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DIGITAL AERIAL PHOTOGRAMMETRY FOR ESTIMATING FOREST INVENTORY ATTRIBUTES: APPLICATIONS FOR SPATIAL AND TEMPORAL ANALYSIS

CHRISTOPH STEPPER

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Chair:		Univ.-Prof. Dr.-Ing. Stephan Pauleit
Dissertation examiners:	1.	Univ.-Prof. Dr. Dr. h.c. Hans Pretzsch
	2.	Univ.-Prof. Dr. Thomas Knoke
	3.	Univ.-Prof. Dr. Clement Atzberger (Universität für Bodenkultur Wien)

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CHRISTOPH STEPPER

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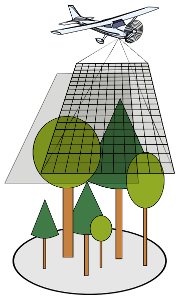

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E-MAIL:
c.stepper@mytum.de

SUPERVISOR:
Prof. Dr. Dr. h.c. Hans Pretzsch

The title page shows an artwork displaying the acquisition of overlapping digital aerial images and trees measured on a ground plot (own drawing).

This document was set in LaTeX using the `classicthesis` and `arsclassica` packages.

I have found the best way to give advice to your children
is to find out what they want and then advise them to do it.
— *Harry S. Truman*

Dedicated to the loving parents Elisabeth and Ludwig Stepper.

ABSTRACT

Information about canopy height and spatial structure is essential for various tasks in forest planning and management. Retrieving this information from remote sensing data has been focus in research as this technique opens the possibility to assess large forested areas. The work presented in this thesis focussed on utilizing digital aerial imagery from airborne platforms to generate accurate measurements of canopy height by means of image matching algorithms. Together with ground information, necessary for model calibration, different forest inventory attributes can be assessed ...

ZUSAMMENFASSUNG

Informationen über die Bestandeshöhe und die räumliche Verteilung der Bäume in einem Bestand ...

PUBLICATIONS

List of scientific papers included in this thesis.

This dissertation was done in a publication-based manner. The developed methods, the results of the different studies, and the findings were published in the following scientific papers:

Immitzer, M., Stepper, C., Böck, S., Straub, C. and Atzberger, C. (2016). Use of WorldView-2 stereo imagery and National Forest Inventory data for wall-to-wall mapping of growing stock. *Forest Ecology and Management* **359**, 232–246. DOI: 10.1016/j.foreco.2015.10.018.

Stepper, C., Straub, C. and Pretzsch, H. (2015a). Assessing height changes in a highly structured forest using regularly acquired aerial image data. *Forestry* **88** (3): 304–316. DOI: 10.1093/forestry/cpu050.

Stepper, C., Straub, C., Immitzer, M. and Pretzsch, H. (submitted). Using canopy heights from digital aerial photogrammetry to enable spatial transfer of forest attribute models: a case study in central Europe. *Scandinavian Journal of Forest Research*.

Stepper, C., Straub, C. and Pretzsch, H. (2015b). Using semi-global matching point clouds to estimate growing stock at the plot and stand levels: application for a broadleaf-dominated forest in central Europe. *Canadian Journal of Forest Research* **45** (1): 111–123. DOI: 10.1139/cjfr-2014-0297.

Straub, C. and Stepper, C. (in press). Using digital aerial photogrammetry and the Random Forests approach to model forest inventory attributes in beech- and spruce-dominated central European forests. *Photogrammetrie, Fernerkundung, Geoinformation (PFG)*.

White, J. C., Stepper, C., Tompalski, P., Coops, N. C. and Wulder, M. A. (2015). Comparing ALS and Image-Based Point Cloud Metrics and Modelled Forest Inventory Attributes in a Complex Coastal Forest Environment. *Forests* **6** (10): 3704–3732. DOI: 10.3390/f6103704.

The papers cover different studies completed during the course of my Ph.D. I realised these studies both with my colleagues at the Bavarian State Institute of Forestry as well as in collaboration with scientists from other research institutes.

In general, the remote sensing problem
can be presented as inferring the order
in the properties and distributions of matter
and energy in the scene from the set
of measurements comprising the image.

— Strahler et al., 1986

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I would like to take the opportunity to thank all those involved in the work I did in the last years. Without your help and support, I would not have been able to mastering the challenges on my way to this thesis.

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ACRONYMS

ABA	area-based approach
ALS	airborne laser scanning
ACS	angle-count sampling
BaySF	Bayerische Staatsforsten
CHM	canopy height model
DAP	digital aerial photogrammetry
DBH	diameter at breast height
DSM	digital surface model
DTM	digital terrain model
GSD	ground sampling distance
LiDAR	Light Detection and Ranging
ME	mean error
MFI	management forest inventory
NFI	national forest inventory
NVI	Northern Vancouver Island
OLS	ordinary least squares
oob	out-of-bag
PAI	periodic annual increment
RF	random forest
RMSE	root mean squared error
SGM	semi-global matching
WV2	WorldView-2

Part I

DIGITAL AERIAL PHOTOGRAMMETRY FOR ESTIMATING FOREST INVENTORY ATTRIBUTES: APPLICATIONS FOR SPATIAL AND TEMPORAL ANALYSIS

1 INTRODUCTION

1.1 REMOTE SENSING IN FORESTRY

The development of remote sensing is strongly linked with the progress of flight – across different realms from sky to space – with a rather short scientific history. Accordingly, the definition of the term *remote sensing* itself has been evolving over the decades, and even today, scientists do not agree on one universal term. However, as a common basis in the scientific field, a general definition in the broad sense can be the following (Franklin, 2001; Hildebrandt, 1996):

General definition of remote sensing.

> Remote sensing is the acquisition of information about objects or areas from a distance, without making physical contact with them. Further, the processing and analysis of the acquired data as well as the interpretation of the achieved results are essential parts of remote sensing. The predominant aim in remote sensing applications is to achieve quantitative and qualitative information about the occurrence (pattern) of objects, their current state as well as the changes over time.

When considering objects on the earth's surface, sensors for acquiring data are typically mounted on aircrafts or satellites. Generally, the sensors collect information by detecting electromagnetic radiation, which is emitted or reflected from the observed objects. Two basic principles of remote sensing data acquisition technologies can be distinguished: (i) passive remote sensing systems, which gather the natural energy that is emitted or reflected by the earth's surface, most commonly the reflected sunlight, and (ii) active remote sensing systems, which themselves emit electromagnetic radiation and measure the reflectance pattern returning from the earth's surface.

Passive and active remote sensing systems.

Examples for passive remote sensing systems include aerial photography or many earth observation satellite systems with multispectral sensors, e. g., Landsat or Sentinel 2. Radar and airborne laser scanning (ALS) are examples of active remote sensing, with both technologies measuring the time delays between emission and return, allowing for the assessment of object location and other properties.

From the advent of these new technologies, remote sensing allowed for the collection of data for vast and difficult-to-access areas. Thus, researchers and practitioners charged with mapping and analysis of natural environments like forests were early adopters to these data sets. Today, due to the fact of a widespread range of applications in forestry, including different scales in space (i. e., from needle to landscape to global) and time (i. e., from seconds to seasons to decades), a large variety of sensors are employed to best meet the research and practical necessities. The following list, which makes no claim to be complete, should facilitate the reader to get a brief overview of important remote sensing systems and their primarily applications.

A large variety of remote sensing systems are used in forestry applications.

EARTH OBSERVATION SATELLITE DATA: Earth observation satellites are purposely designed to acquire data for characterizing environmental systems on a global scale. As the satellites continuously navigate around the globe, images covering vast areas can be recorded with high temporal repetition rates.

In environmental studies, data from earth observation satellites are typically utilized as information source to create maps of land cover and land use. Many of these satellite systems are designed for long-term global observations, and the image series of these satellites recorded through time make them a primary data source when conducting time series analysis for assessing change pattern, e. g., to quantify forest cover change etc. Technically speaking, most of the applications dealing with satellite imagery can be assigned to the image classification domain.

AERIAL PHOTOGRAPHS: Aerial photographs (airphotos) were pretty much the first largely available remotely sensed data source and have been used manifold in forest research and practice with different fields of applications (see section 1.2). For instance, these data found use in forest management planning or forest inventory in different regions.

AIRBORNE LASER SCANNING: Airborne laser scanning (ALS), also referred to as airborne Light Detection and Ranging (LiDAR), has been introduced to forest research in the 1980s and 1990s (Nelson, 2013), and is now widely acknowledged as the primary source to acquire information characterizing the three-dimensional forest vertical structure (Lim et al., 2003; Maltamo et al., 2014). ALS can be used to measure the surface height of objects, e. g., trees, similarly to the photogrammetric measurements from stereo airphotos.

However, the laser pulses emitted from the measuring platform are able to penetrate through small gaps in the canopy, and returns from leaves, branches, or stems additionally allow for the characterization of the vertical canopy structure. Moreover, returns from the ground enable ALS to even map the terrain underneath forest canopies with high accuracy. This property, the availability to actually measure heights of objects within the canopy and of the ground – which is invisible from optical aerial or satellite images – made ALS very attractive for forestry applications and stimulated enormous research efforts to fully explore the usability of these data.

1.2 AERIAL PHOTOGRAPHY, AIRBORNE LASER SCANNING AND THE RENAISSANCE OF AERIAL PHOTOGRAMMETRY

1.2.1 Acquisition principles for aerial photographs

Typically, aerial photographs are considered as perspective pictures of the underlying area taken with cameras mounted on aircrafts. In most acquisition cases, vertical photographs are recorded, i. e., the camera is pointing vertically down towards the mapped area. To cover larger areas of interest, aerial image acquisitions are planned and conducted in a block layout: the aircraft is following a series of parallel flight lines, and photographs are taken such that they overlap to a specified amount in both directions along track (*forward*) and across track (*side*; see Figure 1).

Vertical airphotos are perspective pictures of the underlying area with the camera pointing down vertically to the ground.

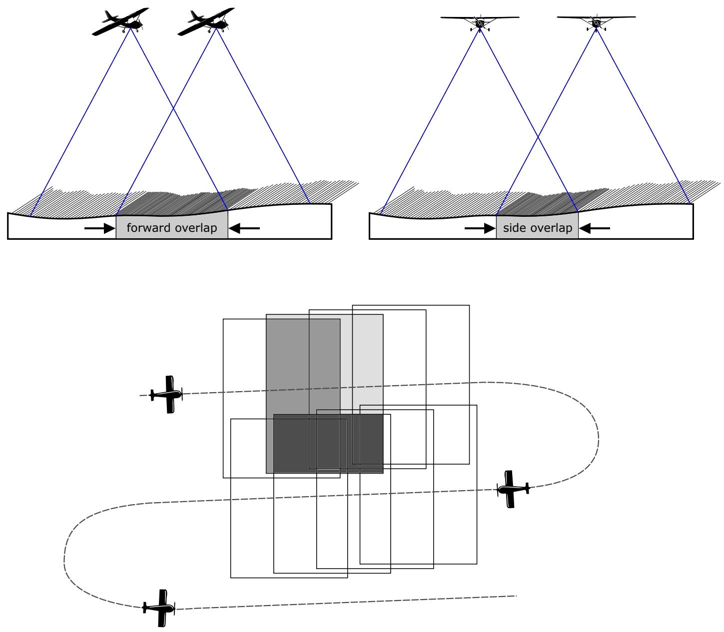

Figure 1: Exemplary setting for aerial photograph acquisitions. The typical overlaps of the images within flight lines (*forward*) and across flight lines (*side*) range between 60–80 % and 20–40 %, respectively (modified after van Laar and Akça, 2007 and Arbeitsgruppe Forstlicher Luftbildinterpreten, 2012).

Overlapping areas of airphotos allow for photogrammetric analysis.

In this way, each object within the study area is depicted from at minimum two different positions. The overlapping parts of the images are referred to as the stereoscopic overlap areas, which can be analysed following the stereophotogrammetric measuring principle. This allows for the recovery of exact positions of surface points, i. e., estimating the three-dimensional coordinates of specific points or objects.

1.2.2 Early forestry related applications of aerial photography

The use of aerial photography for mapping and monitoring forested landscapes can look back upon a long tradition (Hildebrandt, 1996). Airphotos have been routinely interpreted for several decades by natural resource scientists and managers, most commonly to assist in the mapping of large areas and to inform forest inventory programs (Arbeitsgruppe Forstlicher Luftbildinterpreten, 2012; Cohen et al., 1996; van Laar and Akça, 2007) .

The very first documented trial for utilizing aerial photographs for practical forestry was undertaken as early as 1887, when photos taken from a balloon were used to sketch a map of forest stands close to Berlin in Germany (Hildebrandt, 2010). In subsequent years aerial photographs have been employed for forestry routine tasks throughout the world. This development was especially promoted after the First World War when steerable aircrafts were available and aerial frame cameras were invented.

Airphotos have been used for mapping, for support of forest inventory and management planning, and for monitoring forest vitality.

Typical purposes of application include large scale mapping (e. g., 1:10 000) and forest management planning for intensively managed forests (as common in many European jurisdictions) or in support of region-wide inventory programs with delineations of forest cover maps (like often necessary in North American regions). Further, the aerial imagery has been used for laying out and mapping forest road networks, and, especially with the advent of the colour-infrared film, for monitoring forest vitality and detecting areas damaged by, e. g., storms or bark beetle infestations (Hildebrandt, 1996).

Whereas until today aerial photographs are used as one of the main sources of information for the aforementioned areas of application, the full potential of stereoscopic aerial photo-interpretation has not been unfold until the recent past. From the beginning of aerial photography, analogous taken pictures were the primary source of information and a lot of manual processing was necessary prior to analysis. Stereo-interpretation was labour-intensive and required a high level of training. Due to that, orthophotos were utilized for analysis in many applications instead of conducting expensive stereo photo-interpretation. Hildebrandt (1996) emphasized that even 100 years after the first application of airphotos in forestry, these data are seldom used for forest mensuration purposes or for forest site assessment.

1.2.3 Height assessment via stereophotogrammetry

Stereophotogrammetry allows for the measurement of 3d coordinates.

The most valuable technological achievement of stereophotogrammetry is the ability to actually measure the three-dimensional coordinates of objects, which can be identified in at least two overlapping images. Having this stereophotogrammetric measuring principle on hand, it seems logical, that tree height is the most important dendrometric attribute which can be assessed via stereo aerial photographs (Paine and Kiser, 2012).

For exact tree height measurements, tree top and base must be visible in the aerial photographs.

However, the exact measurement of tree heights is restricted to those trees, where both the tree top and base is visible in the photos. In dense forest stands, it actually is impossible to find ground points in the close vicinity to the trees of interest, in order to get the required elevation of the tree base. This shortcoming when using aerial photogrammetry as sole remote sensing information source is one reason which impeded the broad use for tree height measurements – and for assessing stand heights and related attributes of interest.

Cross-sectional canopy profiles can be used to approximate growing stock.

Soon after the widespread integration of aerial photographs in forestry, researchers examined their usefulness for forest mensuration tasks, in particular for determining growing stocks of forest stands. Pioneer work was done by Hugershoff (1933) and Neumann (1933). They introduced an approach based on continuous surface measurements and consecutive derivations of vertical canopy extents, resulting in cross-sectional canopy profiles of forest stands (Figure 2). In their work, they could demonstrate that the cross-sectional areas of the canopy profiles were apparently related to the amount of timber volume at the site of the profile. Spurr (1948) mentioned, that this method is especially useful when approaching uneven-aged stands, as variations in tree height and stand density are considered. By constructing multiple parallel cross-sectional profiles of the forest stand of interest, the *growing space* describing the canopy volume could be constructed and used as proxy for growing stock.

However, due to the difficulty to determine these profiles with the analogue instruments available at that time, the method could not gain acceptance for widespread use. Meanwhile, researchers seized on that approach as the development of better instruments facilitated the construction of canopy profiles based on stereo aerial photographs. As an example, Maclean and Martin (1984) measured cross-sectional canopy profile areas from stereoscopic aerial photographs with a stereoplotter, and related these areas

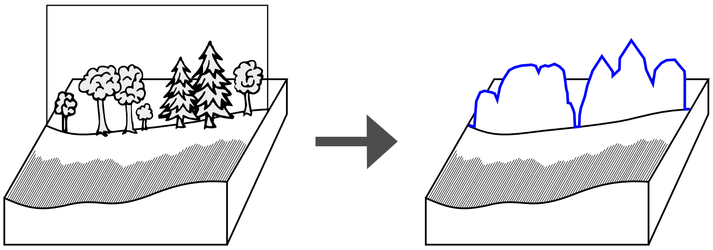

Figure 2: Basic idea of the cross-sectional canopy profile derived from measurements of the three-dimensional forest canopy structure. Detailed measurements of the outer canopy surface are achievable by both the DAP and ALS technology. However, photogrammetric measurements of the ground are restricted to gaps in the canopy. By contrast, active ALS-measurements allow for a detailed description of the terrain even for densely stocked forests. Thus, by combining photogrammetric height measurements of the canopy surface and ALS measurements of the ground, detailed descriptions of actual forest heights become possible (modified after Aldred and Bonnor, 1985, Nelson et al., 1984 and Nilsson, 1996).

to timber volume data. They reported the relations to be highly significant, with regression R^2 values ranging from 0.67 to 0.79.

Drawbacks of photogrammetric tree height measurements impede extensive application.

Nonetheless, two main aspects remained unsolved until the recent decades and hampered the further integration of these approaches for assessing forest inventory attributes:

- Conducting the methods described above with analogous instruments means a high effort in terms of manual work, when height measurements for the coverage of larger forest areas is desired.
- In dense forests, photogrammetric measurements of ground heights are restricted to irregularly distributed canopy openings. Interpolation of these sparse terrain height measurements results in inaccurate descriptions of the forest floor, especially for rough terrains. These errors in terrain height are propagated into tree- and stand-height measurements.

1.2.4 Airborne laser scanning in forestry

ALS was introduced to forest research in the 1980s, focusing on assessing tree height and crown closure.

As mentioned, the three-dimensional characterization of forest canopies by means of remote sensing tools has long been one of the top priority requests. Over the course of the 1980s, a new technology loomed on the horizon. ALS was expected to provide detailed measurements of forest canopies, and in consequence, a lot of research concentrated on exploring the newly opened possibilities. Pioneer work was published, e. g., by Aldred and Bonnor (1985) and Nelson et al. (1984), who primarily focused on the assessment of tree heights and crown closure.

Airborne LiDAR-based cross-sectional profiles were regressed against timber volume.

Maclean and Krabill (1986) picked up the ideas of Hugershoff (1933), and regressed timber volume against cross-sectional areas of canopy profiles of forests obtained by airborne profiling LiDAR systems. They elaborated on the mensurational significance of the variable *cross-sectional profile area* as a remotely sensed wrapper variable for total tree height, crown diameter and crown closure – three sensitive indicators for timber volume. In their study, Maclean and Krabill (1986) demonstrated that the cross-sectional profile area is a very good indicator for the total amount of timber on a site.

Nelson et al. (1988) tested a number of different laser metrics as predictor variables to develop regression models for timber volume and forest biomass. The set of metrics comprised different measurements of forest height and canopy density. In their analysis, mean canopy height (calculated from the laser pulses and directly proportional to the canopy profile area) proved to be best suited as independent laser variable for predicting timber volume and biomass, respectively.

As stated by Baltsavias (1999), commercial ALS systems became widely available during the 1990s. These scanning systems were able to record area-covering measurements in contrast to the early profilers, and such provide much greater distributions of height samples. Research studies, in the beginnings conducted especially in the Scandinavian countries, examined the usability of the ALS systems in forestry applications.

Nilsson (1996) investigated how ALS data acquisition parameters (laser beam footprint size and sampling density) affect stand height estimation. He further explored the usability of these data for determining stand specific volumes in an even-aged stand dominated by Scots pine in Sweden. He found that the laser mean heights underestimated the ground measured mean tree heights, irrespective of beam divergence. In addition, he could demonstrate, for that study site, that there existed a linear relationship between stand volume and an ALS-based metric including laser height and pulse density.

Næsset (1997a) used ALS data to approximate the mean tree height of forest stands in Norway, dominated by either Norway spruce or Scots pine, and reported promising results. For the same stands, he assessed the accuracy of volume estimation by means of multiple regression analysis, utilizing ALS predictor variables describing mean vegetation heights and canopy cover densities (Næsset, 1997b). He found that mean stand height and mean height of the laser returns (which might be regarded as per area unit of normalized canopy volume) were the most significant predictors for stand volume. The inclusion of the canopy cover metric, however, had a significant impact on the regression.

Consecutive research was conducted, e. g., by Magnussen and Boudewyn (1998) or Means et al. (2000), who reported on successful ALS applications in British Columbia and Oregon, respectively. The former study primarily focused on the exploration of a large set of possible predictor variables, which can be calculated from the airborne laser scanner measurements, for approximating forest stand heights. The latter demonstrated that ALS data are capable to produce sound predictions for stand characteristics such as height, basal area and volume. Interestingly, when using the LiDAR metrics in stepwise regression analysis, height percentile metrics as well as canopy cover metrics were selected for the final models of basal area and volume. Means et al. (2000) further proposed, that ALS was now a readily available source of information, which can be used to estimate stand characteristics over large areas – and after streamlining the process, maps displaying the spatial distribution of forest inventory attributes can be produced.

Following Means et al. (2000), Næsset and Bjerknes (2001) explored how accurately mean heights of the dominant trees and numbers of stems can be predicted from ALS metrics over young coniferous forest stands in Norway. In their regression analysis, they applied multiplicative models (in linear form with logarithmically transformed variables) to develop the predictive models. The final models for dominant height and stem number achieved coefficients of determination (R^2) of 0.83 and 0.42, respectively, with the finally selected predictors being the 90th height percentile plus the laser canopy density for the first and canopy density solely for the second attribute. More important for practical use in forest management, Næsset and Bjerknes (2001) proposed a two-stage procedure for the prediction of mean dominant stand height. To do so, empirical relations between various ALS metrics and tree heights measured in the field can be built using small georeferenced sample plots. In the second stage, the forest area of interest gets divided into equal-sized cells with the single areas corresponding to the sample plots. The trained models can then be applied to provide estimates of tree heights for the respective cells, and in consequence, for the stands throughout the forests. They evaluated their approach using 29 sample plots for training and 12 test stands, for which they report a mean height difference of 0.23 m between laser-derived and ground-truth stand heights.

In his 2002 paper, Næsset expanded the practical two-stage procedure for the prediction of six forest inventory attributes: mean tree height, dominant height, mean diameter, stem number, basal area, and timber volume (Næsset, 2002a). He tested the procedure for young and mature forest stands following the same statistical methods as described in Næsset and Bjerknes (2001), and concluded that the selected characteristics can be determined at the stand level with fairly high precision except for stem number. In subsequent years, this approach received much attention and was implemented to practical application for large-scale forest inventory and management throughout different forest ecosystems (Hudak et al., 2006; Hyyppä et al., 2008; Li et al., 2008; Næsset, 2004; Næsset et al., 2004; Woods et al., 2011).

The great relevance of ALS in forestry applications, especially for the approximation of forest inventory attributes using the area-based approach was confirmed by White et al. (2013a), who summarized the state-of-the-art approaches, methods, and data. In their best practices guide, they described the entire process for generating forest inventory attributes from ALS data. Additionally, they discussed the use of different statistical methods for fulfilling the estimation tasks, including machine learning appraoches like random forest (RF), which became popular recently. They further pointed to the fact, that there was currently increasing interest to the use of point clouds generated from high resolution digital aerial imagery, particularly for employing these data to generate estimates of forest characteristics in the same way as described above for ALS data.

1.2.5 Digital images and processing capabilities

During the last decade, aerial photography, and more specifically the photogrammetric evaluation capabilities of stereo airphotos, experienced increased attention in forestry related remote sensing research activities (Holopainen et al., 2015; White, 2016; White et al., 2013b). This development has been instigated by a number of different factors (Haala and Rothermel, 2012; Leberl et al., 2010):

- ongoing improvements in camera technology, especially the introduction and further developments of digital aerial cameras;
- nation-wide availabilities of digitally recorded aerial imagery acquired within routine observation programs run by the surveying authorities;

- inventions of advanced algorithms for image matching such as the pixelwise semi-global matching (SGM) and implementations to popular remote sensing software packages;
- rapid progress in hardware capacities enabling for the processing of large image blocks and the computed DAP products.

The digital acquisition of airborne stereo photography achieved a breakthrough in administrative surveying in many jurisdiction, particularly in central and northern European countries. Due to that, the availability of good quality photographs with large degrees of overlap has been boosted in recent years.

Moreover, the development of new algorithms for image matching, which allow for the computation of dense photogrammetric height measurements from stereo imagery, triggered increasing interest in digital airphotos as additional data source for retrieving 3d information. Thus, today DAP is emerging as an alternate data source to ALS for the three-dimensional characterization of forest structure.

1.3 PREDICTION OF FOREST INVENTORY ATTRIBUTES

As mentioned above, one major field of application for remote sensing in forestry is forest inventory. Remote sensing data, particularly airphotos, have been commonly used to assist in inventory tasks, either as auxiliary data to facilitate inventory design or for other purposes.

Nonetheless, with regard to both large-area inventories like national forest inventories (NFIs) or inventories purposely conducted for management issues (MFIs), the primarily used information is still gathered via ground based measurements at defined field sample plots. Especially with regard to the intensively managed forest compartments as common in many European forest enterprises, these inventories are the basis for both forest management planning and control.

Most often, the ground plots are laid out systematically on a defined grid (e.g., 200 m x 200 m) throughout the forests, and cover specified areas (e.g., 500 m^2), in order to achieve representative measurements (e.g., Neufanger, 2011). Those field measurements allow for reliable assessments of the natural resources when considering the complete forest enterprises or specific strata. However, these inventories were not purposely designed to allow for statements at the level of the forest stand, the primary unit of area for forest management.

In contrast to the sample based measurements from terrestrial forest inventories, remote sensing provides data able to cover large areas. By combining both data sources, the ground based measurements of the current forest state as response variable, and the remotely sensed data providing explanatory information, in a statistical manner, prediction models for forest inventory attributes by means of remote sensing can be trained and consequently applied to generate area-covering predictions (White et al., 2013a). Next, these spatially explicit predictions can be used to assist in forest management, as they can provide information in a high spatial resolution.

One common method to accomplish the described necessity for approximating forest inventory attributes and to consecutively predict their numerical values for wall-to-wall mapping is the area-based approach (ABA). This

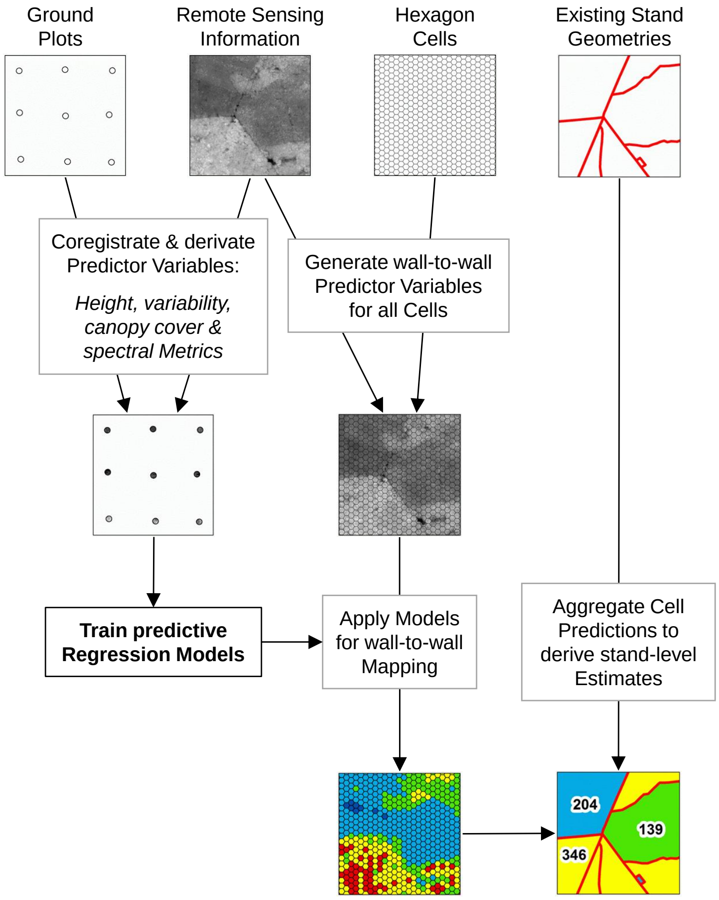

Figure 3: Schematic illustration of the area-based approach for prediction and wall-to-wall mapping of dendrometric forest inventory attributes.

approach, first proposed by Næsset (2002b) for use with ALS data in large-scale inventory, can be summarized in the processing steps as outlined in Figure 3.

In order to compute the statistical metrics summarizing the remotely sensed measurements of the forest canopy, recorded measurements have to be translated into heights above ground before further use. As mentioned above, one of the most beneficial aspects of ALS is the possibility to simultaneously acquire height measurements from the vegetation and the underlying terrain. Thus, ALS data can be directly converted to canopy heights above ground, and used in consecutive analysis. By contrast, photogrammetrically computed heights only describe the outer surface heights – this makes it necessary to employ ground heights from another source (e. g., ALS), to arrive at the canopy heights above ground.

On a related note, when analysing and further processing these kind of 3d data, one has the option to either stick to the point data, or to translate the irregular measurements to rasterized surface models. Following the first option, no loss in information has to be accepted, but specialized software is necessary for further processing. On the other hand, following option two, which is compelling due to the ease in data storage and the availability of raster processing tools, the operator has to select an appropriate spatial resolution for the computed rasters and has to keep in mind that by the rasterization, some detail information gets lost.

1.4 DIGITAL AERIAL PHOTOGRAMMETRY IN FOREST INVENTORY APPLICATIONS: CURRENT STATE

As mentioned in the previous sections, different technical and methodological developments caused the returning interest of forest scientists and practitioners to aerial photographs, in particular to DAP. Therefore, and due to the achievements made with ALS data in the meanwhile, it is logical that this stimulated great interest in exploiting the digital imagery to generate ALS-like characterizations of vegetation three-dimensional structure, especially as airphotos can be acquired at a fraction of the costs of LiDAR.

The recent focus of work with DAP data in forestry applications was particularly on its use in forest inventory. This development is confirmed by the heavily increased number of published research dealing with these questions in recent years. The following is an attempt to summarize the current developments and research results in this specific field, as the aims and objectives of the work in hand are embedded in this general framework and especially focussed on the use of DAP data for forest inventory tasks and to support forest management.

At the beginning of this decade, numerous studies focused on the comparison of DAP-based height data and ALS data for estimation forest inventory attributes following the ABA. Initially, studies from Scandinavia were published (Bohlin et al., 2012; Järnstedt et al., 2012; Nurminen et al., 2013; Vastaranta et al., 2013), investigating the predictive capabilities of DAP-based height data for a set of attributes. These studies were conducted for managed forests in flat terrain – mostly even-aged stands with few species.

ERGEBNISSE DER STUDIEN ZUSAMMENFASSEN

Later on, research was also conducted for different and more complex forests, e. g., in central Europe (Straub et al., 2013) or the boreal of Ontario, Canada (Pitt et al., 2014). Under these more challenging conditions, the comparison of model performance for approximating forest inventory attributes approved the results from the formerly conducted studies: the models using ALS-based predictor variables achieve somewhat higher accuracies than the models using DAP-derived predictor variables.

Zusammenfassung der bisherigen Studien zu ABA and DAP. ***TABELLE***

1.5 RESEARCH AIMS AND OBJECTIVES

The purpose of the presented work was to scrutinize digital aerial photographs, as regularly acquired by the Surveying Authorities nowadays, for use in forest inventory, forest planning, and forest management. During the course of the project, a range of applications was addressed and examined in different studies. The overarching aims of the presented studies were:

Overall aims of the studies.

1. Are digital aerial images acquired within the standardized administrative aerial surveys suitable to compute dense image-based point clouds or digital surface models (DSMs) by means of image-matching techniques (e. g., SGM), that characterize forest canopy surfaces with a sufficient level of detail?

2. Can image-based outputs derived from digital airphotos, i. e., point clouds and raster-based surface models, normalized to heights above

ground using ALS-based digital terrain models (DTMs), be used to model key forest inventory attributes, e. g., mean or top height, basal area, and gross volume?

3. Are repeated aerial image acquisitions and the derived image-based canopy height models (CHMs) capable to assess canopy height changes over time?

Against this background, more specific research objectives were formulated. We focused on these objectives in separate studies:

Specific reseach objectives.

Stepper et al. *Can. J. For. Res.* (2015)

- application of SGM to generate a very dense 2.5D point cloud that would provide a detailed characterization of the surface structure of the forest canopy;
- examination of several spectral features computed from the orthoimagery as additional explanatory variables for estimating gross volume V, in combination with height and structural variables derived from the image-based height data;
- comparative testing of RF regression models vs. ordinary least squares (OLS) linear regression models to estimate V at the plot level, as well as at the stand level;
- investigation of the effect of different sampling densities, i. e., systematically reduced numbers of terrestrial inventory plots, on the accuracy and bias of the estimation of V.

Straub & Stepper *Photogramm. Fernerkund. Geoinf.* (in press)

- adoption of the workflow as developed in Stepper et al. (2015b) for estimating a set of five forest inventory attributes – stem density N, basal area G, quadratic mean diameter QMD, volume V, and Lorey's mean height H_L – using CHM-based predictor variables and the RF approach;
- evaluation of the impact of the prevailing forest type on the performance of models used to predict forest attributes. I. e., study areas representing common broadleaf- and conifer-dominated forest environments in German (beech- and spruce-dominated, respectively) were selected and predictive forest attribute models from both test sites were compared with respect to accuracy and bias.

Stepper et al. *Scand. J. For. Res.* (submitted)

- investigation of predictive RF models for the forest attributes d_{100}, h_{100}, and V. Specifically, we study feature importance of predictor variables derived from SGM point clouds and examine model performance by means of root mean squared error (RMSE) and mean error (ME);
- exploration of the spatial portability of forest attribute models to close-by forests, i. e., by means of large-area-covering aerial image data. The spatial transfer is validated at independent ground plots in neighbouring forest areas;

- demonstrating the effect of training data coverage on model performance by systematically eliminating forest inventory plots for model training.

White et al. *Forests* (2015)

- characterizing the differences between ALS- and image-based point cloud metrics across a range of environmental conditions, defined by topographic slope and canopy cover;
- generation of area-based predictive models for Lorey's mean height H_L, basal area G, and gross volume V from both sources of point cloud data and comparison of model outcomes in the context of the differences for the ALS- and DAP-derived metrics and in the context of different acquisition conditions for the imagery.

Immitzer et al. *Forest Ecol. Manag.* (2016)

- modelling gross volume V using angle-count sampling (ACS) NFI field data and WorldView-2 (WV2) stereo satellite imagery by implementing a multi-circle and multi-metrics approach for prediction at the pixel level;
- evaluating the explanatory power of spectral and height-related metrics computed from the multispectral WV-2 imagery and the image-based CHM;
- developing a wall-to-wall application method for the predictive models by using a moving-window approach.

Stepper et al. *Forestry* (2015)

- application of SGM to automatically compute image-based CHMs for two consecutive image data sets acquired as part of the regularly scheduled aerial image surveys in Bavaria;
- derivation and comparison of the periodic annual increment (PAI) of forest height computed from the two CHMs and two corresponding field inventory data sets at georeferenced ground plots;
- analysis of the PAIs in height for three height classes representing different successional stages – *youth*, *full vigour* and *old age*.

2 MATERIALS

2.1 STUDY AREAS

The research studies, which are compiled in the present work, were conducted using remote sensing data and ground based measurements from different test sites (see Figures 4 and 5, and Table 1). The selection of the test sites in *Bavaria*, Germany, was made in order to best meet the following criteria:

Selection criteria for the study areas in Bavaria.

- Field inventory measurements of recent date are available for larger contiguous forested areas.
- Lapse of time between the acquisition of the airphotos and the ground based measurements is as short as possible.
- Test sites represent different forest conditions, including topography, climate, tree species, tree species mixture, and forest management practice.

The test site on *Northern Vancouver Island (NVI)* was selected in order to scrutinize the developed methods under largely different conditions, i. e., among other factors, the areal extent of the test site, the prevailing tree species, the applied forest management, and the different strategy for ground data acquisition. Timely coincident data of ALS and aerial photography were available for the NVI area, which allowed for a comparative analysis of both remote sensing data types for use in forest inventory applications.

A comparative analysis of ALS- and DAP-based height data was possible for the NVI test site.

Table 1: Overview of the different test sites in Bavaria, Germany, and British Columbia, Canada.

TEST SITE	AREA [km²]	DOMINANT TREE SPECIES	STUDIES
Spessart (northwestern Bavaria)	446	European beech, sessile oak	Straub and Stepper, 2016
Steigerwald (northwestern Bavaria)	556	European beech, sessile oak	Stepper et al., 2015b; Immitzer et al., 2016; Stepper et al., submitted
Frankenwald (northeastern Bavaria)	396	Norway spruce	Straub and Stepper, 2016; Stepper et al., submitted
Traunstein (southeastern Bavaria)	90	Norway spruce, European beech, white fir	Stepper et al., 2015a
Northern Vancouver Island (British Columbia)	662	Western hemlock, Western red cedar	White et al., 2015

Note: detailed descriptions of the test sites are given in the respective research papers. Deviating figures for area sizes are due to use of different subsets for the studies.

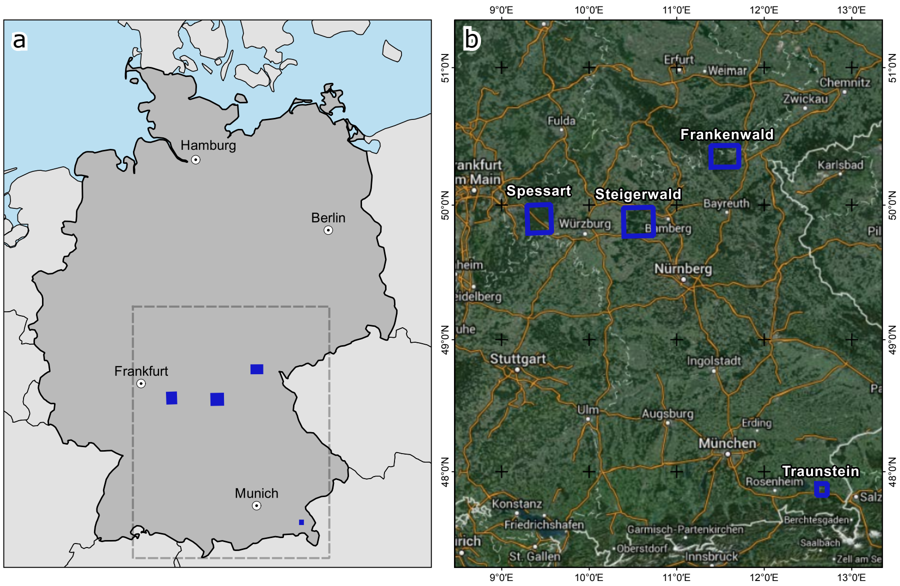

Figure 4: Map of the study areas *Spessart*, *Steigerwald*, *Frankenwald*, and *Traunstein* in Bavaria, Germany. (a) Location in Germany; (b) detailed locations in Bavaria (Images ©Landsat, Mapdata ©GeoBasis-DE/BKG(© 2009), Google).

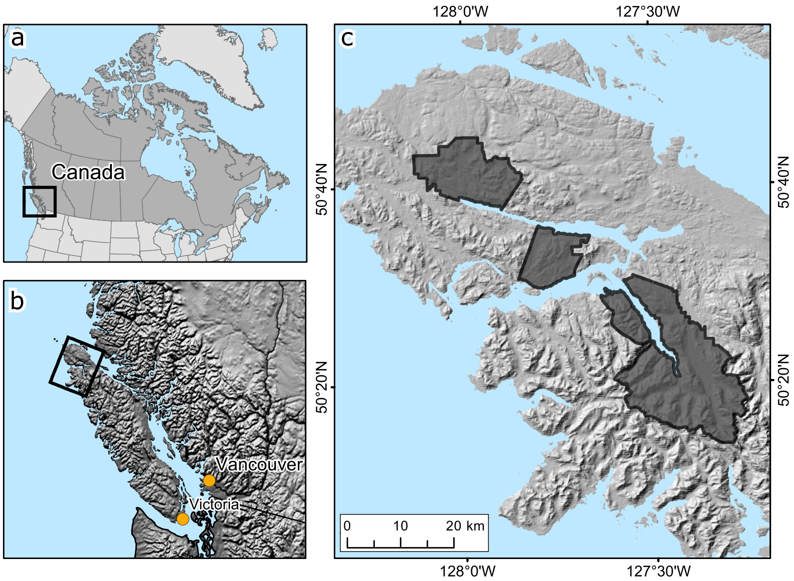

Figure 5: Map of the study area *Northern Vancouver Island* in British Columbia, Canada. (a) Location in British Columbia, Canada; (b) location on Northern Vancouver Island; (c) boundaries of the study area units.

2.2 FIELD DATA

2.2.1 Bavarian State Forest Enterprise

Main parts of the test sites *Spessart*, *Steigerwald*, and *Frankenwald* are state-owned land, mostly managed forests with a great variety of stand development stages. The areas are managed by the Bayerische Staatsforsten (BaySF), and field data are recorded frequently according to their forest management guidelines (Neufanger, 2011).

For the respective forests, recurring terrestrial sample-based forest inventory systems are installed, and comprehensive measurements are carried out on a 10-year frequency basis. The permanent ground plots where the data are collected are laid out in a regular grid pattern of 200 m x 200 m. The plot centres are permanently marked in the field, and during the inventories, each particular plot location is georeferenced using a GPS device.

Ground plots for terrestrial inventory measurements are permanently marked in the Bavarian state forests.

The forest management inventories in the state forests of Bavaria make use of the sampling concept with three concentric measurement circles at the respective ground plots. A general introduction to this concept can be found in van Laar and Akça (2007). Here, the trees are recorded with all relevant attributes in dependency of their diameter at breast height (DBH; measured at 1.3 m above ground) and their distance to the plot centre. For the forest inventories conducted by BaySF, the radii and DBH thresholds for the concentric circles assembling a circular inventory plot typically are set as summarized in Table 2.

Tree measurements at the plots are made according to concentric sampling circles.

Table 2: Radii and DBH thresholds for the concentric sampling circles assembling a ground plot in typical BaySF management inventories.

CIRCLE NO.	RADIUS [m]	AREA [m^2]	DBH [cm]
1	2.82	25	< 12
2	6.31	125	12–29.9
3	12.62	500	$\geqslant 30$

Based on the individual tree measurements, a set of forest inventory attributes is computed. These compiled data sets include, inter alia, mean tree height, basal area per hectare, and gross volume per hectare. In the course of the research project, other attributes, e. g., stand top height, came into focus, and procedures were applied to compute the attributes from the individual tree measurements.

A set of forest inventory attributes is computed based on the individual tree measurements.

The field data for the BaySF test sites included in this work, namely *Spessart*, *Steigerwald*, and *Frankenwald*, were recorded in 2011, 2010, and 2014, respectively. For more detailed descriptions of the field data acquisitions as well as the derivation of forest inventory attributes, refer to the respective sections in the articles.

Field data in the test sites Spessart, Steigerwald, *and* Frankenwald *were acquired in 2011, 2010, and 2014.*

2.2.2 National forest inventory data

Field data from the German NFI were selected as reference data for model training in the study of Immitzer et al. (2016). Contrary to the concentric sampling circles used within the management forest inventories of BaySF, the German NFI is based on angle-count sampling (ACS) as basic sampling principle. Here, the probability of a tree for inclusion to the measurements is proportional to its basal area at a defined height. Each tree trunk is focused from the sample plot centre and is selected if the DBH exceeds a prescribed angle width (defined by the so called basal area factor). For more information regarding the German NFI and the ACS method, refer to the corresponding section in the paper (Immitzer et al., 2016) or to Polley et al. (2010).

ACS is used as basic sampling principle in the German NFI.

Our study was conducted in the *Steigerwald* test site, and a total of 92 sample plots from the most recent NFI were used for modelling. The field measurements were conducted in 2011 and 2012, and field-based estimates of growing stock, separately for conifers and broadleaves, were made available to us.

NFI field data were recorded in 2011 and 2012.

2.2.3 Municipal Forest of Traunstein

The forest area, which was chosen as test site for the study of Stepper et al. (2015a), is part of the municipal forest which belongs to the city of Traunstein. The forest stands are actively managed to support an uneven-aged mixed-species forest and comprise a great variety of successional stages, i. e., heterogeneous species composition, many different age classes, and multi-layered stands.

Similarly to the field sampling design described above for the BaySF inventories (subsection 2.2.1), the permanently marked field plots within the *Traunstein* study area – 228, in total – are distributed in a regular grid pattern of 100 m x 100 m. At the plots, measurements are carried out using concentric sampling circles, based on the following radii and corresponding DBH thresholds: 3.15 m (DBH $<$ 10 cm), 6.31 m (10 $\leqslant$ DBH $<$ 30 cm) and 12.62 m (DBH $\geqslant$ 30 cm).

The *Traunstein* forest test site was selected for our experiment of assessing forest height changes by means of DAP-based CHMs, as field measurements from two terrestrial inventories carried out in 2008 and 2013 were available. Using the ground plot measurements, field-based top heights were calculated for each inventory plot, and in consequence, field-based periodic annual increment (PAI) could be derived as reference for our investigation. Details regarding the ground measurements and the subsequent calculations are given in the respective sections of the paper (Stepper et al., 2015a).

Field measurements collected in 2008 and 2013 were available for the Traunstein *test site.*

2.2.4 Northern Vancouver Island

To select the ground plot locations in the NVI study area, a stratified random sampling design was used. The ground plots were allocated to five different strata, defined by species information, biogeographic data, and elevation data. The sample locations within the strata were selected by a systematic partition, informed by the 3d ALS-derived feature space.

Stratified random sampling was used to select the ground plot locations at NVI.

In total, 140 ground plots were established within the NVI test site (which corresponds to a much greater area representativeness of the individual plots compared to the ones described in subsections 2.2.1 and 2.2.3). In the field, the plot centres were established using a GPS device, and all live standing trees with DBH $\geqslant$ 12.0 cm were measured within a radius of 14 m (615.75 m^2). The individual tree measurements included DBH, stem height, age and other mensurational data, and estimates for different forest inventory attributes, including Lorey's mean height, basal area, and gross volume, were calculated for each plot (White et al., 2015).

2.3 REMOTE SENSING DATA

This work was purposely designed to investigate digital aerial photographs as remote sensing data for use in forest inventory and management applications. Thus, airphotos were the primary remotely sensed data used for analysis in this study. Besides aerial photography, we examined stereo WorldView-2 (WV2) satellite data for generating 3d height measurements of forest canopies, and the consequent use for a wall-to-wall mapping application of forest inventory data. ALS data were used twofold: (i) as indispensable source of information providing detailed elevation models, i. e., ground heights of the terrain; (ii) as reference remote sensing data used in the ABA modelling of forest inventory attributes, i. e., to judge the achieved results when using DAP derived height information.

2.3.1 Digital Aerial Photographs

Digital airphotos are acquired routinely by the Bavarian Administration for Surveying.

The digital aerial photographs used for the studies conducted in the Bavarian test sites (see Table 1) were provided by the Bavarian Administration for Surveying. Currently, the aerial photographs are updated every three years in Bavaria. General specifications for these official aerial photographs are provided in LDBV (2015b).

All images used in our studies were acquired during leaf-on conditions with digital aerial frame cameras, and both panchromatic (PAN) and PAN-sharpened multispectral images (blue, green, red, and near infrared) of the same radiometric resolution (12 bit) were available. The aerial photographs were acquired such that a ground sampling distance (GSD) of 0.20 m could be ensured for all images.

The typical overlaps of the stereo images in Bavaria were 65–75 % in forward and 25–40 % in side direction.

The overlaps of the stereo images varied between different years of data acquisition and different test sites, but, in general, overlaps in forward and side direction of 65–75 % and 25–40 % were achieved. For details regarding the used camera type, the individual image overlaps, and the flight dates of the aerial surveys, the reader is referred to the respective sections of the research articles.

With regard to the study conducted on NVI, digital aerial imagery was acquired by the tree farm licensee Western Forest Products Inc. being responsible for the management of the forests within the study area. For complete coverage of the area, imagery was acquired during four different flights from August to October 2012. The photographs were acquired with a minimum of 60 % along-track (forward) and 20 % across-track (side) overlap. The airphotos were provided as 4-band (blue, green, red, near infrared) multispectral images with a 0.30 m GSD and 8 bit radiometric resolution.

2.3.2 World-View 2 Data

In the study of Immitzer et al. (2016) we explored the usability of high-resolution optical satellite imagery recorded in stereoscopic collection mode for the image-based generation of 3d height data and further application. Therefore, WV2 stereo satellite image data were used. WV2 records panchromatic images plus multispectral images comprising eight spectral bands (coastal, blue, green, yellow, red, red edge, near infrared 1, near infrared 2; Digital Globe, 2013).

For the test site *Steigerwald* complete coverage was achieved through two stereo-image pairs, i. e., four WV2 images, which were recorded under leaf-on conditions in August 2013. The spectral data were atmospherically corrected and thus, top-of-canopy spectral reflectance was available for further analysis. The WV2 data were provided as panchromatic images with 0.50 m spatial resolution, and as 8-band multispectral images resampled to 1.0 m pixel size.

2.3.3 Airborne Laser Scanning Data

As mentioned above, one essential benefit of ALS data sets is that measurements describing the canopy structure and the ground surface can be acquired simultaneously. This allows for the computation of vegetation heights using inherent ground measurements. For the DAP-based reconstruction of vegetation height, additional bare earth information is necessary.

The Bavarian Administration for Surveying routinely runs ALS mapping surveys in order to achieve accurate measurements of the terrain (however, with no distinct repeat cycle). Based on these ALS data, digital terrain models (DTMs) with 1 m ground resolution are available for the entire area of the country (LDBV, 2015a). In the course of the research project, the ALS-based DTMs were used for the height normalization of the DAP-based surface measurements. Canopy heights were consequently calculated as difference of the image-based surface heights and the ALS-based terrain heights.

DTMs with 1 m ground resolution are available for the entire area of Bavaria.

In the NVI study area ALS point clouds were acquired at the same time as the digital airphotos, i. e., in August and September 2012. The data had an average return point density of 11.6 points·m². Based on the ground returns from that data, a DTM with a spatial resolution of 1 m was created. The DTM was used to normalize the ALS point cloud heights to heights above ground level. In addition, the image-based points from the NVI study area were transformed to heights above ground using the same ALS-based DTM.

3 METHODS

3.1 DIGITAL AERIAL PHOTOGRAMMETRY

3.1.1 General Considerations on Image Matching

3d coordinates of objects can be derived from stereo images via photogrammetry.

Photogrammetry is a measurement technique to derive 3d coordinates of object points, which are depicted on images taken from different positions (Lemmens, 2011). By utilizing the stereophotogrammetric measuring principle (see subsection 1.2.3) and with known orientation parameters of the images[1], the coordinates of the objects of interest can be retrieved via triangulation. According to Schenk (1999, p. 231),

Identification and measurement of conjugate points in overlapping images is fundamental in photogrammetry.

> "[o]ne of the most fundamental processes in photogrammetry is to identify and to measure conjugate points in two or more overlapping photographs. Stereo photogrammetry relies entirely on conjugate points. In analogue and analytical photogrammetry the identification of conjugate points is performed by a human operator; in digital photogrammetry one attempts to solve the problem automatically – a process known as image matching."

The introduction of stereo-image matching techniques in photogrammetry allowed for automation in different processing steps, particularly in the creation of dense height measurements, and is the fundamental basis for DAP. Generally speaking, the aim of image matching is to identify corresponding pattern in the stereo-image pairs, i. e., the base and the match image. The problem in finding these correspondences is to trace and locate the pattern in the match image as the conjugate of a pattern in the base image (Lemmens, 2011).

Established image matching categories: feature-based *and* area-based *matching.*

Traditionally, the image-matching methods may be assigned to two categories depending on how the image – an array of pixels storing digital numbers – is approached (ERDAS, 2010; Gruen, 2012). The first category can be classified as *feature-based matching* approaches. These focus on the evaluation of similarities of extracted features in both base and match image, which may be depictions of prominent features like corners of buildings, road crossings, or solitaire trees in case of aerial photographs. The second group of algorithms can be categorized as *area-based matching* approaches. Here, correspondence between the stereo images is sought using the grey level values in regularly shaped patches, e. g., 9 x 9 pixel windows. A reference window, remaining at a constant location in the base image, is defined as source for calculating correlation to candidate windows on the match image. Many different search windows in the match image are evaluated until the location for correspondence is determined by the highest value for the correlation coefficient. Consequently, the centre pixels of the reference and search window are selected as corresponding points. Most commonly, normalized cross-correlation (NCC) is used for calculating correlation and acceptance of the match depends on whether the similarity value exceeds

1 *interior orientation:* focal length, principal point (X, Y), pixel size; *exterior orientation:* position coordinates of the projection centre (X, Y, Z), plus angular parameters (ω, ϕ, κ).

a predefined threshold (Lemmens, 2011). A trade-off is associated with the definition of the correlation threshold: whereas choosing too small values allows for many mismatches, i. e., wrong correspondences of pixels, too high values impede many matches and in consequence, the density of matches found for a stereo-image pair decreases.

3.1.2 Semi-global Matching

Problems with finding correspondences are especially connected to object boundaries, fine structures, low and repetitive textures, and recording and illumination differences in the images. In order to overcome these drawbacks, effort was put into developing new image-matching methods. One approach which have gained considerable attention in recent years, is the so-called semi-global matching (SGM) technique introduced by Hirschmüller (2005, 2008). SGM is based on the idea of pixelwise matching and approximating a global 2d smoothness constraint by combining many 1d constraints. The basic steps of SGM are:

- Generation of epipolar images by projectively warp the base and match images with known geometries such that the epipolar lines are horizontal.
- Calculation of possible disparities for each pixel along the epipolar search lines in the base image and computation of matching costs for each candidate disparity by a similarity measure (e. g., Mutual Information, Census) comparing the pixel grey values.
- Aggregation of costs by pathwise accumulation of minimal costs along a certain number of 1d path directions through the base image. Here, additional smoothness constraints are introduced by penalizing disparity changes.
- Determination of final disparities for each pixel in the base image by selecting the candidate pixel in the match image that corresponds to the minimum cost.
- Intersection of viewing rays in the stereo images according to the final disparity image to achieve dense 3d point clouds in object space.

More details regarding the performed steps in SGM and the implemented algorithms are provided in, e. g., Hirschmüller (2008, 2011) and Gehrke et al. (2010).

We applied the SGM approach for image matching and consecutive derivation of image-based surface heights throughout the studies presented in this work[2]. For the processing, we used the SGM implementation within the Remote Sensing Software Package Graz (RSG). The cost function used in RSG follows the Census disparity measure, and the matching procedure is hierarchically structured as coarse to fine matching, with consequent disparity calculations on four image pyramid levels.

Panchromatic images were used for matching of along-track stereo-image pairs covering the Bavarian test sites.

We selected the panchromatic band of the stereo images for matching in all Bavarian test sites. Due to the low across-track overlaps of the images, we used only stereo-image pairs from the along-track overlap for calculation. For the NVI test site, the airphotos were only available as multispectal images (*RGBI*). Here, the green band was selected for matching.

2 except for Immitzer et al. (2016): here, the area-based normalized cross-correlation method implemented in LPS eATE (ERDAS IMAGINE 2014) was used.

As outputs from dense stereo matching in RSG, we opted for using the raw dense 3d point clouds from the respective stereo pairs and used additional utility software for further processing. In the work concerned with the assessment of height changes (Stepper et al., 2015a), we used DSMs as outputs from the RSG streamline for further analysis.

The products from DAP, i. e., the dense image-based point clouds or the DSMs, were further processed to calculate the object heights above ground by using the ALS-based elevation heights for subtraction. Subsequently, different data processing steps (clipping to inventory point geometries, etc.) were performed in order to prepare appropriate data sets for consequent use in statistical modelling. Details regarding the particular processing steps are given in the respective paper sections.

3.2 STATISTICAL MODELLING

As introduced in sections 1.2 and 1.3, the area-based approach (ABA) gained strong interest for integrating remote sensing data sets, in particular ALS and DAP-based products, for use in forest inventory and mapping applications.

In this context, i. e., for the combination of ground based measurements and the remotely sensed data, statistical models which can produce unbiased and accurate estimates of the forest attribute of interest by means of remote sensing predictor variables play a key role. In the ABA workflow (see Figure 3), the statistical models are trained with known samples, namely the ground-based inventory measurements and the descriptive statistics (*metrics*) calculated from the remote sensing data clipped to the areas of the georeferenced inventory plots – and consequently, these models are applied to predict estimates over entire forest areas.

Therefore it is crucial, that the chosen model type is able to accurately map the statistical dependency between the remote sensing predictor variables and the response variables derived from the ground measurements (e. g., mean stand height or volume). In the literature, different regression approaches (parametric and non-parametric) were applied to fulfil this task. Besides linear regression modelling, the decision-tree based approach random forest (RF) was most widely used for predictive modelling of forest inventory attributes through the course of the presented studies. Therefore, and without judging other approaches for their appropriateness, the main characteristics of RF and its actual application are described.

The statistical model describes the dependency between the remote sensing predictors and the ground-based response.

3.2.1 Random Forest for Regression

RF can be assigned to the domain of non-parametric modelling approaches. Thus, no *a priori* assumptions about relationships between predictor and response variables are made (White et al., 2013a). Due to that, and to the fact that very little tuning is required during model building, RF has become a popular method in predictive modelling.

RF requires no a priori assumption about the relationship of predictors and response variables.

RF, developed by Breiman (2001), is an ensemble regression tree algorithm (see Algorithm 1) based on a large collection of *de-correlated* decision trees (Hastie et al., 2009). RF can be seen as further development of bagging (*bootstrap aggregation*), as the individual trees that constitute the forest are fitted to bootstrap-sampled versions of the training data, and averaged to get the final result (for a schematic of *bootstrap sampling*, see Figure 6).

An ensemble of de-correlated decision trees forms a RF model.

Algorithm 1: Random Forest for Regression (modified after Hastie et al., 2009 and Kuhn and Johnson, 2013).

Select the number of trees to build, B:

for $b = 1$ *to* B: **do**
- (1) Draw a bootstrap sample $\mathbf{Z}^*$ of size N from the training data.
- (2) Train a tree model T_b to the bootstrapped data, by recursively repeating the following steps for each terminal node of the tree, until the minimum node size n_{min} is reached.
- **for** *each split:* **do**
  - (a) Select m variables at random from the p predictor variables ($m \leqslant p$).
  - (b) Pick the best variable/split-point among the m.
  - (c) Split the node into two data nodes.
- **end**

end

Output the ensemble of trees $\{T_b\}_1^B$.

To make a prediction at a new point x:

$\hat{f}_{rf}^B(x) = \frac{1}{B} \sum_{b=1}^{B} T_b(x)$

In RF, a second randomization is introduced to the tree-building process, in order to additionally reduce the correlation between the trees: the algorithm randomly selects a subset of predictor variables as candidates for splitting at each decision node. RF has two potential parameters for adjustment: (a) the number of randomly selected predictors m, from which to choose at each split (commonly referred to as m_{try}). For use in regression, the algorithm inventor Breiman recommended $p/3$ as default value, i. e., one third of the number of predictors (Breiman, 2001); (b) the number of trees in the forest (commonly referred to as n_{tree}). As RF is not prone to overfitting, large numbers of trees do not adversely affect the model accuracy. However, the computational expense increases. Kuhn and Johnson (2013) suggest 1 000 trees as starting point, and adjustment in dependence of the achieved model performance. Important advances and features of RF are:

DISTRIBUTION INDEPENDENCE The variables (x, y) used as predictors and response in modelling do not have to follow a predefined distribution.

DIMENSIONALITY In RF, high-dimensional and highly correlated data sets can be processed without suffering a loss in performance.

OUT-OF-BAG (OOB) For each observation $z_i = (x_i, y_i)$, its random forest predictor can be computed by averaging only those trees corresponding to bootstrap samples in which z_i is not included (see Figure 6). Doing so, an oob error estimate is almost identical to that obtained by N-fold cross-validation (cf. Hastie et al., 2009). Thus, performance measures can be computed along the way during RF model training.

VARIABLE IMPORTANCE Information on the importance of each predictor variable used in model building can be computed twofold: (a) as measure of the total decrease in node impurities from splitting on each variable, averaged over all trees; (b) as mean decrease of prediction accuracy, when permuting the values of the predictor variables in the oob samples, again averaged over all trees.

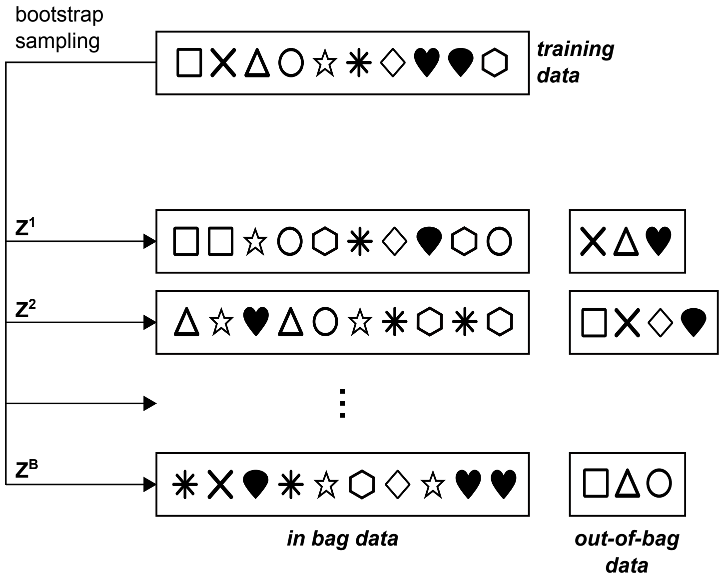

Figure 6: Schematic of bootstrap resampling as used in RF for drawing the training samples for the individual regression trees. The training sample data are depicted as symbols and are allocated to B subsets, each taken as random sample *with replacement*. The subsets are of the same size as the original training data and can contain multiple instances of the same data point. Samples not selected by the bootstrap are the *out-of-bag* data and can be used to estimate model performance (modified after Kuhn and Johnson, 2013).

3.2.2 Model Implementation for predicting Forest Inventory Attributes

We used functionalities and add-on packages of the open-source statistical software R to accomplish all statistical tasks. For model development (using the data gathered at the forest inventory plots) and prediction to unknown samples by means of RF, the functionalities provided in the packages caret (Kuhn, 2015) and randomForest (Liaw and Wiener, 2002) were principally used.

With regard to the tuning parameters of RF, we followed the recommendation of Kuhn and Johnson (2013): The number of regression trees in the respective forests was set to $n_{tree} = 1000$, and the number of variables randomly selected at each split was set to $m_{try} = p/3$.

In all studies, the root mean squared error (RMSE) and mean error (ME) measures were selected to evaluate model performance, i. e., model accuracy and bias. In the studies of Stepper et al. (2015b), Straub and Stepper (2016) and White et al. (2015), we applied a 10-fold cross-validation repeated five times to assess model performance and in the studies of Immitzer et al. (2016) and Stepper et al. (submitted) the oob-estimates were used for model evaluation.

Additionally, the model performance at the stand level, i. e., after wall-to-wall prediction mapping and aggregating to forest stands, was examined in the studies of Immitzer et al. (2016) and Stepper et al. (2015b). Independent inventory data from nearby forests were utilized to assess model transferability in the study of Stepper et al. (submitted), again by means of RMSE and ME. For more details regarding model training and evaluation, the reader is referred to the respective articles.

3.3 HEIGHT CHANGE ASSESSMENT

Elaborating on the aim to test the utility of digital stereo images from repeat surveys for forest height change assessment, we developed a workflow as illustrated in Figure 7.

We followed the SGM approach (see section 3.1) to accomplish image matching of the stereo airphotos. In our study (Stepper et al., 2015a), we chose the RSG software utilities for image matching and used the implemented functionality to output DSMs with 1 m resolution for both dates of image acquisition. Finally, CHMs were derived by subtracting the elevation values of the bare earth DTM from the z-values of the two DSMs.

Terrestrial inventory measurements, acquired for circular 500 m² plots, were used as reference for the assessment of forest canopy height and height changes. H100 was calculated from the field measurements as height metric approximating top heights of forest stands. In our study, H100 was defined as the average height of the 100 stems per hectare with the largest DBHs (see *Algorithm 1* in the article for the explicit computation rule set).

To link the CHM-heights with the field-based H100 top heights, various height percentiles (25th, 50th, 75th, 90th, 95th, and maximum) were calculated from the CHM-values for the areas within each of the 500 m² circular

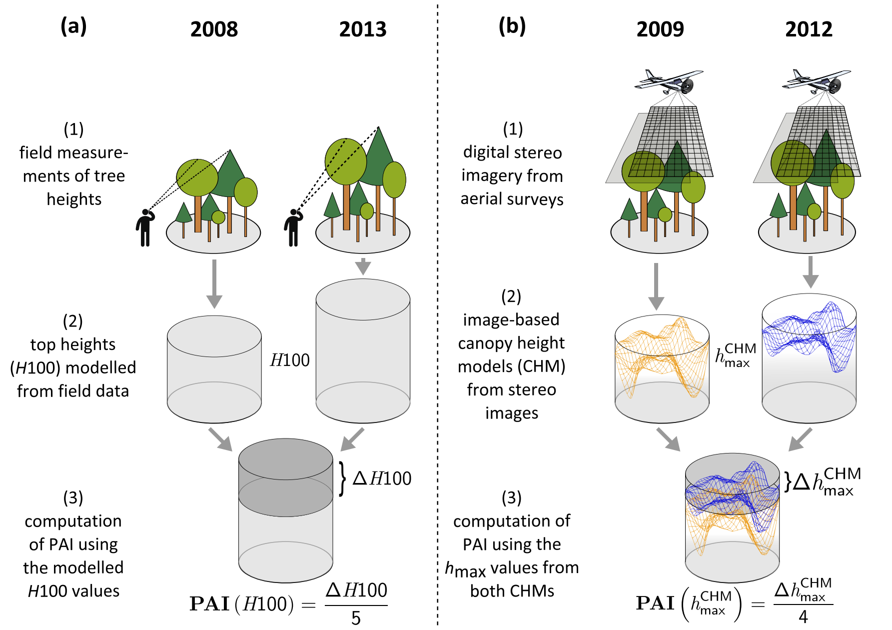

Figure 7: Methodological workflow for height change assessment using terrestrial measurements and CHMs based on stereo airphotos from repeat aerial image surveys. **(a)** Terrestrial assessment: (1) tree crown heights are measured for representative samples at the respective inventory plots, (2) top heights (H100) are modelled using the height measurements of trees from the overstory and emergent tree layers, (3) PAI is calculated as the difference between the modelled H100 values for the two inventory dates divided by the time lapse between the two inventories. **(b)** Aerial image assessment: (1) digital stereo images are acquired in regularly scheduled aerial surveys, (2) CHMs are created by subtracting LiDAR-derived terrain heights from image-based surface models, (3) PAI is computed as the difference between the maximum height values (h_{max}) from the two CHMs divided by the time lapse between the two image dates.

plots. The percentiles were correlated to the field-based top heights and the maximum height of the CHM (h_{max}) turned out to achieve highest correlation values. Thus, this variable was selected for the height change assessment.

Height differences between the two points in time from the terrestrial and the aerial image acquisitions were used to calculate periodic annual increments (PAIs) as standardized increment measures per unit of time (see Figure 7). The PAIs, both from the field measurements and the image-based height data, were regressed against the H100 top height values based on the initial field data (from $t_{1,field}$) to analyse the relationship between initial forest height and height growth. Finally, differences between increments for initial height classes representing various forest successional stages were examined.

4 RESULTS

The results of the conducted research studies were presented to scholars in different scientific papers published in peer-reviewed journals (see list of publications on page vi). In the following, the main findings of the respective papers are summarized (section 4.1). Afterwards, the results of each paper are given in detail and my personal contribution to each paper is highlighted (section 4.2).

4.1 OVERALL RESULTS OF THE PRESENTED WORK

In Table 3, a very general overview of the achieved results according to the overall aims of this work (see section 1.5) is given. The first aim, i.e., the examination of image-based height measurements derived from stereo remote sensing data sets for the description of forest canopy surfaces, was pursued in all studies.

Table 3: Overview of research aims and achieved results covered by the respective studies.

STUDIES	AIM 1: Are digital aerial images and DAP suitable to compute image-based outputs to characterize forest canopy surfaces?	AIM 2: Can image-based point clouds or raster-based surface models be used to model forest inventory attributes?	AIM 3: Are CHMs derived from repeated airphoto acquisitons capable to assess canopy height changes over time?
Stepper et al. *Can. J. For. Res.* (2015)	✓	✓	
Straub & Stepper *Photogramm. Fernerkund. Geoinf.* (in press)	✓	✓	
Stepper et al. *Scand. J. For. Res.* (submitted)	✓	✓	
White et al. *Forests* (2015)	✓	✓	
Immitzer et al. *Forest Ecol. Manag.* (2016)	✓[a]	✓[b]	
Stepper et al. *Forestry* (2015)	✓		✓

[a] Stereo satellite image data were used in this study for image matching and consecutive computation of canopy surface heights.
[b] In contrast to the other studies, ACS-based field data from NFI measurements were used for model training in this study.

4.2 DETAILED DESCRIPTION OF THE RESULTS PER ARTICLE

4.2.1 Stepper et al. *Can. J. For. Res.* (2015)

TITLE Using semi-global matching point clouds to estimate growing stock at the plot and stand levels: application for a broadleaf-dominated forest in central Europe

AUTHORS *Christoph Stepper*, Christoph Straub, and Hans Pretzsch

JOURNAL Canadian Journal of Forest Research (Publisher: National Research Council Canada, NRC Research Press, ISSN: 0045-5067, Journal Impact Factor, *2014*: 1.683)

ABSTRACT Dense image-based point clouds have great potential to accurately assess forest attributes such as growing stock. The objective of this study was to combine height and spectral information obtained from UltraCamXp stereo images to model the growing stock in a highly structured broadleaf-dominated forest (77.5 km^2) in southern Germany. We used semi-global matching (SGM) to generate a dense point cloud and subtracted elevation values obtained from airborne laser scanner (ALS) data to compute canopy height. Sixty-seven explanatory variables were derived from the point cloud and an orthoimage for use in the model. Two different approaches — the linear regression model (lm) and the random forests model (rf) — were tested. We investigated the impact that varying amounts of training data had on model performance. Plot data from a previously acquired set of 1875 inventory plots was systematically eliminated to form three progressively less dense subsets of 937, 461, and 226 inventory plots. Model evaluation at the plot level (size: 500 m^2) yielded relative root mean squared errors (RMSEs) ranging from 31.27% to 35.61% for lm and from 30.92% to 36.02% for rf. At the stand level (mean stand size: 32 ha), RMSEs from 14.76% to 15.73% for lm and from 13.87% to 14.99% for rf were achieved. Therefore, similar results were obtained from both modeling approaches. The reduction in the number of inventory plots did not considerably affect the precision. Our findings underline the potential for aerial stereo imagery in combination with ALS-based terrain heights to support forest inventory and management.

CONTRIBUTION Christoph Stepper and Christoph Straub developed the concept for the study and Christoph Stepper designed the experimental setting. Hans Pretzsch gave helpful comments on the study structure and the relevance of the research.

Christoph Stepper processed all ground inventory and remote sensing data. He performed the photogrammetric working steps to gain the image-based canopy height information and the orthoimage for the complete test site. In this study, we scrutinized both height and spectral variables as predictor variables for modelling gross volume. Christoph Stepper computed the point-cloud variables and Christoph Straub computed the variables extracted from the gridded CHM and the orthoimage. Christoph Stepper performed the area-based modelling workflow testing both regression approaches and applied the models for wall-to-wall mapping. He conducted the model evaluation at the stand level and compiled all results. Christoph Stepper and Christoph Straub interpreted the model outcomes and formulated the findings of this research.

Christoph Stepper prepared the manuscript including all figures and tables in close collaboration with Christoph Straub. Hans Pretzsch gave valuable advice for the interpretation of the results, for the discussion of the findings and the composition of the manuscript. All authors contributed to the critical revisions of the article.

4.2.2 Straub & Stepper *Photogramm. Fernerkund. Geoinf.* (in press)

TITLE Using digital aerial photogrammetry and the Random Forest approach to model forest inventory attributes in beech- and spruce-dominated central European forests

AUTHORS Christoph Straub and *Christoph Stepper*

JOURNAL Photogrammetrie–Fernerkundung–Geoinformation, *PFG* (Publisher: Schweizerbart Science Publishers, ISSN: 1432-8364, Journal Impact Factor, *2014*: 0.733)

ABSTRACT Surface models generated using dense image matching of aerial photographs have potential for use in the area-based prediction of forest inventory attributes. Few studies have examined the impact of forest type on the performance of models used to predict forest attributes. Moreover, with regard to central European forests, little is known about how accurately attributes other than volume and basal area can be estimated using image-based surface models. Thus, in this study, we assessed the accuracy of such estimates for five forest attributes — stem density N, basal area G, quadratic mean diameter QMD, volume V, and Lorey's mean height H_L — for a beech- and a spruce-dominated forest in northern Bavaria, Germany. These estimates were made using a workflow combining data from aerial photographs obtained from regularly scheduled surveys and field plot measurements from periodic forest inventories conducted in Bavarian state forests. Semi-Global Matching was used to derive surface models from the air photos which were normalized with terrain models from airborne laserscanning to derive canopy height models (CHM). Based on the CHM values at the respective field plots, a set of 14 predictor variables characterizing the height distribution was computed. For the prediction, individual Random Forests models were trained and cross validated separately for both test sites. With respect to relative RMSEs, i.e. divided by the observation means, most distinct differences were observed for the prediction of QMD with a slightly higher level of accuracy for the spruce-dominated forest. Best results were achieved for H_L, while poorest model performances were obtained for N. The relative plot-level RMSEs for N, G, QMD, V, and H_L were: 70.3%, 36.0%, 32.3%, 37.8%, and 12.4% for the beech-dominated and 74.9%, 35.2%, 24.9%, 33.3%, and 12.4% for the spruce-dominated forest. Thus, with the exception of QMD, forest type did not considerably influence the model accuracies.

CONTRIBUTION The idea for this comparative analysis of models for a set of forest inventory attributes across two different forest types was developed together by both authors.

For the implementation, Christoph Stepper processed the aerial imagery and the SGM data to generate the CHMs for both test sites. He also computed the not readily available forest inventory attributes based on the tree list data from the ground plot measurements. Christoph Straub calculated the set of predictor variables from the CHM height values at the inventory plots and built the predictive RF models based on existing code developed in Stepper et al. (2015b).

Both authors conducted the analysis and interpretation of the modelling results and wrote the manuscript.

4.2.3 Stepper et al. *Scand. J. For. Res.* (submitted)

TITLE Using canopy heights from digital aerial photogrammetry to enable spatial transfer of forest attribute models: a case study in central Europe

AUTHORS *Christoph Stepper*, Christoph Straub, Markus Immitzer, and Hans Pretzsch

JOURNAL Scandinavian Journal of Forest Research (Publisher: Nordic Forest Research Cooperation Committee, Taylor & Francis, ISSN: 0282-7581, Journal Impact Factor, *2014*: 1.537)

ABSTRACT This paper describes a workflow utilizing detailed canopy height information derived from digital airphotos combined with ground inventory information gathered in state-owned forests and regression modelling techniques to quantify forest growing stocks in private woodlands, for which little information is generally available. Random forest models were trained to predict three different variables at the plot level: quadratic mean diameter of the 100 largest trees (d_{100}), basal area weighted mean height of the 100 largest trees (h_{100}), and gross volume ((V). Two separate models were created – one for a spruce- and one for a beech-dominated test site. We examined the spatial portability of the models by using them to predict the aforementioned variables at actual inventory plots in nearby forests, in which simultaneous ground sampling took place. When data from the full set of available plots were used for training, the predictions for d_{100}, h_{100}, and V achieved out-of-bag model accuracies (scaled RMSEs) of 15.1%, 10.1% and 35.3% for the spruce- and 15.9%, 9.7%, and 32.1% for the beech-dominated forest, respectively. The corresponding independent RMSEs for the nearby forests were 15.2%, 10.5%, and 33.6% for the spruce- and 15.5%, 8.9%, and 33.7% for the beech-dominated test site, respectively.

CONTRIBUTION Christoph Stepper developed the idea for this study and the other authors contributed to the experimental layout.

Christoph Stepper conducted the analysis. He processed the image data and prepared the inventory data for subsequent use in modelling. He wrote the R code following previous work (Stepper et al., 2015b) and performed all modelling steps. Christoph Stepper discussed the results, considering helpful comments of the co-authors.

Christoph Stepper wrote the manuscript and compiled the figures, with comments and advise from all other authors.

4.2.4 White et al. *Forests* (2015)

TITLE Comparing ALS and image-based point cloud metrics and modelled forest inventory attributes in a complex coastal forest environment

AUTHORS Joanne C. White, *Christoph Stepper*, Piotr Tompalski, Nicholas C. Coops, and Michael A. Wulder

JOURNAL Forests (Publisher: MDPI, ISSN: 1999-4907, Journal Impact Factor, *2014*: 1.449)

ABSTRACT Digital aerial photogrammetry (DAP) is emerging as an alternate data source to airborne laser scanning (ALS) data for three-dimensional characterization of forest structure. In this study we compare point cloud metrics and plot-level model estimates derived from ALS data and an image-based point cloud generated using semi-global matching (SGM) for a complex, coastal forest in western Canada. Plot-level estimates of Lorey's mean height (H), basal area (G), and gross volume (V) were modelled using an area-based approach. Metrics and model outcomes were evaluated across a series of strata defined by slope and canopy cover, as well as by image acquisition date. We found statistically significant differences between ALS and SGM metrics for all strata for five of the eight metrics we used for model development. We also found that the similarity between metrics from the two data sources generally increased with increasing canopy cover, particularly for upper canopy metrics, whereas trends across slope classes were less consistent. Model outcomes from ALS and SGM were comparable. We found the greatest difference in model outcomes was for H ($\Delta RMSE = 5.04\%$). By comparison, $\Delta RMSE$ was 2.33% for G and 3.63% for V. We did not discern any corresponding trends in model outcomes across slope and canopy cover strata, or associated with different image acquisition dates.

CONTRIBUTION This research was made possible by international collaboration of the Bavarian State Institute of Forestry, the Department of Forest Research at University of British Columbia, and the Canadian Forest Service. The contact was made by Christoph Stepper and Joanne White.

Joanne White and Christoph Stepper set up the design of the study, with conceptual advice of all other authors. Joanne White coordinated the progress of the study, including the contacts with external partners for acquisition of all field inventory and remote sensing data used. Christoph Stepper conducted all photogrammetry work for obtaining image-based canopy height information. Piotr Tompalski and Christoph Stepper processed the ALS and DAP data for further analysis. Joanne White lead investigations on the comparison of point cloud metrics across a series of strata defined by slope and canopy cover and Christoph Stepper was responsible for modelling and analysing plot level predictions for Lorey's mean height, basal area, and gross volume. All authors discussed the results and implications and contributed in formulating the findings of that research.

Joanne White and Christoph Stepper wrote the manuscript. Christoph Stepper, Joanne White, and Piotr Tompalski prepared the figures and assembled the artwork. All authors commented on the manuscript and participated in revising the manuscript.

4.2.5 Immitzer et al. *Forest Ecol. Manag.* (2016)

TITLE Use of WorldView-2 stereo imagery and National Forest Inventory data for wall-to-wall mapping of growing stock

AUTHORS Markus Immitzer, *Christoph Stepper*, Sebastian Böck, Christoph Straub, and Clement Atzberger

JOURNAL Forest Ecology and Management (Publisher: Elsevier, ISSN: 0378-1127, Journal Impact Factor, *2014*: 2.660)

ABSTRACT Angle-count sampling (ACS) is an established method in forest mensuration and is implemented in different National Forest Inventories (NFI). However, due to the lack of fixed reference areas of the inventory plots, these ACS-based field data are seldom used as training data for wall-to-wall mapping applications at forest enterprise level. In this paper, we demonstrate an approach to overcome this shortcoming. For a study area in northern Bavaria, Germany, we used ACS-based NFI data for model training to generate wall-to-wall maps of growing stock for broadleaf, conifer and mixed forest stands. Both spectral and height information from the very high resolution WorldView-2 (WV2) satellite were used as auxiliary information and the non-parametric Random Forests (RF) algorithm was chosen as modeling approach. The growing stock predictions were validated using out-of-bag (OOB) samples and further verified at the plot and stand level using additional data. For validation, field plots from a Management Forest Inventory (MFI) and delineated forest stands were used. Compared to stand-level aggregations based on field plots from the MFI, our approach explained 56% of the variability in the growing stock (R^2) with a relative RMSE of 15% at the stand level ($n = 252$). As expected, the scatter was higher at the plot-level ($n = 3973$). Nonetheless, the models still achieved acceptable performance measures ($R^2 = 0.44$; RMSE = 34%).

CONTRIBUTION Markus Immitzer and Clement Atzberger initiated the study. Markus Immitzer, Clement Atzberger, and Christoph Stepper contributed to the initial experimental design and developed the new approach for using ACS-based NFI plot data as training data for wall-to-wall mapping applications. The novelty of the approach, i. e., the simultaneous use of multiple concentric circles around the NFI plot centres for calculating explanatory variables based on remote sensing information, was developed by Markus Immitzer and Clement Atzberger in close collaboration with Christoph Stepper.

Markus Immitzer processed the remote sensing data and conducted the main parts of the analysis, including programming of the procedures and compiling the results in tables and figures. Christoph Straub computed the vegetation mask based on the WV2 data. Christoph Stepper prepared the inventory data used for model training (NFI) and model evaluation (MFI). Sebastian Böck helped in programming and analysis.

Markus Immitzer and Christoph Stepper prepared all figures and flowcharts for the article and wrote the initial draft of the manuscript together with Clement Atzberger. All authors contributed to the final manuscript and participated in revising the manuscript for publication.

4.2.6 Stepper et al. *Forestry* (2015)

TITLE Assessing height changes in a highly structured forest using regularly acquired aerial image data

AUTHORS *Christoph Stepper*, Christoph Straub, and Hans Pretzsch

JOURNAL Forestry (Publisher: Institute of Chartered Foresters, Oxford University Press, ISSN: 0015-752X, Journal Impact Factor, *2014*: 2.093)

ABSTRACT In this paper,we demonstrate the effectiveness of digital stereo images and canopy height models (CHMs) derived from them for forest height change assessment. Top heights were derived for 199 terrestrial inventory plots from forest inventories conducted in 2008 and 2013 in a forest near Traunstein, Germany. Semi-Global Matching was applied to two sets of aerial stereo images, acquired in 2009 and 2012, respectively, to compute CHMs. Subsequently, several height percentiles were calculated from the areas in the CHMs that lay within the inventory plot locations. The maximum CHM value (h_{max}) had the highest correlation with the field-based canopy top heights and was selected for use in all further analysis. Periodic annual increments (PAIs) of forest height were calculated from both the remote sensing and the field data at the inventory plot locations. Scatterplots of the PAIs over top height revealed similar patterns in the results derived from the two data sets. The inventory plots were assigned to three height classes representing various forest successional stages — *youth*, *full vigour* and *old age*. The PAI distributions within the three height classes were significantly different from one another. Our findings suggest that CHMs derived from repeat aerial image surveys can be a viable tool to measure canopy heights and to assess forest height changes over time, even for a highly structured, mixed forest in central Europe.

CONTRIBUTION All authors contributed to the idea of the work and jointly conceived the experiment.

Christoph Stepper made all data ready for analysis, including the processing of the aerial imagery and the ground inventory data. He conducted the main parts of the statistical analysis, i. e., selecting the appropriate methods, writing the code and carrying out the experiments. Christoph Stepper and Christoph Straub examined and discussed the results. Hans Pretzsch contributed in result interpretation and in placing the findings into a broader context in the forest research discipline.

Christoph Stepper wrote the first draft of the manuscript and prepared all figures and artwork, with valuable contributions of Christoph Straub. Hans Pretzsch added helpful edits to the manuscript and gave advice on the content.

5 DISCUSSION

Different aspects of utilizing digital airphotos and height measurements derived thereof by means of DAP for forest inventory and forest management were considered in the studies presented in this thesis. Overall, the results confirm that image-based point clouds and CHMs are a viable source of information to characterize the three-dimensional structure of forest canopies, at least for the forest types examined in the different studies (see Table 1).

The primary motivations for initiating this work were:

- the need for spatially explicit information on the current state of forest stands in order to facilitate forest management practice;
- the unexploited potential of using digital aerial photographs for the three-dimensional characterization of forest canopies;
- the recently launched algorithms to process stereo airphotos to generate image-based height measurements covering large areas;
- the possibility to test the DAP-based height measurement as surrogate for ALS-based data when spatially predicting forest inventory attributes.

As mentioned in the introduction, large parts of the theoretical framework on using 3d information in forest inventory were developed based on ALS data (e. g., Næsset, 2002b). Meanwhile, airborne imaging technologies (e. g., digital cameras) and image processing algorithms and software (e. g., SGM) have emerged that enable workflows possible to generate image-based point clouds and DSMs covering large areas (White, 2016). Those 3d measurements achieve similar degrees of detail for forest canopy surfaces as the airborne LiDAR-based measurements, and with the large-scale availability of ALS-based DTMs, canopy heights above ground can be derived from the photogrammetric data with little additional effort.

- Schwerpunkt der Studien: Mitteleuropäische Waldverhältnisse –> Ergebnisse für Schätzung wichtiger Forstlicher Kennzahlen ok
- Vergleich mit LiDAR in Canada –> DAP Daten sind ein sinnvolle Ergänzung zu Laser Scanning Daten –> Ermöglichen neue Inventurfortschreibungsverfahren –> viel billiger als Lidar
  –> regelmäßige Befliegung
  –> zusätzliche Verfügbarkeit der Spektralen Information

- Wie genau lassen sich die verschiedenen forstlichen Parameter mit der gewählten Methode abschätzen?
- auf die unterschiedlichen Kennzahlen eingehen.
- Holzvolumen –> nächste Schritte: Einzelbaum-Verfahren / Durchmesserverteilung approximieren

- stärkere Integration der spektralen Kennwerte in die Modellierung (evtl. auch Verwendung von hochaufgelösten Satellitendaten (Phänologie), um Tree species unterscheidbar zu machen)
- was waren die wichtigsten Prädiktoren für die unterschiedlichen forstlichen Parameter –> Vergleich der Studien –> allgemeingültige Aussage möglich? Tendenzen? Vergleich mit Lidar?
- untersucht: Wie verhalten sich die Modelle in nadel- bzw. laubdominierten Wäldern! Frankenwald vs. Spessart/Steigerwald // Mischwald (Wald der Zukunft) –> Traunstein?
- ungelöste Aufgaben: Aussagen über die Baumarten-spezifischen Angaben (z.b. Holzvorrat Nadelbäume vs. Holzvorrat Laubbäume)

6 CONCLUSION

The presented methods and achieved results from the different studies approved the high potential of DAP for use in forest inventory and monitoring tasks. In the studies, image-based height data were employed in combination with different field-measured information sources (management forest inventorys, national forest inventory) on a range of spatial scales. Additionally, due to the lower acquisition costs compared to ALS, and the high recurrence frequency of the administrative aerial surveys, airphotos and derived DAP products can provide an important bridge between the operational, tactical, and strategic forest management levels.

The studies confirmed that DAP-based height information can be used in conjunction with ground-based measurements to establish predictive models for a set of forest inventory attributes (see Stepper et al., submitted, 2015b; Straub and Stepper, 2016; White et al., 2015). Similar to ALS, the most predictive canopy metrics derived from the DAP-based measurements were height metrics, which are most appropriate to describe the canopy *growing space*. It could be demonstrated, that the intra-metric correlation is higher for the image-based data compared to the ALS data (see White et al., 2015), indicating that it is sufficient for modelling to work with a subset of the computed metrics. In Stepper et al. (2015b) we could show, that ...

- Baumartenklassifikation ?!?
- UAV?

Part II

APPENDIX

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