datum. The cell centres were overlain with the field plots, based on the stem map. To compare the VAI and PI values with the reference data, the non–random positioning of the trees perpendicular to the viewing direction had to be taken into account. Figure 8.4 gives an example of the polar grid, with VAI values, the plot boundary, and the position of the trees. It is clear that at a specific cell distance only one or two cells contain vegetation. To compensate for this effect, the vegetation density had to be computed over all cells with an equal distance to the scanner \( (D_{\text{VAI},d1-d2}) \) by:

\[
D_{\text{VAI},d1-d2} = \frac{1}{d_{2,i} - d_{1,i}} \cdot \ln \left( \frac{\sum_{d1,i}^{d2,i} N_{\text{tot},i} - N_{d0-d1,i}}{\sum_{d1,i}^{d2,i} N_{\text{tot},i} - N_{d0-d2,i}} \right) \quad (8.6)
\]
which combines all hits within the cells with an equal distance within the plot. The correction for the random distribution of trees had no effect on the $PI$ model, because the value for $N_{tot}$ is equal for all cells with an equal distance to the scanner. The $D_{VAI, d1-d2}$ values were assigned to all cells with an equal distance within the plot. Furthermore, a weighted average of the cells of which the centres fall within the plot area was used to compare with the reference density value ($D_{N,d}$) based on the stem map. Weights were based on the surface area of the cells and applied to both models.

Most reference plots were covered by more than one scan, therefore, the scan closest to the plot was used. The $D_{PI}$ and $D_{VAI}$ values were compared to the reference data. The comparison was done, initially, without the correction for missing points and random distribution of trees. Subsequently the corrections were applied. Finally, the values for the plots were compared for different scans positions, to assess the repeatability of the method. Linear regression was used to assess the predictive quality of the models.
Chapter 9

Results of terrestrial laser scanning

In this chapter, the results from the field measurements using terrestrial laser scanning are presented. The \( PI \) and \( VAI \) model predictions were compared to the reference data plots, based on the stem map. The influence of the correction for the limitations of the models are presented separately.

9.1 Raw laser scan data

Figure 9.1 shows the TLS point cloud for single scans. The points in figure 9.1(a) and 9.1(b) are color-coded with height. The points in figure 9.1(c) and 9.1(d) were assigned an RGB color from the onboard digital camera. The resolution of the scan data was high, so no individual points are visible. The red line in figure 9.1(d) shows the cutoff value, which was set at 25 \( m \) distance to the scanner. The black parts in figure 9.1(c) and 9.1(d) are occluded areas, where no points were recorded because all pulses were captured by trees closer to the scanner. The regions with missing points and the areas which were not covered by the scan are shown in figure 9.1(a) as the gray areas. The occluded areas become larger with increasing distance to the scanner, because the occlusion was enhanced by the radial emission of the pulses.

9.2 Cylinder fitting

A cylinder fitting procedure was done by Romain Auger, a trainee at Delft university, who participated in the laser scanning study. In this procedure trees were recognized by selecting dense parts around breast height in the point cloud and a cylinder was fitted through the points (section 3.5.2; Thies et al., 2004). The fitted cylinders show a good agreement with the manually measured trees of the stem map (figure 9.1(e)).

9.3 Results of the \( PI \) and \( VAI \) models

9.3.1 \( D_{VPi} \) and \( D_{VVAI} \) results in the polar grid

Figure 9.2 shows the results of the \( PI \) and \( VAI \) calculation in a polar grid, with and without correction for missing points, for a single scan position. The surface area of the circles represents the value
9.3. Results of the \( P \)I and \( VAI \) models

(a) 3D image of the laser data in side view with height colors (created by R. Auger, 2005)

(b) 3D image in bird view of the scan data with height colors (created by R. Auger, 2005)

(c) Laser scan data from inside the forest with camera colors

(d) Laser scan data in top view with camera colors

(e) Cylinder fitted trees (yellow) show a good agreement with the stem map (white) (created by R. Auger, 2005)

Figure 9.1: Images of the point cloud generated by the laser scanner and cylinder fitting
of the \textit{PI} and \textit{VAI} in that cell. Cells with zero values are not shown. This figure shows that $D_{\text{PI}}$ decreases with distance to the scanner, due to occlusion. The \textit{VAI} is corrected for occlusion and the decrease with distance is absent. At larger distances, however, more cells without or with zero $D_{\text{VAI}}$ values occurred. Zero or infinite $D_{\text{VAI}}$ values occurred at locations where not enough laser pulses were present to predict a reliable density, because all laser pulses were captured by trees closer to the scanner. The $D_{\text{PI}}$ corrected for missing points, generally, was smaller than the $D_{\text{PI}}$, without the correction for missing points. This can be explained, because the total number of points through each cell ($N_{\text{tot}}$) is larger when missing points are taken into account. The $D_{\text{VAI}}$ values without correction, also shows larger values than the corrected $D_{\text{VAI}}$. This effect is discussed in section 9.3.3.

Figure 9.2: The \textit{PI} and \textit{VAI} model results in the polar grid, without and with the correction for missing points. The surface area of the circles is scaled to the value of the \textit{PI} and \textit{VAI} in the cell.
9.3. Results of the PI and VAI models

9.3.2 PI and VAI model results without corrections

For comparison with the reference data, the PI and VAI models, not corrected for missing points and the random distribution of trees, were computed for the reference plots. The scatter plot of the $D_{vPI}$ is shown in figure 9.3(a). $D_{vN\bar{d}}$ values ranged from 0.02 to 0.20 m$^{-1}$, while the $D_{vPI}$ values ranged from 0.003 to 0.16 m$^{-1}$. The predicted $D_{vPI}$ values show a large scatter around the $y = x$ line and no variance was explained by the regression line with a zero intercept ($R^2 = -0.81$). The $D_{vVAI}$ model results are shown in figure 9.3(b). The $D_{vVAI}$ shows a higher correlation with the $D_{vN\bar{d}}$ values than the $D_{vPI}$, but little variance is explained by the regression line ($R^2 = 0.29$). Furthermore, the VAI model without the correction for missing points resulted in a large overestimation of the vegetation density. This overestimation is visualized by figure 9.2(b), which shows large values for the $D_{vVAI}$, when no correction for missing points was applied.

![Scatter plots of the $D_{vPI}$ and $D_{vVAI}$ on plot level, not corrected for missing points and the random distribution of trees](image)

Figure 9.3: Scatter plots of the $D_{vPI}$ and $D_{vVAI}$ on plot level, not corrected for missing points and the random distribution of trees

9.3.3 Correction for missing points

Figure 9.4 shows the PI and VAI model results, corrected for missing points. When the correction for missing points was applied, the correlation between $D_{vPI}$ and the reference data increased (figure 9.4(a)). The linear regression line with zero intercept, however, explained only 24 percent of the variance. The $D_{vPI}$ shows an increasing underestimation with increasing values of $D_{vN\bar{d}}$. This underestimation is explained, because no correction for occlusion is included in the PI model.

For the $D_{vVAI}$ values (figure 9.4(b)), the correction for missing points resulted in a reduced overestimation. The slope of the regression line increased from 0.25 to 0.60 and explained 93 percent of the variance. The large improvement in the predictive quality of the VAI model, indicates that this model is sensitivity to missing points. This sensitivity is caused by the ratio of $N_{d1}$ and $N_{d2}$ (equation 8.2). When missing points were reconstructed, the values of both $N_{d1}$ and $N_{d2}$ equally increased. This resulted in a decrease of the ratio and, therefore, in a decrease of the predicted $D_{vVAI}$. For example: if $N_{d1} = 25$ and $N_{d2} = 100$, will result in a $D_{vVAI}$ of 2.77, for a cell length of 0.5 m. When 250 missing point are reconstructed in the wedge, the $D_{vVAI}$ will reduce to 0.48. This effect, generally, increased with distance to the scanner, because fewer points went through a cell. The effect is visualized by figure 9.2, where the $D_{vVAI}$ values corrected for missing points are smaller, especially at large distances to...
9.3. Results of the PI and VAI models

the scanner. After the correction for missing points, however, the overestimation of the \( Dv_{N\bar{d}} \) remained, resulting in an empirical model. Therefore, the correction for the random distribution of trees was applied.

Figure 9.4: Scatter plots of \( Dv_{PI} \) and \( Dv_{VAI} \) values on plot level, corrected for missing points. The \( Dv_{VAI} \) is not corrected for a random distribution of trees

9.3.4 Correction for missing points and the random distribution of trees

The correction for the random distribution of trees had no effect on the PI model (section 8.3.3). Therefore, only the VAI model is considered in this section.

Figure 9.5(a) shows the results of the comparison of the \( Dv_{VAI} \) values with the \( Dv_{N\bar{d}} \) values obtained by the manual method on plot level, corrected for missing points and the random distribution of trees (equation 8.6). The regression line with zero intercept shows that the overestimation decreased, due to the correction for the random distribution of trees. The linear regression model of the \( Dv_{VAI} \) fits well with the data, but the higher density values show larger residuals:

\[
Dv_{N\bar{d}} = 0.82 \cdot Dv_{VAI} \cdot d_1 - d_2 (n = 23; R^2 = 0.77; SE = 4.6 \cdot 10^{-3})
\]  

(9.1)

A student’s t-test on differences in slope, showed that the slope of the regression line significantly differed from the line of identity at the 99.9 percent confidence level. On average, the \( Dv_{VAI} \) values were 0.015 higher than the \( Dv_{N\bar{d}} \) values.

Linear regression on the \( Dv_{VAI} \) predictions for field plots that were scanned from multiple angles (figure 9.5(c)), explained only 31 percent of the variance. The \( R^2 \) value, however, was largely influenced by one outlier. When this outlier was excluded, \( R^2 \) increased to 0.73, with a slope of the regression line of 0.998. This indicated that a single plot was strongly over– or underestimated from one of the scan positions. The largest outliers in the scatter plot are \( Dv_{VAI} \) values from small plots at large distances to one of the scanners. For the \( Dv_{PI} \) predictions from multiple angles, no correlation is visible (figure 9.5(d)). This is caused by the different distances for a plot to the two scan positions. Therefore, the occlusion is different for the two scan positions, resulting in different \( Dv_{PI} \) values. The repeatability of the method will be discussed in chapter 10. The regression equations and \( R^2 \) values for all models are presented in table 9.1.
9.3. Results of the \( PI \) and \( VAI \) models

Table 9.1: Regression equations for the different models

<table>
<thead>
<tr>
<th>Method</th>
<th>Regression Equation</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D_{VPI} ) not corrected for missing points</td>
<td>( \bar{N}d = 0.69 \cdot D_{VPI} )</td>
<td>-0.81</td>
</tr>
<tr>
<td>( D_{VPI} ) not corrected for missing points</td>
<td>( \bar{N}d = 0.35 \cdot D_{VPI} )</td>
<td>0.29</td>
</tr>
<tr>
<td>( D_{VPI} )</td>
<td>( \bar{N}d = 1.34 \cdot D_{VPI} )</td>
<td>0.25</td>
</tr>
<tr>
<td>( D_{VAI} ) not corrected for random distribution</td>
<td>( \bar{N}d = 0.60 \cdot D_{VAI} )</td>
<td>0.93</td>
</tr>
<tr>
<td>( D_{VAI} )</td>
<td>( \bar{N}d = 0.82 \cdot D_{VAI} )</td>
<td>0.77</td>
</tr>
<tr>
<td>( D_{VAI} ) from multiple angles</td>
<td>( D_{VAI,1} = 1.1 \cdot D_{VAI,2} )</td>
<td>0.31</td>
</tr>
<tr>
<td>( D_{VAI} ) from multiple angles, omitting the outlier</td>
<td>( D_{VAI,1} = 0.998 \cdot D_{VAI,2} )</td>
<td>0.73</td>
</tr>
<tr>
<td>( D_{VPI} ) from multiple angles</td>
<td>( D_{VPI,1} = 0.20 \cdot D_{VPI,2} + 0.04 )</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Figure 9.5: Scatter plots of vegetation density predictions, corrected for missing points and the random distribution of trees on plot level.
The $D_{VAI}$ predictions from the 9 scans were combined to create a 2D map of the vegetation density at breast height (figure 9.6). The polar grid cells with the $D_{VAI}$ value per scan were plotted in the forest area. Subsequently, an inverse distance weighted interpolation was used to calculate the $D_{VAI}$ value in a square grid with cell sizes of 2x2 m. The resulting grid was clipped to fit the boundaries of the scanned forest. The northern part of the forest was not covered by the laser scans. The south–western edge of the forest patch show up as a denser part, which was observed in the field.

Figure 9.6: Spatial distribution of vegetation density at breast height ($D_{VAI}$) of the forest patch (left) and aerial photograph (right). Dense forest edges show up along the south–western edge.
Chapter 10

Accuracy and objectivity of the terrestrial laser scanning method

The results show that the VAI model, corrected for missing points was a good predictor for the aggregated vegetation density. The predicted $D_{N\bar{d}}^{VAI}$ for different scans, omitting one outlier, show a strong correlation and the regression line matched the line of identity, which indicated a reasonably good repeatability of the method. The field measurements and the calculation of the $PI$ van $VAI$ values included some inaccuracies and parameters, which were studied. The accuracy, objectivity and field time of the terrestrial laser scanning method will be discussed in this chapter.

10.1 Accuracy of the field data

Accuracy of the reference data

The locations of the trees in the stem map and the locations of the scan positions were measured using the tacheometer and had an accuracy of 10 cm. The inaccuracy was caused by manually holding the reflector at the location of the trees and the accuracy of the positioning of the tacheometer. The error in the location of the trees on the stem map may result in uncertainties in the $D_{N\bar{d}}^{VAI}$ value for the reference plots. The uncertainty of the stem map and the errors in georeferencing between the point cloud and the stem map, may cause a single tree to be included in the reference plot, but excluded in the model calculation. This error is increasingly important in open parts of the forest, when a single tree has a large influence on the resulting $D_{N\bar{d}}^{VAI}$ value. The size of the reference plots, however, was between 10 and 75 m$^2$ and a small error in the location of the plot may result in a large error of the $D_{N\bar{d}}^{VAI}$, especially for the small plots.

Resolution of the scan data

The resolution of the scanner was set between 238 and 656 pulses per radial horizontally and between 414 and 1104 vertically. In this study, the influence of the resolution of the scan data on the predictive quality of the model was not assessed. Some remarks, however, can be made in this respect:

1. A higher resolution will probably increase the penetrating capacity. Consequently, a larger area can be covered by a single scan, because more points are available at larger distances.
2. A higher resolution will give a better representation of the density, because smaller objects will be recognized. Table 8.2 shows the spacing between the points at 20 meter distance from the scanner. At the lowest resolution a tree with a diameter of 4.6 cm can be missed by the scanner.

10.2 Accuracy of the density calculation

The Digital Terrain Model of the forest was created by taking the minimal height of the laser points for each square grid cell of 0.5x0.5 m. The extreme values were filtered out by taking the average values for each 9x9 window. This method is simple, but was seemed sufficient for calculating the average height of ground level in the scan area. The inaccuracy in the height where reference data was collected (breast height = 1.3 m ± 10 cm) was larger than the inaccuracy in the DTM. These inaccuracies had little influence on the results, because there was little variation in the diameter in the height interval of uncertainty around breast height.

Reconstruction of missing points

The point density is an important parameter in the determination of the $D_v$ values. It determines the theoretical number of pulses that went through a cell (equation 8.3). The percentage of missing points was calculated by subtracting the recorded points from the total number of emitted pulses, divided by the total number of emitted pulses. The percentage of missing points in the point clouds varied between 0.5 and 4.1 percent, but introduced a large error in the predicted density values. A possible explanation is that most missing points were located in the height interval of the slice. At breast height, fewer side branches and leaves were present, than in the crown of the forest or the ground surface (figure 9.1(a) and 9.1(c)).

Inaccuracies caused by the polar grid

The use of the polar grid introduced uncertainty in the prediction of the density values for the reference plots. The $D_{vpl}$ and $D_{vpl}$ values on plot level were determined by averaging the centres of the polar cells that fall inside the plot area (figure 10.1). This caused uncertainty, because the cell boundaries did not match the plot boundaries. For all cells close to the borders of the reference plot, the cell value was only included in the calculation of the reference data if the centre was covered by the reference plot. Due to this uncertainty, a tree (or part of a tree) inside the reference plot, may be excluded in the calculation of the $D_{vpl}$ value. This effect is larger at large distance to the scanner, because the polar grid cells represent a larger surface area, up to 0.9 m$^2$ at 25 meter distance. A possible solution is to match the borders of the reference plots to the polar grid cells. This is, however, only possible for a single scan position, because the locations of the polar grid cells are different for each scan.

The polar shape of the grid was introduced, because the calculations were more easy. The polar grid, however, resulted in uncertainties in the prediction, which increased with distance to the scanner. These uncertainties are caused by the central projection of the laser pulses, which resulted in similar problems as described by the centrally projected photographic method (section 3.4). Therefore, the largest disadvantage of the laser scanner is the radial emission of the pulses. A parallel laser scan method can solve these problems and make the calculation more easy and accurate. In future studies it is recommended to use a square grid instead or to resample the polar grid to a square grid before comparison. A square grid makes it possible to match the borders of the grid cells with the reference
10.3 Parameters in the terrestrial laser scanning method

plots and makes a comparison between the different scans possible on cell level. Furthermore, the vertical variation in vegetation density will probably be more easily introduced on a square grid.

Figure 10.1: The point in polygon operation: the $D_{VAI}$ and $D_{PI}$ value of the reference plot was calculated by averaging the $D_{VAI}$ and $D_{PI}$ values of the cells, which centres (represented by the points) fall inside the plot area

10.3 Parameters in the terrestrial laser scanning method

Penetrating capacity and cutoff value

During the field measurements, the penetrating capacity of the scanner was lower than expected. Figure 10.2 shows the decrease of the number of points in the slice with distance to the scanner. The first few meters contain no points, because the scanner was placed at an open area in the forest. Figure 10.2(a) shows that the first trees were located at 7.5 meter. Figure 10.2(c) shows the histogram of scan 8, where almost all points were captured in the first meters. In all histograms a rapid decrease with distance, after the first peak is visible.

Calculation parameters

The only parameters that were chosen in the calculation, were the size of the cells in the polar grid, the cutoff value and the height of the slice. The cell size was chosen to be about 0.5x0.5 meter at 7 meter distance to the scanner. The height of the slice was chosen to contain enough points at larger distances. In future studies other shapes and sizes of the grid cells can be studied. The other parameters needed in the calculation were the locations of the scan positions, the point density and the ground elevation at the position of the scanner. These parameters were measured in the field. Because few decisions were made by the observer, the calculation of the $D_{VAI}$ had a high degree of objectivity.
A large number of points was captured by the first trees visible to the scanner. Afterwards a rapid decrease in the number of points is visible.

**Prediction models**

The VAI model, corrected for missing points and the random distribution of trees proved to be a better predictor for vegetation density than the PI model. The VAI model, however, assumed that \( N_{d2} \) was large. When a large percentage of the pulses was captured in a cell, the ratio between \( N_{d1} \) and \( N_{d2} \) became very large. This resulted in a very large value for the \( D_{v_{\text{VAI}}} \). When all points were captured in a certain cell, \( N_{d2} \) became zero. This resulted in an infinite value for the \( D_{v_{\text{VAI}}} \) and the cell was not taken into account in the computation of the \( D_{v_{\text{VAI}}} \) for the reference plot. When the cell sizes are small, a tree can cover multiple cells at the same distance, and all points are captured, resulting in infinite \( D_{v_{\text{VAI}}} \) values. This effect can explain the sensitivity of the VAI model for missing points. When the missing points are reconstructed, the number of cells with a infinite value are reduced and more cells are used to calculate the \( D_{v_{\text{VAI}}} \) of the reference plot. The PI model was less sensitive to this effect, but did not take occlusion into account and, therefore, performed less.

After the correction for missing points there were negative values for \( N_{d1} \) and \( N_{d2} \) present in the polar grid. These negative values resulted in an infinite value of \( D_{v_{\text{VAI}}} \). These negative values show up for cells behind dense clusters of trees. Here, number of pulses through a cell was close the theoretical number of pulses through the cell (\( N_{\text{tot}} \)). Small errors in \( N_{\text{tot}} \) (equation 8.3) could lead to negative values. Another explanation for the negative values is that \( N_{\text{tot}} \) is overestimated, due to the fixed cell boundaries. \( N_{\text{tot}} \) is calculated based on the average number of pulses that went through a cell. The actual number of points through a cell, however, can be larger when the cell boundaries are narrowly fixed around the laser pulses. Figure 10.3 shows that the actual pulse density (number of pulses inside the red rectangle divided by the surface area) is larger than the average pulse density (number of pulses inside the blue rectangle divided by the surface area; equation 8.3), for the same number of points. The average pulse density calculated for the area inside the red rectangle is, therefore, smaller than the actual pulse density. When, in this case, all pulses are recorded in a single cell, the calculated \( N_{d2} \) is smaller than zero. Likewise, the \( N_{\text{tot}} \) can be the underestimated when the cell boundaries are narrowly fixed inside the laser pulses, resulting in an overestimation of \( N_{d2} \). This will, however, not result in an infinite value of \( D_{v_{\text{VAI}}} \) and the cell will be included in the computation of the \( D_{v_{\text{VAI}}} \) for the reference plot. Because, at plot level multiple cells are averaged to compute \( D_{v_{\text{VAI}}} \), the random overestimation of \( N_{d2} \) will have little influence.
10.4 Objectivity and time requirements of the TLS method

In the previous sections it was shown that the accuracy of the TLS method depended on the accuracy of the field measurements and the averaging of the $Dv_{PI}$ and $Dv_{VAI}$ values per cell to predict the density at plot level. The radial emission of the laser pulses resulted in large “shadows”, where no points were recorded. Due to the averaging of the polar cells in the plot areas, uncertainties were caused, because cells with infinite $Dv_{VAI}$ values or zero $Dv_{PI}$ values occurred in the “shadow” areas. The $VAI$ model gave the best result for the reference plot ($R^2 = 0.77$) with a slope of the regression line of 0.82. When the $Dv_{VAI}$ predictions for the reference plots were compared for different scan positions (figure 9.5(c)), 31 percent of the variance was explained by the regression line. However, when one outlier was omitted, the $R^2$ value increased to 0.73 with a slope of the regression line of 0.998. This indicated a reasonably high repeatability of the method. Regression analysis on the predicted $Dv_{PI}$, however, explained little variance ($R^2 = 0.25$), because no correction for occlusion was included in the model.

The choices made in the TLS method were: (1) the decision for the cell sizes of the polar grid, (2) the height of the slice, and (3) the cutoff value, which was mainly determined by the penetrating capacity of the laser scans. The two random effects which influenced the results were: (1) the inaccuracy in the determination of the locations of the trees, which can cause a tree to be excluded from the reference plot, but included in the $Dv_{VAI}$ prediction on plot level and (2) the under or overestimation of $N_{tot}$, which resulted in an erroneous, real number for $N_{d1}$ and $N_{d2}$. In the calculation of the vegetation density, few arbitrary decisions were made. The assumptions underlying the method were that: the trees were randomly distributed, all laser pulses were recorded, and the pulses travelled parallel through the forest. Because of the small cells in the polar grid, parallel pulses were assumed, the missing points were reconstructed and the a correction for the random distribution of the trees was included on plot level.

A disadvantage of the terrestrial laser scanning method was that field measurements were costly compared to the photographic method and manual methods, because laser scanning equipment is expensive. For this research, a specialized company had to be hired to conduct the scanning. Furthermore, collecting the laser scan data in the field was time consuming. In one day, 8 laser scans were made,
covering tree quarters of a relatively open forest. The resulting data acquired by this method, however, was very detailed and spatially variable. Instead of the time of flight type scanner, used in this research a phase–based scanner (section 3.5.1) can be used. This type of scanner is less accurate and has a limited range (100\text{m}), but the penetrating capacity in the forest was only 25 meter in this study. The advantage of the phase–based scanner is that it is much faster than a time of flight scanner.

The amount of data resulting from a single scan was around 3.5 million points. This resulted in a significant calculation time. The use of the slice approach reduced the number of points needed for calculation from 3.5 million to 200000 per scan. The calculation time was, thereby, reduced from 3 hours per scan to 10 minutes. The time needed for the total data analysis was about 3 hours, but can be reduced by optimizing the algorithm. The data analysis was fully automated and needed no interaction of the surveyor.
Chapter 11

Comparison of parallel photography and terrestrial laser scanning

In this research several methods were discussed to measure the hydrodynamic vegetation density in the lowland floodplains. The TLS method was applied in a floodplain softwood forest and the CP and PP method were applied to various vegetation types. In this chapter the application and the strengths and weaknesses of the different methods are compared.

11.1 Accuracy of the methods

The manual method used for collecting reference data, was applicable on forest plots with few side branches. This method was based on the assumption of cylindrical vegetation. Inaccuracies were caused by the decision of the measurement height. For plots with complex vegetation, the measurement errors were significant and the method was not applicable, because the assumption was not valid. For the validation plots, the manual method seems accurate. This should be tested by multiple inventories of the same plot.

The parallel photographic method performed equally well as the manual method for the validation plots ($R^2 = 0.996$) and the regression line matched the line of identity. Because the manual method was an accurate measurement technique for vegetation density of cylindrical vegetation, it was concluded that the PP method had a very high accuracy. The PP method does not depend on the underlying assumption of the manual method and, therefore, can be applied on more complex vegetation types. The inaccuracies in the resulting $D_{vpp}$ values were mainly caused by the measurement error of the plot length in the field and errors in the classification of the pixels.

The terrestrial laser scanning method performed well for the prediction of the vegetation density in the studied forest. The $VAI$ corrected for missing points and the random distribution of trees explained 77 percent of the field variance. The slope of the regression line was 0.82 and significantly differed from 1. $PI$, corrected for missing points explained little variance ($R^2 = 0.25$), because no correction for occlusion was included in the model. The averaging of the $D_{vp}$ and $D_{vVAI}$ values for the reference plots included uncertainty in the method.

The PP method, therefore, is a more accurate method to measure the vegetation density at plot level, while the TLS method is more efficient to map 2D distribution.
11.2 Objectivity of the methods

$Dv_{Nd}$ lacks objectivity for complex vegetation, because a decision has to be made, which stems are selected to measure the diameter. The decisions that had to be made using the PP method were the height and distance of the camera to the plot and the camera settings (resolution, opening angle and exposure). The resulting $Dv_{PP}$ proved sensitive to the resolution of the photographs, which must be set as high as possible for complex vegetation. The threshold on the intensity histogram has a certain degree of subjectivity, depending on the contrast of the initial photographs. The threshold on the hue histogram needs calibration, but depends only on the color of the screen.

For the TLS method, few arbitrary decisions were made during the measurement and the data analysis. The decisions made by the researcher were the choice of the type of calculation grid and the locations and resolution of the scans. The consequences of changes in the grid or resolution were not studied in this research. Further research is needed to investigate the influence of these parameters on the vegetation density predictions. Overall can be said that the PP and TLS method have a high degree of objectivity.

11.3 Time and equipment needed for the methods

Besides the accuracy and objectivity of the methods, the time and equipment needed to carry out the field measurements determined the applicability of the methods. The advantage of the manual method was that only a notebook, tape measure and sliding gauge were needed in the field. The PP method needed a lot of equipment (section 5.2.1), thereby reducing the accessibility in complex vegetation. For the TLS method a lot of advanced equipment was needed. This made the method expensive compared to the other two methods.

Besides the price of the equipment, the costs of a method are determined by the time needed in the field and for data analysis. The time needed for the field measurements was difficult to compare, because the methods have different support. The manual method took about 5 minutes for a forest plot, but the measurement time increased to 45 minutes for complex vegetation. The PP method method took about 30 minutes, which was independent of the complexity of the vegetation. Including the time for relocation, an experienced surveyor can measure 8 to 10 plots per day. When fewer pictures were taken per plot, which had a minimal effect on the vegetation density prediction (section 7.3.2), the field time decreased, down to 10 minutes. A further decrease of the time in the field can be achieved by improving the field equipment. This can reduce the time to setup the screen and rail, significantly. The time needed for the data analysis of the parallel photograph method is minimal, when automated.

The data collection of the laser data was done in one day (8 hours) and 9 laser scans were made. Creating the dGPS points around the forest took about 4 hours. The 9 scans covered three quarters of a forest of 120x80 meters. The laser scanner can cover, in the same amount of time, a larger area than the PP method, but a coordinate system is needed in the study area. The time required in the field can be reduced using a phase–based scanner. The data analysis for the TLS method was more complicated and time consuming than for the PP method. Delfitech, the company responsible for post processing the raw laser data, used about three days for georeferencing. The calculation of the $Dv_{VAI}$ value for the scans took about 90 minutes of computer time, but can be fully automated.
11.4 Application of the methods in the field

The advantages and disadvantages of the methods are summarized in table 11.1. The manual method is an appropriate measurement method when the assumption underlying the method is valid. It is an easy and fast method to measure the vegetation density of forests, with little side branches and leaves.

The strongest point of the TLS method is the spatial variability of the vegetation density measurements. The method proved to be accurate, although less than the PP method, without the need for calibration and had a high degree of objectivity (section 11.2). Therefore, it was concluded that the TLS method is an appropriate measurement method for measuring aggregated vegetation density data.

The parallel photographic method proved to be a reliable tool to measure accurate and objective field data without the need for calibration. This data can be used as input data for the ecotope approach or as reference data for airborne laser scanning or other methods, which need calibration. The PP method was the only method in this research, which can objectively measure herbaceous vegetation. The equipment must be adapted, to measure vegetation lower than 0.5 meter. When no spatial variability is needed, the PP method will produce the best results.

<table>
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<th>PP method</th>
<th>CP method</th>
<th>TLS VAI</th>
<th>TLS PI</th>
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Chapter 12

Conclusions and recommendations

12.1 Conclusions

The aim of this research was to develop a photographic method and terrestrial laser scanning on floodplain vegetation to determine the vegetation density for hydrodynamic roughness calculations. In this research, the parallel photographic method and the terrestrial laser scanning method, both based on the optical point quadrat method, were used to quantify the hydrodynamic vegetation density of floodplain vegetation. The manual method, where the $D_v$ was calculated by multiplying the average diameter by the number of stems per square meter, was used as validation data.

12.1.1 Parallel photography

In this thesis, a new measurement tool was developed: the parallel photographic method (PP), which predicts the vegetation density very well ($R^2 = 0.996$) up to vegetation densities of 0.12 ($m^{-1}$), which is dense forest, without the need for calibration. The PP method was an improvement of the central photographic method ($R^2 = 0.87$). The PP method consists of the computation of the fractional coverage of vegetation against a contrasting background on a digital photo mosaic of parallel images. The diameters of individual trees measured in the field were reconstructed on the parallel photo mosaic and showed an $R^2$ of 0.97.

The PP method was applied on more complex vegetation and gave consistent results. The method used to measure herb vegetation gave the best results using a red screen and apply the threshold on the hue value of the photographs. PP is an accurate and objective measurement tool for the hydrodynamic vegetation density of floodplain vegetation. The method is applicable on summer and winter vegetation. Some remarks on the methodology of the PP method are:

- Measured density values range from 0.01 $m^{-1}$ for open forest, to 6.17 $m^{-1}$ for the lower layer of a herb plot.
- The method took about 25 minutes per plot and a lot of equipment was needed, thereby reducing the accessibility in dense vegetation. The time needed for the data analysis was 5 minutes.
- The accuracy of $D_{vPP}$ was mainly determined by inaccuracies in the plot length measurements in the field and the resolution of the photographs.
- The spacing between the photographs needed to create a parallel photo mosaic, producing accurate results, was 20 cm for the studied forest plot and 10 cm for the herb plot.
12.2. Recommendations

• On plot level, the PP method outperformed terrestrial laser scanning.

12.1.2 Terrestrial laser scanning

In this thesis, a second new method is presented to extract the aggregated vegetation density from terrestrial laser scanning (TLS) data for application in hydraulic models. Two different models were tested to predict the vegetation density: (1) the Percentage Index ($PI$) and (2) the Vegetation Area Index ($VAI$). The results show that:

• The $PI$ model was a bad predictor for the vegetation density for the reference plots ($R^2 = 0.25$).
• The $VAI$ model gave the best predictions for the reference plots ($R^2 = 0.77$).
• Correction for missing point and the assumptions of the random distribution of trees is required.
• No calibration is required for the $VAI$ model.
• The presented method has a high degree of objectivity.

Some remarks on the methodology of the TLS method are:

• The accuracy of the $D_{VAI}$ on plot level was mainly determined by inaccuracies caused by the averaging of the $D_{VAI}$ values per cell.
• The radial emission of the laser pulses resulted in increasingly large areas where no data was collected.
• Time required for the data analysis and the field time was 2 and 8 hours respectively, for 9 scans covering three quarters of the studied forest.
• Using the slice approach, the 2D $VAI$ method can easily be extended to 3D using multiple slices.
• The $VAI$ model provide surveyors with a new methods for accurate vegetation density field measurements: averaged over a plot or spatially variable.

12.2 Recommendations

12.2.1 Parallel photography

For future research using the PP method some recommendations are:

• Improve the guide rail and screen setup to reduce field time.
• When low vegetation is measured, the equipment needs to be improved by decreasing the height of the tripods.
• Using a collapsible board as background instead of the screen will reduce differences in illumination.
• A frame around the plot area reduces distortions of the plot and increases the accuracy of the plot length measurement.
• Fewer photographs are needed to create a representative parallel photograph of woody vegetation.
• A blue or purple background will probably improve the discrimination between screen and vegetation by the hue threshold.
• The resolution of the photographs has a large influence on $D_{PP}$. The optimal resolution is of interest to future research.
12.2. Recommendations

12.2.2 Terrestrial laser scanning

Some recommendations for future research are:

- The laser scans should be made from inside the forest, the edge of the studied forest was too dense to penetrate.
- Use a phase–based scanner instead of the time of flight scanner, to increase point density and reduce scan time.
- An increased scan resolution will increase the penetrating capacity of the scanner. The optimal resolution of the scanner is of interest to future research.
- The slice and polar grid approach show limitations. A square calculation grids might give better results, but is more complicated.
- In this study a single slice around breast height was used. The method can be expanded with multiple slices, to determine the vertical variation in vegetation density of the forest.
- Future studies are needed to test the applicability of terrestrial laser scanning on more complex vegetation.

When measurements of the spatial variability of the vegetation density is required, the terrestrial laser scanning method gives good results. It is recommended to use the parallel photographic method as calibration data, especially, for herb vegetation and as density values of herb vegetation used for the ecotope approach. It is concluded that TLS and PP are two complementary techniques, that show high accuracies for field measurements of vegetation density.
References


REFERENCES


REFERENCES


J. Warmink, 2007


Appendix A

Maps of the study areas

A.1 Topographic maps of the study areas

A.2 Maps with vegetation classes and measurement locations

Duursche Waarden I
Duursche Waarden II
Gamerensche Waard
TLS forest in the Gamerensche Waard
Topographic maps of the study areas

Topographical map of the Duursche Waard, with the natural reserve area: “Duursche Waarden and the area around Fortmond

Topographical map of the Gamerensche Waard floodplain, with the old brick factory in the centre. The arrow is pointing towards the forest where the tls measurements were conducted
Fieldmap of the Duursche Waarden: the area around Fortmond with topographical vegetation descriptions from DTB - River and measurement locations

Legend

Topography
- hardwood forest
- softwood forest
- young softwood forest
- shrub vegetation
- orchard
- reed marshes
- natural grassland
- agricultural area
- lake

Parallel photography plots
- validation plots
- leaved forest plots
- herbaceous plots
- lower layer plots
- large opening angle
- reed marsh
- grass plots
- omitted plots
- plots measured summer and winter

from: Ministry of Public Works and Transportation:
"Digitaal Topografisch Bestand (DTB) Rivier
Meetkundige Dienst afdeling Topografische GEO-informatie"
Version: 3.1 Date of last change: 5 March 1999

Jord Warmink
January 2007
Fieldmap of the Duursche Waarden II: the nature reserve area with topographical vegetation descriptions from DTB - River and the measurement locations

from: Ministry of Public Works and Transportation:
"Digitaal Topografisch Bestand (DTB) Rivier Meetkundige Dienst afdeling Topografische GEO-informatie"
Version: 3.1 Date of last change: 5 March 1999
Fieldmap of the Gamerensche Waard with topographical vegetation descriptions from DTB - River and measurement locations

Legend
Topography
- softwood forest
- herbaceous vegetation
- water
TLS
- Laser scan positions
- Parallel photography plots
- Validation plots
- Leaved forest plots
- Lower layer plots
- Large opening angle
- Omitted

from: Ministry of Public Works and Transportation: "Digitaal Topografisch Bestand (DTB) Rivier Meetkundige Dienst afdeling Topografische GEO-informatie"
Version: 3.1 Date of last change: 5 March 1999

Jord Warmink
January 2007
Appendix B

Flowcharts and scripts

B.1 Parallel photographic method

Flowchart of the python script to create a parallel photo mosaic
Python script to create a parallel photo mosaic
Flowchart of hue thresholding using MeVisLab

B.2 Terrestrial laser scanning method

Flowchart of the terrestrial laser scanning method
Explanation of the python script to compute $D_{V_{VAI}}$
Python script to compute $D_{V_{VAI}}$ based on the point cloud
Flowchart of the Python script to create a parallel photo mosaic

1. **Files**
   - Original photographs

2. **Function**
   - Determine the number of original photographs (\(p\)ics)

3. **Width value**

4. **Function**
   - Select the centre box out of the original photograph with size: (width, height _pics_)

5. **Function**
   - Create new image with size: (width*\(n\)_pics* height _pics_)

6. **Function**
   - Paste the selected box in the new picture. And write the mosaic new to the disk

7. **Parallel Photo mosaic**
import os
import Image
from string import split
from os import system
from matplotlib.pylab import hist, show, bar, plot, subplot, title, ylabel

### Global module works in ./
# General Flowchart:
# create a dirlist --> make piclists --> enter directory-->
## read infofile --> extract plotnr -->
### create the new image and write it to p-photo -->
#### write a new infofile [with first line is the number of centre columns]

### General Settings...
borders = [[0,56],[57,61]]  # Set range of plots-IDs for which the
# values are valid (more can be added)
format = ['img','dcp']  # The characters to select the photographs
# in the folder
extension = ['jpg','jpg'] # Set the extension of the photographs

# Function to read the names of the photographs in all plot folder
# defined in "dirlist.txt" to a file "piclist.txt"
def create_dirlist(borders, format, extension):
    print 'create_dirlist() started'
    print 'dirlist created...
    for x in file('dirlist.txt','r').readlines():
        directory = x[:-1]; plot = split(directory,'_')[1][4:]
        for i in range(len(borders)):
            if borders[i][0] <= int(plot[:2]) <= borders[i][1]:
                ## Execute the bash command to create a file with all
                ## directories containing photographs
                command = 'ls -d
                ./'+directory+'/*.'+extension[i]+' | '+directory+'/piclist.txt'
                os.system(command)
                print "piclist written in: "+directory
    fileexists('piclist.txt','dirlist.txt')

### General Settings...
borders = [[0,56],[57,61]]  # Set range of plots-IDs for which the
# values are valid (more can be added)
format = ['img','dcp']  # The characters to select the photographs
# in the folder
extension = ['jpg','jpg'] # Set the extension of the photographs

target = 'p-photos/'  # Photo mosaics are saves to this folder

def create_dirlist(borders, format, extension):
    print 'create_dirlist() started'
    print 'dirlist created...
    for x in file('dirlist.txt','r').readlines():
        directory = x[:-1]; plot = split(directory,'_')[1][4:]
        for i in range(len(borders)):
            if borders[i][0] <= int(plot[:2]) <= borders[i][1]:
                ## Execute the bash command to create a file with all
                ## directories containing photographs
                command = 'ls -d
                ./'+directory+'/*.'+extension[i]+' | '+directory+'/piclist.txt'
                os.system(command)
                print "piclist written in: "+directory
    fileexists('piclist.txt','dirlist.txt')

# Function to check if "filename" exists in the folders named in
# "folderfile"
def fileexists(filename, folderfile):
    for x in file(folderfile,'r').readlines():
        directory = x[:-1]
        try:
            open('./'+directory+'/*'+filename)
            continue
        except:
            print "ERROR...\nCreate "+filename+" first!\nScript Terminated" break
    print filename+" exists in all directories listed in "+folderfile
    return True
# Function to write the initial infofile in all folders in "folderfile"
def write_ini_info():
    for x in file('widths.txt', 'r').readlines():
        for directory in file('dirlist.txt','r').readlines():
            plot=split(x,'	')[0]
            width=split(x,'	')[1]
            plot_dir=split(directory[:-1],'_')[1][4:]
            if plot_dir == plot:
                write_file(plot,width[:-1],directory[:-1])
            else:
                continue

# Function to write "plot" and "width" to "infofile.txt"
# needed by write_ini_info()
def write_file(plot, width, directory):
    print  plot+'	'+width+'	'+'WRITTEN TO	'+ directory+'/infofile.txt'
    infofile=file(directory+'/infofile.txt','w')
    infofile.write(plot+'	'+width)
    infofile.close

# Function to define the parameters needed for further calculation
# read them from the infofile or the name of the directory
def parameters(directory, target):
    try:
        open(directory+'infofile.txt','r')
        raw_data =
        split(file(directory+'infofile.txt','r').readline(),'	')
        plot = raw_data[0]
        width = int(raw_data[1])
    except:
        plot = split(directory,'_')[1][4:]
        width = int(input("Enter width belonging to "+plot))
    nrpics = len(file(directory+'piclist.txt', 'r').readlines())
    outputfilename = './'+target+'p'+plot+'_par_w'+str(width)+'.jpg'
    return plot,width,nrpics,outputfilename

# Function to create a parallel photo mosaic!
# by clipping the centre columns and merging them together
# the number of centre columns is defined by "width"
# (modified after Menno Straatsma)
def clipmid(width, nrpics, directory, outfilename):
    sizefile = file(directory+'piclist.txt', 'r').readline()[:-1]
    dx,dy = Image.open(sizefile).size
    newim = Image.new('RGB', (width*nrpics,dy))
    filenamelist=[];
    ii = 0
    for jpgnameXL in file(directory+'piclist.txt', 'r').readlines():
        filename = jpgnameXL.strip()
        im = Image.open(filename)
        mid = dx/2
        ## Clip out the centre columns if width is even use and even
        ## number of columns else use an odd number
        if width % 2 == 0:
            box = (mid-(width/2), 0, mid+(width/2), dy)
        elif width % 2 == 1:
            box = (mid-(width/2), 0, mid+(width/2)+1, dy)
        else: print "Syntax Error, odd nor even!"
        region = im.crop(box)
        xul = ii * width;    yul = 0
        xlr = xul + width;    ylr = dy
        filenamelist.append(filename)
        ## Paste the centre columns to a new image
        newim.paste(region, (xul,yul, xlr,ylr))
        ii += 1
newim.save(outputfilename)
return newim, dx, dy, ii

# Function to write an extended infofile the the directory
# containing the original photographs
def writeinfofile(directory, newim, outfilename, ii, dxi, dyi, width):
    info = file(directory+'infofile.txt','w')
    info.write(plot+'	'+str(width))
    info.write('
New parallel file created and written to: '+outfilename)
    info.write('
nrpics	'+str(nrpics))
    info.write('
original filesizes (pixels)	'+str(tuple([dxi,dyi])))
    info.write('
created filesize (pixels)	'+str(newim.size))
    info.close()

##############
### RECALL ###
##############

## Now do the actual operations:
# 1) create a file with all directories containing photographs
# 2) create a file with all photographs in all directories
# 3) write initial infofiles in those directories
# 4) extract the parameters needed for the calculation
# 5) create the parallel photo mosaic and write it to "target"
# 6) write an extended infofile in all photo directories
os.system('ls -d DW* | more > dirlist.txt') # Note: specify the selection
criteria
create_dirlist(borders, format, extension)
write_ini_info()
# check if a file exists with the names of the original photographs in all
directories
if fileexists('piclist.txt','dirlist.txt'):
    for directory in file('dirlist.txt','r').readlines():
        directory = directory[:-1]+'/
        plot,width,nrpics,outputfilename = parameters(directory,target)
        newim, dxi, dyi, ii = clipmid(width, nrpics, directory,
        outputfilename)
        print 'plot: '+plot+' with width: '+str(width)+' saved as:
        '+outfilename
        writeinfofile(directory, newim, outputfilename, ii, dxi, dyi, width)
        print 'nScript finished succefully!!!\nMore info can be found in the
"infofile.txt" created in each directory'
else:
    print 'Error create proper infofiles first!'
Flowchart of the MeVisLab calculation to apply the hue threshold to a single image. The image was loaded by the “ImgLoad” module, subsequently the image was converted to HSV by the “ColorModelConverter” and the first band was used for further calculation (“Red Subimage”). The threshold was set by the “IntervalThres” module between 15 and 300 degrees. The “ImageStat” module calculated the fractional coverage. The other modules in the flowchart were used for visualization during the process.
Flowchart of the Python script to calculate the $VAI$ and $P$ values

**Slicing module**

**Function**
Select all laser points with a z-value in the disc, 1 meter around breast height

**File**
Locations of corners of the reference plots

**Density calculation module**

**Function**
Create polar grid

**Function**
Calculate the total number of points through distal cell boundary
$$N_{tot} = ppr_h \cdot \alpha \cdot ppr_v \cdot \beta$$

**Function**
Sample points before proximal and distal cell boundaries
$$N_{d0-d1} \quad N_{d0-d2}$$

**Function**
Convert the centres of all polar grid cells to xyz ordnance. Write coordinates and parameters to a file for Dv calculation

**Comparison module**

**File**
Tree locations and diameters (stem map)

**File**
Locations of corners of the reference plots

**File**
Scan locations (x,y,z)

**Function**
Calculate the $D_{V_{Nd}}$ value for the reference plots, based on the stem map

**Function**
Select polar grid cells inside the plot area

**Function**
Calculate $D_{V_{VAI}}$ and $D_{V_{P}}$ for every plot and write to a file
$$D_{V_{P}} = L^{-1} \cdot \ln \left( \frac{\sum N_{tot} - N_{d1-d2}}{\sum N_{tot}} \right)$$
$$D_{V_{d1}} = L^{-1} \cdot \ln \left( \frac{\sum N_{tot} - N_{d0-d1}}{\sum N_{tot} - N_{d0-d2}} \right)$$

**File**
Results: with plot ID, reference data and model calculations

**Function**
Present the data in scatter plots

**Files**
Xyz coordinates of polar grid cells with density parameters

**Files**
Input data from scanner (ASCII, xyz file)

**Function**
Select all laser points with a z-value in the disc, 1 meter around breast height

**Function**
Convert the points in the disc from xyz to $q\beta d$ ordnance

**Slicing module**

**Function**
Convert the centres of all polar grid cells to xyz ordnance.

**File**
Results: with plot ID, reference data and model calculations

**Function**
Calculate the $D_{V_{VAI}}$ and $D_{V_{P}}$ for every plot and write to a file

**Function**
Present the data in scatter plots
The Python script for PI and VAI

A Python script was programmed for the calculation of the PI and VAI values. The algorithm consists of three modules: the slicing module, the module for the density parameter calculation and the comparison module. In the slicing module the points, which have a z coordinate within the range of the slice were selected. Subsequently, for each point cloud, the points in the slice were converted from the orthogonal ordnance datum (x y z) to a polar coordinate system, around the scanner position (α β d). In the slicing module data reduction was applied by reducing the number of digits, to reduce the calculation time.

The density calculation module created the polar grid, sampled the Nd0-d1, Nd0-d2 and computed the N_{tot} values per cell. The α and d values of the centre of the polar grid cells were converted to x, y. Subsequently, the coordinates and all parameters needed for the calculation of the VAI were written to a file. When less than 20 points were reconstructed after the distal cell boundary, the cell was set to no data and was not included in the averaging process.

Finally, the comparison module was loaded, where the predicted density values were compared to the reference data. The closest scan position was selected using a lookup table. In this module, a crossing number algorithm was used to determine which centres of the polar grid cells fall inside the area of the reference plots, using the coordinates of the corners. After selecting all cells inside the plot area, the PI and VAI value were calculated using equation 8.4 and 8.6 and written to an ASCII file.
import os, sys
from numarray import *
from math import *
import numarray.ieeespecial as iee

Operations:
# (1) Define functions, data files and assign parameters
# (2) Select points in slice and convert points to angle-distance format
# (3) Calculate the min and max angles to the distal cell boundaries
# (4) Sample the points before the proximal and distal cell boundaries
# (5) Calculate the total number of points through the distal cell boundary
# (6) Calculate the VAI value per cell
# (7) Convert angle-distance of centre of cell to xy coordinates, create matrix
#     with all parameters needed for the density calculation and write to file

###############################
### FUNCTIONS ###
###############################

# Function to calculate the horizontal angle (0-360)
def arctanhorizontal(x,y):
    if x >= 0 and y >= 0:
        angle = atan(x/y)
    elif x >= 0 and y < 0:
        angle = pi + atan(x/y)
    elif x < 0 and y < 0:
        angle = pi + atan(x/y)
    elif x < 0 and y >= 0:
        angle = 2*pi + atan(x/y)
    else: print "Error in input values"
    return angle

# Function to calculate the vertical angle (0=looking down; 180=looking up)
def arctanvertical(l,z):
    # Where l is distance to scanner; z is height compared to scanner
    if -z < 0:
        b = atan(l/-z) + pi
    elif -z > 0:
        b = atan(l/-z)
    elif -z == 0:
        b = 0.5*pi
    else: print "Error in input values"
    return b

# Function to select values out of a 2 column matrix with row index "scan"
def get2cols(locations, scan):
    for a in locations:
        if a[0] == scan:
            x0 = a[1]; y0 = a[2]
        else:
            continue
    return x0, y0
# Function to get x, y, z locations out matrix with scan as index
def get3cols(locations, scan):
    for a in locations:
        if a[0] == scan:
            x0 = a[1]; y0 = a[2]; z0 = a[3]
        else:
            continue
    return x0, y0, z0

# Function to read a file with the TXT format (no header)
# and return a matrix. created by Menno Straatsma
def read(incolfile):
    lines = file(incolfile, "r").readlines()
    l = len(split(lines[0]))
    l_lines = []
    for line in lines:
        tokens = split(line)
        assert len(tokens) == l
        l_line = []
        for token in tokens:
            value = float(token)
            l_line.append(value)
        l_lines.append(l_line)
    del lines
    print "file", incolfile, "read: module ios.read()"
    return array(l_lines)

# Function to read a file with the EAS format and return a matrix
# created by Menno Straatsma
def read_eas(easfile):
    lines = file(easfile, "r").readlines()
    ncols = int(lines[1][:-1])
    liness = lines[ncols+2:]
    l = len(split(liness[0]))
    l_lines = []
    for line in liness:
        tokens = split(line)
        assert len(tokens) == l
        l_line = []
        for token in tokens:
            value = float(token)
            l_line.append(value)
        l_lines.append(l_line)
    print "file", easfile, "read: module ios.read_eas()"
    return array(l_lines)

# Function to read an file with the GEN format and return a listed matrix
# created by Menno Straatsma
def readGenfile(generatefile):
    a = file(generatefile, 'r').read()
    b = split(a, 'END')
    lop = [] # list of raw polygon information
    for polygon in b:
        c = split(polygon, '\n')
        if c[0] == '':
            del c[0]
        if c[-1] == '':
            del c[-1]
        if len(c) > 0:
            lop.append(c)
    labels = []
    vertexes = []
    for ii in lop:
J. Warmink  Utrecht University

label_ii = split(ii[0])
labels.append(float(label_ii[0]))
X = []
Y = []
for jj in ii[2:]:
    xy = split(jj)
    x,y = xy[0], xy[1]
    X.append(float(x))
    Y.append(float(y))
aX = array(X)
aY = array(Y)
aX.setshape(len(X),1)
aY.setshape(len(Y),1)
XY = concatenate(arrs=(aX,aY), axis = 1)
vertexes.append(XY)
return labels, vertexes

# Function to write a matrix to a file with the TXT format
# created by Menno Straatsma
def array2txt(array, tofile, format):
    fileout = file(tofile, "w")
    for row in range(array.getshape()[0]):
        for col in range(array.getshape()[1]):
            entry = array[row, col]
            entry = format % (entry)
            fileout.write(entry)
            fileout.write('
')
    fileout.close()
    print "file",tofile,"written"

# Function to write a matrix to a file with the EAS format
# created by Menno Straatsma
def array2eas(array, tofile, header, format):
    fileout = file(tofile, "w")
    fileout.write(header)
    for row in range(array.getshape()[0]):
        for col in range(array.getshape()[1]):
            entry = array[row, col]
            entry = format % (entry)
            fileout.write(entry)
            fileout.write('
')
    fileout.close()
    print "file",tofile,"written"

# Function to select the crossing number (odd or even) for a point in a polygon
# created by Menno Straatsma
def cn_PnPoly(P, V):
    cn = 0         # the crossing number counter
    V = tuple(V[1:])+(V[0],)
    # loop through all edges of the polygon
    for i in range(len(V)-1):
        if ((V[i][1] <= P[1] and V[i+1][1] > P[1])
            or (V[i][1] > P[1] and V[i+1][1] <= P[1])):
            # compute the actual edge-ray intersect x-coordinate
            vt = (P[1] - V[i][1]) / float(V[i+1][1] - V[i][1])
            if P[0] < V[i][0] + vt * (V[i+1][0] - V[i][0]):
                cn += 1
    return cn % 2

# Function to select the points inside a polygon
# using the crossing number algorithm (created by Menno Straatsma)
def PinP(points, pol):
    ll = []
    for point in points:
        ...
if cn_PnPoly(point, pol) == 1:
    ll.append(point)
return array(ll)

# Function to select the point outside a polygon
def PoutP(points, pol):
    ll = []
    for point in points:
        if cn_PnPoly(point, pol) == 0:
            ll.append(point)
    return array(ll)

# Function to sort a matrix on a specified column
def sort_along_col(array, index):
    col = array[:,index]
    indices = argsort(col, axis=0)
    out = zeros(array.getshape(), type=Float64)
    for ii in arange(len(col)):
        out[ii,:] = array[indices[ii,:]]
    return out

# Function to select the point in a slice and convert to abd.
#def calcABDslice(infilename, sldata):
    print "AlfaBetaDistance calculation started on file:",infilename
    x0, y0, z0 = sldata[0], sldata[1], sldata[2]
    dem, bh, sl, upper, lower = sldata[3], sldata[4], sldata[5], sldata[6],
    sldata[7]
    outfilename = infilename.split('.xyz')[0] + '_sl.abd'
    outfile = file(outfilename, 'w')
    infile = file(infilename, 'r')
    pins, pouts = 0, 0
    while 1:
        # Read the file line by line
        line = infile.readline().split()
        if len(line) < 2: break
        z = float(line[2])/1000-z0
        if lower <= z < upper: # Select points in slice
            x = float(line[0])/1000-x0
            y = float(line[1])/1000-y0
            a = arctanhorizontal(x,y)
            l0 = sqrt(x**2+y**2)     # Horizontal distance to scanner
            d = sqrt(l0**2+z**2)     # Hor+Vert distance to scanner
            b = arctanvertical(l0,z) # b is zero looking down to the bottom
            if b < 0 or b > pi: print 'ERROR beta:',b; break
            entry = "%.6f %.6f %.3f\n" % (a, b, d) # 6 digits results in a
accuracy of 2.5mm @ 25m distance
            outfile.write(entry); pins += 1
        else: pouts += 1
        print pins,"Points in slice and",pouts,"Points outside slice"
    outfile.close()
    print outfilename, 'written! conversion finished'
    return outfilename

# Function to calculate the angle from the scan position to the top and
bottom
# of the slice for each distal cell boundary to the scanner
#def calcBbins(sldata, lbins):
    print "Beta Bins calculation started...",
    bibins, b2bins = [], []
    upper, lower = sldata[6], sldata[7]
The first column of \( \text{lbins} \) is not used, cause it has an infinite angle so "\( \text{len(\text{bbins})=len(\text{lbins})-1} \)" results in \( b \) of the distal cell bounds for \( d \) in \( \text{lbins}[1:] \):
\[
\begin{align*}
  b1 &= \arctan_{\text{vertical}}(d, \text{upper}) \\
  b2 &= \arctan_{\text{vertical}}(d, \text{lower}) \\
  \text{bbins}.append(b1); \text{bbins}.append(b2) \\
\end{align*}
\]
\( \text{bbins} = \text{array(\text{bbins})}; \text{bbins} = \text{array(\text{bbins})} \)

Calculate vertical angle per cell from top to bottom of slice
\( \text{bbins} = \text{bbins} - \text{bbins} \) #The first cell has value of END of first cell!

print "Finished!"

return \( \text{bbins}, \text{bbins}, \text{bbins} \)

# Function to sample the number of points in the 3D-triangle
# before each proximal and distal cell boundary

\[
\text{def pointsBeforeCell(\text{matrix}, \text{abins}, \text{bbins}, \text{bbins}, \text{lbins})}:
\]

print 'Points Before Cell sampling started...' 

\[
\begin{align*}
  \text{polarBeforeBegin} &= \text{zeros((len(\text{abins})-1, len(\text{lbins})-1)))} \\
  \text{polarBeforeEnd} &= \text{zeros((len(\text{abins})-1, len(\text{lbins})-1)))} \\
  c &= 0; \ t = \text{float(len(\text{matrix}))}; \steps = \text{int(t/10)} \ # \ % \ printed \ to \ screen \\
\end{align*}
\]

# Put each laser point in a cell where polar[0,0] means angle <= astep and length <= lstep
for line in \text{matrix}:
    # next 2 lines are counter for percentage completed
    \[
    c += 1; \ j = c \ % \ steps \\
    \text{if } j == 0: \ \text{print } "%.0f percent completed"%(c/t*100) \\
    \]
    # DETERMINE IN WHICH WEDGE. # -1 needed to put between 0 and astep in polar cell 0.
    \[
    a = \text{searchsorted(\text{abins}, line[0])-1} \\
    \]
    # DETERMINE IN WHICH CELL. defined by: Bmin < B < Bmax AND d < d(cell-boundary)
    for \( i \) in arange(0,len(lbins)-1): 
        \[
        \begin{align*}
        b1, b2 &= \text{bbins}[i], \text{bbins}[i] \\
        \text{if } (b2 < line[1] < b1): \\
        \text{if line[2] < lbins[i]:} \\
        \text{polarBeforeBegin[a,i]} &= 1 \ # \ point \ before \ the \ proximal \\
        \text{cell \ boundary} \\
        \text{if line[2] < lbins[i+1]:} \\
        \text{polarBeforeEnd[a,i]} &= 1 \ # \ point \ before \ the \ distal \\
        \text{cell \ boundary} \\
        \end{align*}
        \]

print "Finished!, with size",polarBeforeBegin.getshape(),"and",polarBeforeEnd.getshape()
return \( \text{polarBeforeBegin}, \text{polarBeforeEnd} \)

# Function to calculate the theoretical number of pulses through the distal cell boundary

\[
\text{def pointsThroughCell(\text{polarBefore}, \text{astep}, \text{abins}, \text{bbins}, \text{HPRdef})}:
\]

print "Polar Grids with points THROUGH cell calculation started...", polarT = \( \text{zeros((\text{polarBefore.getshape()})}, \text{type=Float64)}) \\
for a in arange(len(polarT)):
    for d in arange(len(polarT[a])):
        polarT[a,d] = \text{astep*HPRdef[0]*bbins[d]*HPRdef[1]} \\
        if polarT[a,d] < polarBefore[a,d]: \\
        neg += 1 \\
        # Uncomment the line below to print an exception when the 
        # number of sampled points is larger then the reconstructed 
        # number for the same cell.
        ## print "Still too many points before", 
        a,d,polarT[a,d],'<',polarBefore[a,d] \\
        print "Finished!
\text{\"}\n\text{\"}with",neg,"cells where more points are before a 
\text{\"}cell, than went through"
        return polarT

# Function to convert the cell centres to xy coordinates and create a
# matrix with parameters needed

\text{J. Warmink}
# to calculate the Dv-VAI on plot level

def angle2coord(abins, lbins, sldata, csize, bMaxBins, bMinBins, polarIn, polarBeforeBegin, polarBeforeEnd, polarTotal, polarVAIc, polarVAI, polarInSampled, nBehindCutoff, polarP, polarA1nc, polarA2nc, polarTnc):
    print "Angle 2 coordinate started...",
    x0, y0 = sldata[0], sldata[1]
    # Determine the alpha, d coords of the centre of the cells and delete the last obsolete cell.
    abins = abins[:-1] + 0.5*astep;
    lbins = lbins[:-1] + 0.5*lstep
    mat, pnan, neg = [], 0, 0
    for a in range(len(abins)):
        for d in range(len(lbins)):
            x = lbins[d]*sin(abins[a]) + x0
            y = lbins[d]*cos(abins[a]) + y0
            # Enter all parameters to enter in the matrix
            nBegin = polarBeforeBegin[a,d]
            nEnd = polarBeforeEnd[a,d]
            nTot = polarTotal[a,d]
            nVAI = polarVAI[a,d]; if ieee.isnan(nVAI): nVAI = -999
            # Append them to the list
            mat.append([x, y, lbins[d], abins[a], bMinBins[d], bMaxBins[d], csize[d], nBegin, nEnd, nTot, nVAI])
    print "Finished!"
    return array(mat)

### FUNCTIONS TO COMPARE WITH REFERENCE DATA ###

# Function to calculate the Dv-Nd on plot level
# based on the stem map

def getDv(trees, plotdata, plots, names):
    ll = []
    for line in plotdata:
        nr, area = line[0], line[1]
        ii = searchsorted(names, nr)
        pol = plots[ii]
        intrees = PinP(trees, pol)
        Ntree = intrees.getshape()[0]
        d = average(intrees[:,2])
        Dv = Ntree * d / area
        ll.append(Dv)
    dv2 = array(ll)
    dv2.setshape(len(plotdata[:,0]),1)
    dv3 = concatenate(arrs = (plotdata, dv2), axis = 1)
    return dv3

# Function to calculate the Dv-Nd on plot level based on the stem map
# with the nr of twigs per stem

def getDvTwigs(trees, plotdata, plots, names):
    ll = []
    for line in plotdata:
        nr, area = line[0], line[1]
        ii = searchsorted(names, nr)
        pol = plots[ii]
        intrees = PinP(trees, pol)
        Ntree = intrees.getshape()[0]
        d = average(intrees[:,2])
        Dv = Ntree * d / area
        ll.append(Dv)
    dv2 = array(ll)
    dv2.setshape(len(plotdata[:,0]),1)
    dv3 = concatenate(arrs = (plotdata, dv2), axis = 1)
    return dv3

# Function to calculate the Dv-Nd on plot level based on the stem map, including the nr of twigs per stem
# using the nr of twigs per stem

def getDvTwigsNt(trees, plotdata, plots, names):
    ll = []
    for line in plotdata:
        nr, area = line[0], line[1]
        ii = searchsorted(names, nr)
        pol = plots[ii]
        intrees = PinP(trees, pol)
        Ntree = intrees.getshape()[0]
        d = average(intrees[:,2])
        Dv = Ntree * d / area
        dTwigs = diameterTwigs * nrTwigs
        Ntwigs = nrTwigs*Ntree
        ll.append(Dv)
    dv2 = array(ll)
    dv2.setshape(len(plotdata[:,0]),1)
    dv3 = concatenate(arrs = (plotdata, dv2), axis = 1)
    return dv3
Dvtwigs = Ntwigs * diameterTwigs / area
ll.append(Dv + Dvtwigs)
dv2 = array(ll)
dv2.shape(len(plotdata[:,0]),1)
dv3 = concatenate(arrs = (plotdata, dv2), axis = 1)
return dv3

# Function to merge scan position 2 and 3
def merge23(b):
    mat2 = read_eas('.\pointdata\Scan2_par.xyz')
    mat3 = read_eas('.\pointdata\Scan3_par.xyz')
a = 3
    mat2s = sort_along_col(mat2,a)
    mat3s = sort_along_col(mat3,a)
s2 = searchsorted(mat2s[:,a],b[0])
e2 = searchsorted(mat2s[:,a],b[1])
s3 = searchsorted(mat3s[:,a],b[0])
e3 = searchsorted(mat3s[:,a],b[1])
    mat = concatenate((mat2s[:s2],mat3s[s3:e3],mat2s[e2:]))
assert mat.getshape() == mat2s.getshape() == mat3.getshape()
array2eas(mat,'\pointdata\Scan23_par.xyz',outputformat,'%.8f ')
return mat

# Function to calculate the average Dv-VAI for the reference plot
# corrected for the random distribution of trees
# created by Menno Straatsma
def getDvTLS(plotdata, plots, names, scanID):
    dv1,dv2,dist = [], [], []
    for line in plotdata: # loop over plots
        nr = line[0] # Plot number
        scannr1 = line[scanID+1] # Select Scanner to use
        ii = searchsorted(names, nr)
        pol = plots[ii]
        VAIfile1 = '.\pointdata\Scan' + str(int(scannr1)) + '_par.xyz'
        VAIdata1 = read_eas(VAIfile1)
        TLS = PinP(VAIdata1, pol)
        TLS = sort_along_col(TLS, 2)              # sort along distance
        dmin, dmax = min(TLS[:,2])-0.25, max(TLS[:,2])+0.75
        bins = arange(dmin, dmax, 0.5)
        ll = []
        for ii in arange(len(bins))[0:-1]: # loop over cells with equal distance
            start, end = searchsorted(TLS[:,2], bins[ii]),
            searchsorted(TLS[:,2], bins[ii+1])
            cells_dx = TLS[start:end,:]
        # Calculate the total for all cells inside the plot area with equal distance
            Ntot = sum(cells_dx[:,10])
            Nd0d1 = sum(cells_dx[:,8])
            Nd0d2 = sum(cells_dx[:,9])
        # Calculate the VAI
            VAI_dx = (1 / 0.5) * log((Ntot-Nd0d1) / (Ntot-Nd0d2))
            a = [VAI_dx] * cells_dx.getshape()[0] # Multiply with number of cells
        for jj in a:
            ll.append(jj) # Create array with cell values
    VAI_dx_plot = array(ll)
    VAI_dx_plot.setshape(len(VAI_dx_plot),1)
    TLS = concatenate(arrs = (TLS, VAI_dx_plot), axis = 1)
    # Calculate the weighted average VAI value for the reference plot
    VAI = average(TLS[:,12], weights = TLS[:,6])
    dv1.append(VAI)
    # Calculate average distance of plot
distii = average(TLS[:,2], weights=TLS[:,6])
dist.append(distii)
dv1 = array(dv1)
dv1.setshape(len(plotdata[:,0]),1)
dist = array(dist)
dist.setshape(len(plotdata[:,0]),1)
## Create matrix with: [plotID, Ap, cs1, cs2, Nd, VAI-1, VAIpc, dist]
## where Ap is the total plot area and cs=closest scan position
return concatenate(arrs = (plotdata, dv1, dist), axis = 1)

######################
### SET PARAMETERS ###
######################
## Set the directory where the scan data is located
pref = '/home/jord/Graduate/TLSdata/
pdir = pref+'pointdata/

## Import the files containing the scan positions, number
## of points per radial and the elevation at the scan position:
locFile = read_eas(pref+'ScanLocations.eas')
HPRdefs = read_eas(pref+'pointsPerRad.eas')
groundLevel = read_eas(pref+'demAtScan.eas')

## Define the size and shape of the polar grid
lstep, cutoff, angleparts, sl, bh = .5, 25., 90., 1., 1.3
# Array of distance boundaries between the cells (columns)
lbins = arange(0,cutoff+lstep,lstep)
# Array of angle boundaries between the cells (rows)
astep = 2*pi/angleparts
abins = arange(0,2*pi+astep,astep)

# Set the threshold on the number of points behind a certain cell,
# below which no VAI is calculated
lnpt = 20.
# Calculate array with surface area of all cells
Acell = (pi*(lbins[1:])**2 - pi*(lbins[:-1])**2) / angleparts

# Set Format output format (header) of eas file...
outputformat="Density Per Scan Position (VAI output per scan)
11
Easting (m)
Northing (m)
Distance scanner-cell centre
Alpha
Beta min
Beta max
Cell size (m2)
N up to proximal cell boundary
N up to distal cell boundary
N total through distal cell boundary
VAI value (m-1)
"

# Read the data for the comparison with the reference data
gen = readGenfile('stemplots7.gen') # File with coordinates of
reference plots
names = gen[0]; plots = gen[1]
scanlocos = read_eas('ScanLocations.eas') # File with the scan locations
trees = read_eas('treesCoordRad.eas') # File the stem map
for scan in arange(1,10):
    HPRdef = get2cols(HPRdefs,scan)
    infilename = pdir+'Scan'+str(scan)+'.xyz'
    base = infilename.split('.')[0]
    print "\n1) PROCESSING SCAN:"
    dem = groundLevel[scan-1,1]
    x0,y0,z0 = get3cols(locFile,scan)
    upper = 0.5*sl+bh+dem-z0
    lower = upper - sl
    slicedata = tuple([x0, y0, z0, dem, bh, sl, upper, lower])
    # i) Select points and convert *.xyz to *.abc
    outfilename = calcABDSlice(infilename, slicedata)
    # Read all points in the memory
    matrix = read(outfilename)
    # ii) Calculate Bmin, Bmax
    bbins, b1bins, b2bins = calcBbins(slicedata, lbins)
    # iii) Sample points in wedge between scanner and proximal and distal
    cell boundary
    polarBeforeBegin, polarBeforeEnd = pointsBeforeCell(matrix, abins, bbins, b2bins, lbins)
    # iv) Calculate total points through cell
    polarT = pointsThroughCell(polarBeforeEnd, astep, abins, bbins, HPRdef)
    # v) Calculate VAI-value per cell
    polarA1=polarT-polarBeforeBegin
    polarA2=polarT-polarBeforeEnd
    # Set the VAI for all cells with less than "lnpt" points to no-data
    polarA2[polarA2<lnpt] = ieee.nan
    # Apply the VAI model
    polarVAI=1/lstep*log(polarA1/polarA2)
    # vi) Convert the cell centres to xy coordiantes and create matrix with
    # parameters
    ParMat = angle2coord(abins, bbins, slicedata, Acell, b1bins, b2bins, 
    polarBeforeBegin, polarBeforeEnd, polarT, polarVAIc)
    # Write this matrix to a file for comparison with the reference data
    array2eas(ParMat, base+'_par.xyz', outputformat, '%.8f ')
    print "\n\nI finished the density parameter calculation"
    print "\nContinue to compare the results with your manual measurements"

## Merge scans 2 and 3 according to borders
borders = [1.29, 3.30]
polar23 = merge23(borders)

## Calculate the reference data
plotdata = read_eas('plotdata.eas')
plotdataDv = getDvTwigs(trees, plotdata, plots, names)
# Calculate the VAI values for the reference plot
plotTLS1 = getDvTLS(plotdataDv, plots, names, 1)
plotTLS2 = getDvTLS(plotTLS1, plots, names, 2)
# Write the data to a file for further use
array2txt(plotTLS2, 'ResultsVAI.txt','%.4f\t')
Appendix C

Field results

C.1 Fieldform

C.2 Field results
## Field Form

<table>
<thead>
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**Gebiedsomschrijving; Opmerkingen & Weersomstandigheden**

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**Gebiedstekening**

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**Digitale Fotografie (parallelle projectie)**

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Plot ID
Different plot numbers are measured at different locations. The characters after the plot number represent different measurements at the same location.

Where:
ctr = the centre of the photo mosaic is at the photo height
lwr = a layer is used to determine the fractional coverage, which is selected from the original photo mosaic and represents the vegetation layer 15 cm above ground level
a, b = variation in the measurement method: for example small and large opening angle or different plot length etc.
The number between brackets for the winter plots, represent the plot number of the summer measurement at the same location.

Vegetation classes (for comparison with the reference data)
val = validation plot
leaf = forest plot not suitable for validation, because many side branches or leaves were present
herb = herbaceous vegetation, measured with a red background at the half vegetation height
low = herbaceous vegetation, measured at 15 cm above ground level
large = plot measured with a large opening angle of the camera
grass = natural grassland (not compared to the reference data, because only 2 measurements were taken)
omitted = erroneously measured plot (no fractional coverage was determined)

Vegetation types recorded in the field following the vegetation handbook (Van Velzen et al., 2003)
hf = hardwood forest
swf = softwood willow forest
shrub = shrub vegetation consisting of hawthorn
grass = natural grassland
h-ct = herbaceous vegetation with dominant creeping thistle
h-sn = herbaceous vegetation with dominant stinging nettle
h-sr = herbaceous species rich vegetation
reed = reed marches