Prediction of stem volume in complex temperate forest stands using TanDEM-X SAR data

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A B S T R A C T
Reliable estimations of stem volume are important for sustainable forest management planning as well as for monitoring of global changes. However, the derivation of stem volume in cubic meters per hectare based on traditional sampling-based forest inventories (usually with a repetition rate of ten years) is very expensive, labor-intensive and only available for the minority of the forest areas worldwide. Thus, spaceborne synthetic aperture radar (SAR) data can provide estimations of forest parameters with sufficient spatial and temporal resolution for large areas. Height information extracted from two interferometric dual-polarized TanDEM-X data sets were used to investigate the potential of polarimetric interferometric X-band SAR data for stem volume estimation in the complex forest stands of the Traunstein forest in Southeast Bavaria, Germany. In contrast to other studies of forest parameter estimation from X-band SAR data carried out in boreal or tropical forest stands, the current study investigated stem volume estimation based on X-band SAR data in complex temperate forest stands. A linear regression model based on the allometric relationship of forest height (estimated from SAR data combined with an airborne LiDAR-based Digital Terrain Model) and stem volume per unit area (deduced from traditional forest inventory) was derived. Moreover, the model was extended and thus improved by integrating novel parameters derived from the co-occurrence matrix as surrogates for horizontal forest structure. This linear regression model predicted stem volume at plot (circular plots of 500 m²) level with a coefficient of determination of $R^2 = 69\%$ and a root mean square error of RMSE $= 155$ m³ ha$^{-1}$ and stand (areas of 1.5 to 6.4 ha) level with $R^2 = 94\%$ and RMSE $= 44$ m³ ha$^{-1}$ respectively.

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1. Introduction

Stem volume is one of the key parameters in forest inventory. Reliable estimations of stem volume per unit area have been the basis for sustainable forest management planning since the beginning of the 18th century (von Carlowitz, 1713) as well as for monitoring of global changes in recent times (IPCC, 2014). Especially in the context of climate change, felling budget can be adapted to damages caused by increasing extreme weather events and calamities. Moreover, stem volume can be directly related to stem biomass as a function of the tree species-specific wood density. For generalization and simplification, a first-order approximation with a density of 500 kg m$^{-3}$ (corresponding to a density factor of 0.5 t m$^{-3}$) is assumed (Pretzsch, 2009), while the Food and Agriculture Organization of the United Nations (FAO) suggests generalized region-specific density factors of about 0.6 t m$^{-3}$ (FAO, 2001). The total above ground biomass can be estimated by the additional use of the biomass expansion factor, which expands stem biomass to account for non-merchantable biomass components such as branches, foliage, and non-commercial trees (Brown, 1997). Stem volume estimations provide the required basis for sustainable management, and by means of conversion into biomass a crucial parameter to understand and quantify the global carbon cycle. Carbon is stored by building up biomass and emitted to the atmosphere by destroying biomass due to fire, logging with subsequent energetic use, storms, decomposition, etc. (Houghton, Hall, & Goetz, 2009). By means of forest management strategies this process can be controlled and the CO₂ emissions can be reduced (Schlamadinger & Matlaid, 1996).

Stem volume per unit area is expressed in cubic meters per hectare. For the purpose of this study we use its definition as harvested timber volume under bark which is most widespread among practitioners. It can be derived from terrestrial forest inventory based on diameter at breast height (dbh) and tree height measurements (Pretzsch, 2009). Traditional forest inventories, like National Forest Inventory in Germany, Sweden or Great Britain (usually with a repetition rate of ten years) are very expensive, labor-intensive and only available for the minority of the forest areas worldwide. A unique example at global scale is the Forest Resources Assessment (FRA) conducted by the FAO every five to ten years in order to assess the areal extent and changes of forests worldwide (FAO & JRC, 2012). This information can be used as the basis for global sustainable forest management but is still lacking more detailed information on forest volume, associated biomass and its

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changes. For this purpose, remote sensing offers area-wide information with high spatial and temporal resolution and thus can enable sustainable forest management planning and detailed monitoring of changes in a global context.

Radar systems are all-weather systems, which is an advantage over optical systems. The penetration depth of microwaves into the forest canopy depends on the wavelength. The TanDEM-X mission is composed of the two almost identical satellites TerraSAR-X (launched in 2007) and TanDEM-X (launched in 2010) flying in a closely controlled formation. The TanDEM-X mission provides high resolution, multi-polarized, single-pass interferometric X-band (9.65 GHz) data. Especially single-pass interferometry is very suitable for forest applications due to the simultaneous acquisition of the two interferometric images (Kugler, Schulze, Hajnsek, Pretzsch, & Papathanassiou, 2014). The simultaneous acquisition avoids possible errors due to temporal decorrelation and atmospheric disturbances, which is one of the significant benefits of the TanDEM-X mission (Krieger et al., 2007).

Numerous studies investigate the potential of SAR data at different wavelengths from different sensors on satellite and airborne platforms for biomass and stem volume estimation over boreal, temperate and tropical forests. At lower frequencies like P- (0.3–1 GHz) and L- (1–2 GHz) band, the radar signals penetrate deep into the forest canopy and are backscattered at big branches, tree trunks and the ground (Dobson et al., 1992; Le Toan, Beaudoin, Riom, & Guyon, 1992). Due to the high penetration capability and thus high sensitivity to vertical forest structure, the intensity of radar backscatter at longer wavelengths are in particular suitable for biomass retrieval (e.g. Engelhart, Keuck, & Siegert, 2011; Luckman, Baker, Honzák, & Lucas, 1998; Rauste, 2005) but can also be used for stem volume estimations (e.g. Antropov, Rauste, Ahola, & Häme, 2013; Askne, Smith, & Santoro, 2004; Gonçalves, Santos, & Treuhaft, 2011). In contrast, microwaves with higher frequencies (i.e. shorter wavelength) such as C- (4–8 GHz) and especially X- (8–12 GHz) band are just as well able to penetrate down to the ground but are mostly backscattered in the upper part of the crowns (Gama, Santos, & Mura, 2010; Pulliainen, Engdahl, & Hallikainen, 2003). Consequently, the radar backscatter intensity at these bands is less sensitive to the vertical forest structure but hence is well suited to derive height information of the canopy by use of ancillary information on ground elevation (e.g. LiDAR-based DTM).

Thus, C- and X-band microwaves tend to be more appropriate for both biomass (e.g. Gama et al., 2010; Solberg, Riegler, & Nonin, 2015; Treuhaft et al., 2015) and stem volume (e.g. Karila, Vastaranta, Karjalainen, & Kaasalainen, 2015; Solberg, Astrup, Breidenbach, Nilsen, & Weydahl, 2013; Wagner et al., 2003) estimation by means of height information derived from SAR data. Biomass and stem volume estimations by means of height information derived from shortwave radar data are based on either SAR radargrammetry (e.g. Karjalainen, Kankare, Vastaranta, Holopainen, & Hyppä, 2012; Solberg et al., 2015; Vastaranta, Holopainen, Kankare, & Hyppä, 2014) or SAR interferometry (e.g. Gama et al., 2010; Solberg et al., 2013; Treuhaft et al., 2015).


In contrast to previous studies which were carried out in boreal or tropical forest stands using X-band radar data, the current study investigates stem volume estimation based on height information derived from polarimetric interferometric SAR (PolInSAR) data from TanDEM-X in temperate complex forest stands. Nevertheless, few studies based on non-X-band interferometric SAR data already exist in temperate forests. Li, Chen, Li, Ke, and Zhan (2015) estimated biomass from vertical reflectivity profiles based on airborne L-band data in temperate forest stands in Traunstein, Southeast Germany. Neumann, Ferro-Famil, and Reiger (2010) derived forest height information based on polarimetric interferometric airborne L-band SAR data in temperate forest stands in Traunstein. In Lavalle, Solimini, Pottier, and Desnos (2010) the potential of compact-polarimetric airborne InSAR data of multiple frequencies was investigated for estimation of forest parameters in temperate forest stands of Traunstein forest.

The objective of this study is to explore the potential of height information derived from X-band PolInSAR data for stem volume estimation based on a statistically fitted regression model in temperate forest stands. Thereby, this study is linked to previous studies which investigated the potential of X-band PolInSAR data to derive height information over complex temperate and tropical forest stands (e.g. Hajnsek, Kugler, Lee, & Papathanassiou, 2009; Kugler et al., 2014) while applying the derived height information for stem volume estimation. In detail, the aims of this study were defined as (i) estimation of stem volume per unit area at plot (circular plots of 500 m²) and stand level (areas of 1.5 to 6.4 ha) based on height information derived from polarimetric interferometric TanDEM-X data in combination with airborne LiDAR data and terrestrial measurements and (ii) improvement of the predictions by integration of texture parameters representing the horizontal stand structure.

2. Materials

2.1. Study area

The study area (Fig. 1) is located in a highly structured, mixed, temperate municipality owned forest close to the city of Traunstein, Germany (47°52′ N, 12°38′ E). Traunstein forest covers an area of about 580 ha and is supervised and used as teaching and research forest by the Chair for Forest Growth and Yield Science of the Technische Universität München (TUM). The study area is limited to a forest area of 243 ha bounded by the districts Bürgerwald and Heiligengeistwald. The topography ranges from 630 to 720 m a.s.l. and includes small areas with steep slopes. The soils are composed of glacier sediments which belong to the pre-alpine moraine landscape. The climatic conditions are characterized by a mean annual temperature of 7.3 °C and precipitation of up to 1600 mm/year. The main tree species are Norway spruce (Picea abies), European silver fir (Abies alba), European beech (Fagus sylvatica) and Sycamore maple (Acer pseudoplatanus). The forest stands are very complex concerning tree species richness and heterogeneous stand structures due to close-to-nature silviculture (Pretzsch, 1998) which is reflected by the distribution of tree species (Table 1) and percentage of development stages (Table 2) within the study area.

2.2. Remote sensing data

Two dual-polarized interferometric TanDEM-X image pairs acquired on January 09, 2012 and May 18, 2013 were used. The images were acquired in bistatic StripMap mode in ascending orbit and almost identical incidence angles of roughly 43°. The baseline between the two sensors was 108.74 m and 142.72 m, respectively. A summary of
the TanDEM-X acquisition parameters is given in Table 3. In addition, an airborne LiDAR survey was conducted on November 18, 2012 with a flight height of about 500 m and a point density of about 25 dots/m² using the LMS-Q680i Scanner from RIEGL. The associated Digital Terrain Model (DTM) as well as Digital Surface Model (DSM) was provided by MILAN Geoservice GmbH.

2.3. Reference data

A forest inventory comprising 228 permanent circular sampling plots was carried out in summer 2013. Forest condition and the dynamics of stand parameters are detected based on the survey guidelines of the Bavarian State Forest Enterprise (Bayerische Staatsforsten, 2011). In Traunstein forest, inventory has been carried out according to this concept since 1988. For permanent systematic inventory sampling according to these guidelines, the center of the concentric inventory plots is permanently marked with buried lodestones. For each inventory plot the polar coordinates (azimuth and range relative to the center of the plot) are recorded for all measured trees with a diameter at breast height (dbh) of at least 10 cm. Thus, repeated surveys can be easily conducted and the sampling error for alterations of the stand parameters can be reduced. The plots are arranged on a regular 100 m by 100 m sampling grid (Fig. 2a) with a resulting sampling density of 1 plot/ha. The spatial distribution of the inventory plots within the study area is depicted in Fig. 3. Each circular inventory plot covers an area of 500 m² and consists of three concentric sub-circles with radii of 12.62 m, 6.31 m and 3.15 m respectively. For each sub-circle, a specific threshold dbh for a tree in order to be recorded is defined (as shown in Fig. 2b). The dbh is measured for any tree above the relevant threshold value. Tree height measurements are taken for a representative sample of each tree species per stand layer. Additionally, other tree and forest stand attributes such as species, age, layering, damages, dead wood, and stem quality are recorded. Standard height curve systems are used for estimating tree height based on the measured height sample. Subsequently, stem volume per unit area is calculated for all living trees based on tree height, basal area (derived from dbh) and a form factor according to Eq. (1).

\[ V = \sum_{i=1}^{N} b_{ai} \cdot h_{i} \cdot f_{1,3i} \cdot r_{i} \]  

where \( V \) is stem volume per hectare, \( N \) is the number of trees within the plot, \( b_{ai} \) is the basal area of tree \( i \), \( h_{i} \) is the height of tree \( i \), \( f_{1,3i} \) is the form factor of tree \( i \) and \( r_{i} \) is the number of representation per hectare of tree \( i \). Stem volume per unit area ranges from 0 m³ ha⁻¹ up to 1049 m³ ha⁻¹ in the study area as shown in Table 4 containing the minimum, mean and maximum values of inventory parameters. In general, the error for volume estimations can be assumed as ±10–15% (Kramer & Akça, 1987).

In Traunstein, inventory plots are attributed to different stages of development. The following development stages are distinguished, describing the condition and structure of the stands:

- Youth stage: slow growing up until a closed canopy has established.
- Growth stage: rapid growth, increase of growing stock until culmination of increment of volume.
- Maturity stage: subsiding growth of growing stock and growth; typically, trees are concentrated in one stand layer, and regeneration is missing due to absence of light at the forest floor.
- Regeneration stage: upcoming regeneration under the cover of the old trees.
- Plenter stage: forest structure is at least three-layered (including understorey and regeneration).

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Area percentages of tree species within the study area.</th>
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</thead>
<tbody>
<tr>
<td>Area percentages of tree species [%]</td>
<td></td>
</tr>
<tr>
<td>Spruce</td>
<td>41</td>
</tr>
<tr>
<td>Fir</td>
<td>14</td>
</tr>
<tr>
<td>Pine</td>
<td>1</td>
</tr>
<tr>
<td>Larch</td>
<td>2</td>
</tr>
<tr>
<td>Douglas fir</td>
<td>1</td>
</tr>
<tr>
<td>Beech</td>
<td>23</td>
</tr>
<tr>
<td>Oak</td>
<td>1</td>
</tr>
<tr>
<td>Real deciduous woods</td>
<td>12</td>
</tr>
<tr>
<td>Other deciduous woods</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Area percentages of development stages within the study area.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area percentages of development stages [%]</td>
<td></td>
</tr>
<tr>
<td>Youth stage</td>
<td>21</td>
</tr>
<tr>
<td>Growth stage</td>
<td>15</td>
</tr>
<tr>
<td>Maturity stage</td>
<td>12</td>
</tr>
<tr>
<td>Regeneration stage</td>
<td>31</td>
</tr>
<tr>
<td>Plenter stage</td>
<td>21</td>
</tr>
</tbody>
</table>
These development stages were used for the selection of stands for stem volume estimation at stand level, while only those stands containing at least three inventory plots were chosen. Characteristic values for each stand can be found in Table 5. In total 20 stands with sizes ranging from about 1.5 ha to about 6.4 ha were used. The development stages represent areas of similar structure. Therefore, the range of stand areas of about 4 ha is negligible concerning the accuracy of stem volume estimations at stand level. The spatial distribution of the 20 stands is given in Fig. 3. Plot-wise stem volume derived from the inventory data as well as the height information deduced from the SAR data over the inventory plots were averaged per stand for linear regression.

Stem volume estimations are based on both scales, plot- and stand level. Since the terrestrial measurements are carried out on spatial units of 500 m², this scale is convenient to avoid uncertainties due to aggregation or extrapolation of in-situ measurements. However, stem volume predictions at stand level are more suitable to provide area-wide information. By using stands which are based on repeated forest inventories and defined concerning structure and growth stage, the terrestrial measurements can be aggregated to reliable and meaningful stem volume values per stand and thus enables area-wide stem volume estimations.

3. Methods

3.1. Generation of height information from PolInSAR data

Two different height information data sets were derived from the polarimetric interferometric SAR data. A DSM calculated from the interferometric TanDEM-X data, which represents the height of the earth surface including all elevated objects (i.e. buildings and vegetation), was normalized by subtracting the LiDAR-based DTM, which represents the height of the earth surface without elevated objects. The normalized DSM (nDSM) corresponds to the phase height (scattering center height), which reflects the average of tree height dependent on penetration depth and spatial resolution. Tree height is clearly defined in forestry as the height difference between tree top and tree base. Furthermore, the top height (modeled top height) is derived from the TanDEM-X data by a PolInSAR modeling technique and is related to the silvicultural relevant parameter top height H100 which corresponds to the hundred largest trees per hectare (Kugler et al., 2014). Both data sets are correlated with stem volume and used for stem volume estimation by comparison.

For estimation of the scattering center height, a DSM was calculated from the interferometric data (Bamler & Hartl, 1998). From the available dual-polarized TanDEM-X data the VV polarization was chosen for height estimation. Previous studies in Traunstein showed that the VV polarization is probably more suitable since it has less ground scattering contribution compared with HH (Kugler, Hajnsek, & Papathanassiou, 2011). Nevertheless, it has to be noted that in general VV and HH polarizations lead to similar results (Kugler et al., 2014). The scattering signals, acquired simultaneously from slightly different positions by the TanDEM-X sensors, were coherently combined in an interferogram for digital elevation model generation (Krieger et al., 2013; Rosen et al., 2000). The interferometric phase describes the phase differences of the two acquisitions mainly affected by the differences in range (Bamler & Hartl, 1998). After resolving the ambiguity of the interferometric phase by phase unwrapping, the phase differences can be converted into height based on the interferometer geometry for terrain reconstruction (Rosen et al., 2000). The derived DSM was normalized by subtracting the LiDAR-based DTM and thus, a vegetation height model corresponding to the height of scattering center was generated. The scattering center height underdetermines the actual vegetation height due to the penetration of the radar wave.

The modeled top height was derived by applying the Random Volume over Ground (RVoG) model, a PolInSAR technique (Cloude & Papathanassiou, 2003; Kugler et al., 2014; Papathanassiou & Cloude, 2001; Treuhaft, Madsen, Moghaddam, & van Zyl, 1996). The RVoG model represents the scattering from volume and ground by means of a two-layer vegetation model. It is based on volume decorrelation which is observed in interferometric radar acquisitions over forested areas (Papathanassiou & Cloude, 2001). Volume decorrelation is interpreted as a function of the vertical distribution of scatterers along the height of a volume. A decrease of backscattering along volume height can be interpreted as signal extinction. In case of no extinction and uniform backscattering along height, the volume layer has the form of a rectangle (Fig. 4a). If the electromagnetic wave is attenuated during its transition through the volume — as assumed for higher frequencies like X-band — the volume layer has an exponential form.

![Fig. 2. a) Inventory sampling grid and b) thresholds in diameter measuring.](image-url)
In general, the magnitude of the ground scattering depends on frequency, polarization and extent of extinction. For TanDEM-X data of Traunstein forest ground scattering is assumed to be extremely low and was therefore neglected in the height estimation (Kugler et al., 2014). The implementation of the RVoG model for TanDEM-X data is detailed as described in Kugler et al. (2014) and Cloude and Papanathanassiou (2003). In this study TanDEM-X single-polarization data in VV was used since it yields the best results for Traunstein forest (Kugler et al., 2014). However, in the case of single-polarization data the inversion problem is underdetermined and requires external information on the ground elevation under the modeled forest layer. Information on the elevation of the ground was taken from a LiDAR-based DTM (Kugler et al., 2011, 2014).

Fig. 5 depicts the comparison of the modeled top height (Fig. 5a), the scattering center height (Fig. 5b) and the LiDAR-based nDSM (Fig. 5c) along a transect of about 250 m. The LiDAR-based nDSM is only used for comparison and not included in the stem volume estimations. Additionally, two ground measured values of top height H100 are inserted at the position 5 m and 140 m of the transect (Fig. 5d). Modeled top height is related to the top height H100, i.e. average height of the hundred largest trees per hectare. The top height H100 is a silvicultural relevant parameter and can be calculated for reference units of at least 100 m² by considering the height of the dominating tree. Dependent on the reference unit of commonly 1 ha, top height H100 does not reflect small-scale forest structure due to considering solely the dominating trees. Modeled top height is based on reference units of about 15 × 15 m². Therefore, the forest structure concerning areas smaller than units of about 15 × 15 m² is not reflected. The scattering center height underestimates the vegetation height due to the penetration of the microwaves into the forest. In general, the LiDAR-based nDSM also underestimates vegetation height because of penetration into the forest (Nilsson & Holgren, 2003; van Laar & Akça, 2007), which is increased due to acquisition in the off-leaf season. As the modeled top height considers only the dominating trees and the scattering center height as well as the LiDAR-based nDSM underestimates vegetation height obvious height differences between the data sets occur. Comparing the top height H100 values based on in-situ measurements from the forest inventory, the modeled top height yields reasonable values. On closer consideration of the area along the transect in combination with the height profiles of Fig. 5d, the differences between modeled top height and LiDAR-based nDSM become reasonable. Between 0 m and 50 m as well as between 150 m and 200 m the forest stand has very low parts and gaps, i.e. it is less dense. For this reason the LiDAR-based nDSM as well as the scattering center height is variable. In contrast, the modeled top height has higher height values due to the larger reference unit of about 15 × 15 m² which also contains higher trees. As opposed to this, between 50 m and 100 m the forest stand is much denser. Therefore, the height differences between LiDAR-based nDSM, scattering center height and modeled top height are less. Moreover, additional effects such as spatial resolution of the data sets, spatial offset and side-looking acquisition of the SAR sensor influence the differences between the height data sets (modeled top height, scattering center height and LiDAR-based nDSM). A comparison between scattering center height and the LiDAR-based nDSM, the scattering center height shows less variation in height mainly as a consequence of worse spatial resolution of the SAR data.

The scattering center height and the modeled top height were generated for the two polarimetric interferometric TanDEM-X acquisitions. All

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Statistics of forest parameters per plot acquired during forest inventory 2013. Volume is specified as timber harvested (&gt;7 cm at the smaller end) without bark.</th>
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</thead>
<tbody>
<tr>
<td>Mean stem diameter [cm]</td>
<td>Mean tree height [m]</td>
</tr>
<tr>
<td>Min</td>
<td>0.00</td>
</tr>
<tr>
<td>Mean</td>
<td>32.44</td>
</tr>
<tr>
<td>Max</td>
<td>67.53</td>
</tr>
</tbody>
</table>
data sets were processed to a pixel spacing of 6 m. In total, four height data sets were used for stem volume estimation in this study, the scattering center height as well as the modeled top height, both for the winter (January 2012) and the summer (May 2013) acquisition, respectively. A summary of the derived height information is given in Table 6.

3.2. Linear regression model based on allometric equation

Allometry is the science of size-correlated variations in organic form and process (Niklas, 1994). Allometry describes the unproportional growth of two dimensions to each other compared with isometry which denotes a proportional growth of two dimensions to each other according to the constant allometric ratio of growth rates \( a \). In terms of tree growth, an allometric relation between stem volume and tree height exists, where \( y \) is the stem volume and \( x \) is the tree height:

\[
a \frac{dV}{dt} = \frac{y}{x} \frac{dx}{dt}
\]

where \( V \) is volume in cubic meters per hectare, \( H \) is scattering center height or modeled top height in meters per inventory plot.

Stem volume and tree height grow unequally however constant to each other according to the constant allometric ratio of growth rates \( a \). By integration and logarithmic representation of Eq. (2) a linear relationship is formed which expresses that the stem volume grows proportional to a power of the tree height:

\[
y = b \cdot x^a
\]

\[
\ln y = \ln b + a \cdot \ln x.
\]

The linear model (5) is represented as a straight line with the constants \( b \) and \( a \). \( b \) is known as the integration constant specifying the value of \( y \) at \( x = 1 \). \( a \) is the constant allometric ratio of growth rates and defines the slope of the straight line. If \( a > 1 \), \( y \) increases faster than \( x \) (positive allometry). If \( a < 1 \), \( x \) and \( y \) increase proportionally (isometric growth). If \( a < 1 \), \( x \) increases faster than \( y \) (negative allometry) (Huxley, 1932; von Bertalanffy, 1951). In general as well as in the present case of the inventory conducted in 2013, stem volume per unit area \( V \) and averaged tree height \( H \) per inventory plot possess a positive allometric relationship as depicted in Fig. 6a. The logarithmic representation of this relationship is shown in Fig. 6b.

In order to determine the relationship between the two forest variables, stem volume per unit area and averaged scattering center height or modeled top height, a linear model based on the log-transformed allometric Eq. (5) was fitted:

\[
\ln V = \ln a_0 + a_1 \cdot \ln H
\]

where \( V \) is volume in cubic meters per hectare, \( H \) is scattering center height or modeled top height in meters per inventory plot, \( \ln a_0 \) is the intercept with the \( y \)-axis and \( a_1 \) is the slope. Stem volume per unit area is predicted by the calculated regression line of model (6), deriving the expected mean value of \( \ln V \) for specific values of \( \ln H \). The regression line describes the best line of fit between stem volume and scattering center height or modeled top height (Niklas, 1994). To fit model (6), total stem
volume per hectare and mean scattering center height or modeled top height for each inventory plot, were used. For plot level estimations, stem volume was calculated according to Eq. (1) from the in-situ measurements for each inventory plot and scattering center height and modeled top height were averaged per inventory plot. For stand level estimations, stem volume and averaged scattering center height or modeled top height per inventory plot were averaged per stand.

3.3. Extension of the linear regression model

Stem volume per unit area depends mainly on tree height and stand density. In terms of volume prediction using the linear model (6), height information was derived from the TanDEM-X data. However, stand basal area representing stand density as used in (1) was not considered in the model. To improve the prediction results, the linear model has to be extended by additional parameters that describe stand density, or, more generally, horizontal forest structure. For this purpose, novel texture parameters were derived from the TanDEM-X height information using the Co-occurrence Matrix according to Haralick (1971). The co-occurrence matrix is a second-order statistical analysis for the extraction of texture within an image. This method determines how often a pair of pixels of certain values and a certain spatial relationship occurs within the image (Haralick, 1979). With respect to the inventory plots used in this study, the neighborhood relation of tree height values within each inventory plot is identified by means of the amount of pairs of pixels with certain height values and a certain spatial relationship. The spatial relationship is defined by the distance $d$ and the direction $\alpha$ of the pixels to each other which fixed at the beginning of the analysis. In general, the analysis can be performed for each distance and direction. The directions according to $\alpha = 0^\circ$, $\alpha = 45^\circ$, $\alpha = 90^\circ$, $\alpha = 135^\circ$, $\alpha = 180^\circ$, $\alpha = 225^\circ$, $\alpha = 270^\circ$ and $\alpha = 315^\circ$ can be used for texture extraction. In this study, the co-occurrence approach was applied to the scattering center height of each inventory plot with a distance of $d = 1$ and all non-redundant directions with the angles $\alpha = 0^\circ$, $\alpha = 45^\circ$, $\alpha = 90^\circ$ and $\alpha = 135^\circ$. The scattering center height was used since it reflects the horizontal forest structure better compared with the modeled top height (Fig. 5). Fig. 7 shows an example of the derivation of the Co-occurrence Matrix for angle $\alpha = 0^\circ$. The height data had to be classified, because otherwise all height values were slightly different to each other and accordingly the Co-occurrence Matrix entailed no meaningful results. For this purpose, the Jenks natural breaks classification algorithm was applied to define ten height classes in relation to the maximum height value of the height data set in the whole study area to make all plots comparable. This method seeks to group the data into classes based on the histogram in order to minimize within-class variance and maximize between-class variance while iteratively optimizing the class allocation according to the minimum sum of squared deviations from the class mean values (Jenks & Caspall, 1971).

Subsequently, the resulting Co-occurrence Matrices were interpreted according to the diagonal deriving the following four parameters for each Co-occurrence Matrix:

1) The weighted center of gravity of the Co-occurrence Matrix along the diagonal, called center diagonal $c_d$,

$$c_d = \frac{\sum \left( \frac{(i+j)}{2} \right) M(i,j)}{\sum M(i,j)}$$  \hspace{1cm} (7)

where $i$ and $j$ are the indices of columns and rows and $M(i,j)$ are the values of the Co-occurrence Matrix elements at position $(i,j)$.
The center diagonal describes the weighted mean of occurring height classes within each inventory plot. Thus, the center diagonal is a measure in direct relation to stand height.

2) The weighted center of gravity of the Co-occurrence Matrix perpendicular to the diagonal, called center perpendicular $c_p$.

$$c_p = \frac{\sum ((i-j) \cdot M(i,j))}{\sum M(i,j)}$$  \hspace{1cm} (8)

where $i$ and $j$ are the indices of columns and rows and $M(i,j)$ are the values of the Co-occurrence Matrix elements at position $(i,j)$.

The center perpendicular describes the variation of height as a function of occurring differences of neighboring height classes. Thus, the center perpendicular is a measure of homogeneity.

3) The standard deviation along the diagonal of the Co-occurrence Matrix, called standard deviation diagonal $s_d$.

$$s_d = \frac{\sum (M(i,j) - \mu_d)^2}{\sum M(i,j)}$$  \hspace{1cm} (9)

where $i$ and $j$ are the indices of columns and rows, $M(i,j)$ are the values of the Co-occurrence Matrix elements at position $(i,j)$ and $\mu_d$ is the mean of the values projected onto the diagonal.

The standard deviation diagonal is derived by projecting all values onto the diagonal and calculating the standard deviation as shown in Fig. 8. Thus, the standard deviation diagonal is a measure of homogeneity.

4) The standard deviation perpendicular to the diagonal of the Co-occurrence Matrix, called standard deviation perpendicular $s_p$.

$$s_p = \frac{\sum (M(i,j) - \mu_p)^2}{\sum M(i,j)}$$  \hspace{1cm} (10)

where $i$ and $j$ are the indices of columns and rows, $M(i,j)$ are the values of the Co-occurrence Matrix elements at position $(i,j)$ and $\mu_p$ is the mean of the values projected perpendicular to the diagonal.

The standard deviation perpendicular is derived by projecting all values onto the perpendicular of the diagonal and calculating the standard deviation (Fig. 8). Thus, the standard deviation perpendicular is a measure of homogeneity.

It can be assumed that stem volume increases with increasing center diagonal, since this parameter is directly related to stand height and thus the stands become higher (Fig. 9a). In contrast, it is assumed that stem volume decreases with increasing center perpendicular at constant center diagonal, because the differences in height become larger within the considered area and consequently the stand becomes less dense (Fig. 9b). For the same reason, stand density decreases with increasing standard deviation of the Co-occurrence Matrix along the diagonal (Fig. 9c) as well as perpendicular to the diagonal (Fig. 9d) at constant center diagonal.
Fig. 8. Illustration of the derivation process of standard deviation diagonal and standard deviation perpendicular, where $\mu_d$ and $s_d$ are mean and standard deviation along the diagonal and $\mu_p$ and $s_p$ are mean and standard deviation along the perpendicular to the diagonal.

Fig. 9. Interpretation of the Co-occurrence Matrix based on forest height information. a) Stem volume increases with increasing center along the diagonal. b) Stem volume decreases with increasing center perpendicular to the diagonal. c) Stand density decreases with increasing standard deviation of the Co-occurrence Matrix along the diagonal. d) Stand density decreases with increasing standard deviation of the Co-occurrence Matrix perpendicular to the diagonal.
Consequently, the three co-occurrence parameters center perpendicular, standard deviation diagonal and standard deviation perpendicular are related to center diagonal since they represent a different kind of information. It is assumed that the three ratios \( \frac{cp}{cd} \), \( \frac{sd}{cd} \) and \( \frac{sp}{cd} \) in combination based on all directions can capture forest structure.

In order to improve the regression of stem volume per unit area, the linear model (6) was expanded by these ratios:

\[
\ln V = \ln a_0 + a_1 \cdot \ln H + a_2 \cdot \ln \frac{cp}{cd} + a_3 \cdot \ln \frac{sd}{cd} + a_4 \cdot \ln \frac{sp}{cd} + \ldots \\
+ a_{13} \cdot \ln \frac{sp}{cd}_{135} \tag{11}
\]

where \( V \) is volume in cubic meters per hectare, \( H \) is averaged scattering center height or modeled top height in meters per inventory plot, \( \frac{cp}{cd} \), \( \frac{sd}{cd} \) and \( \frac{sp}{cd} \) are the ratios based on the Co-occurrence Matrix with the subscripts according to the angle \( \alpha \) (0, 45, 90, 135), \( \ln a_0 \) is the intercept with the y-axis and \( a_1 - a_{13} \) are the regression coefficients.

The expanded linear regression model for stem volume estimation was applied at plot as well as at stand level. To fit the model, total stem volume and averaged scattering center height or modeled top height for each inventory plot were used and averaged per stand. The co-occurrence parameters were calculated per inventory plot according to (7)–(10) at plot level and averaged per stand at stand level.

Metrics describing the relative importance of each predictor were used to quantify the contribution of the co-occurrence parameters to the coefficient of determination \( R^2 \) of the multiple regression model (11). Relative importance indices give information about the contribution of each explanatory variable to the prediction by itself and in combination with other variables (Tonidandel & LeBreton, 2011). Traditional measures include the comparison of zero-order correlations of an explanatory variable with the criterion, the increase in \( R^2 \) by adding each explanatory variable to all others and standardized regression coefficients (Johnson & LeBreton, 2004). However, these measures are only valid for uncorrelated explanatory variables (Johnson & LeBreton, 2004). Since the co-occurrence parameters are correlated, these traditional measures are not suitable. Moreover, different orderings of the explanatory variables lead to different decompositions of the explained sum of squares for the same multiple regression model (Grömping, 2006). This disregard of the ordering of the explanatory variables entails that the relative importance of explanatory variables is dependent on the ordering. Alternative measures overcome these problems by averaging the contribution of each explanatory variable across all possible orderings of variables (Johnson & LeBreton, 2004).

According to Grömping (2006) the Proportional Marginal Variance Decomposition (PMVD) metric is a suitable solution to address
relative importance to the explanatory variables based on averaging the contributions across all possible orderings. The PMVD approach uses data-dependent weights for the averaging process to avoid that variables benefit from each other due to their correlation. This method was applied to the expanded linear model \((11)\) in order to quantify the contribution of the co-occurrence parameters to stem volume estimation.

4. Results

4.1. Correlation of stem volume and TanDEM-X height information

Fig. 10 shows the scatterplot of stem volume in cubic meters per hectare estimated from terrestrial inventory against height information (scattering center height and modeled top height) in meters derived from TanDEM-X data of the winter and the summer acquisition for each inventory plot with the corresponding correlation coefficients \((r)\). Stem volume per hectare exhibits a positive linear correlation with scattering center height as well as modeled top height. The scattering center height has a stronger correlation with stem volume compared with the modeled top height. For scattering center height the correlation coefficient is slightly higher for the summer acquisition than for the winter acquisition as opposed to the modeled top height. The best correlation was achieved with the scattering center height derived from the summer acquisition.

4.2. Stem volume estimation at plot level

Table 7 shows the results of stem volume prediction based on the linear model \((6)\) for the winter as well as for the summer acquisition for scattering center height and modeled top height respectively. Predictions of stem volume per unit area at plot level (circular plots of 500 m²) were more accurate based on scattering center height compared with the results based on modeled top height. The regression model including scattering center height from the summer acquisition explains 60% of the variance of stem volume and thus led to the highest coefficient of determination.

The extension of the linear model by the three ratios of the co-occurrence parameters for each direction according to Eq. \((11)\) led to predictions in the best case with \(R^2\) of 69.92% and RMSE of about 155.00 m³ ha⁻¹ (RMSE related to mean stem volume = 41.90%) based on the scattering center height from the summer acquisition (Table 8). This can be related to the original estimation of stem volume (Table 7) in terms of improvement of coefficient of determination of almost 10%. Concerning deviation of absolute values, RMSE is reduced by about 25 m³ ha⁻¹. Quantifying the contribution of the co-occurrence parameters according to the relative importance metric of PMVD, the co-occurrence parameters possess a contribution of 12.54% of the explained variance of stem volume. This contribution is equally distributed across all co-occurrence parameters and thus, all ratios and directions are important.

Fig. 11 illustrates the correlation between the predicted stem volume values at plot level based on the model employing the scattering center height and the co-occurrence parameters from the summer acquisition and the measured values. Slight saturation effects occur at about 400 m³ ha⁻¹.

4.3. Stem volume estimation at stand level

At stand level (areas of 1.5 to 6.4 ha), the predictions of stem volume using the linear model \((6)\) improved substantially compared with the results at plot level (Table 7). As shown in Table 9 the estimations of stem volume were more accurate based on the scattering center height compared with the modeled top height. The best results at stand level with \(R^2\) of 88% and RMSE of about 73 m³ ha⁻¹ were achieved using the scattering center height from the summer acquisition. This is consistent with the results at plot level.

Table 7

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Intercept ((\ln a_0))</th>
<th>SE(a_0)</th>
<th>(a_1)</th>
<th>SE(a_1)</th>
<th>RMSE ([\text{m}^3 \text{ha}^{-1}])</th>
<th>RMSE [%]</th>
<th>(R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scattering center height</td>
<td>4.50 ***</td>
<td>0.09</td>
<td>0.57</td>
<td>0.04</td>
<td>164.30</td>
<td>44.40</td>
<td>0.56</td>
</tr>
<tr>
<td>Modeled top height (winter)</td>
<td>0.45</td>
<td>0.40</td>
<td>1.59</td>
<td>0.12</td>
<td>180.00</td>
<td>48.64</td>
<td>0.54</td>
</tr>
<tr>
<td>Scattering center height</td>
<td>2.86 ***</td>
<td>0.19</td>
<td>1.09</td>
<td>0.07</td>
<td>179.81</td>
<td>48.59</td>
<td>0.60</td>
</tr>
<tr>
<td>Modeled top height (summer)</td>
<td>0.76 *</td>
<td>0.49</td>
<td>1.96</td>
<td>0.15</td>
<td>181.22</td>
<td>48.97</td>
<td>0.54</td>
</tr>
</tbody>
</table>

4.5. Comparison of the results from the simple linear regression model and the extended linear regression model at plot level described by the standard error SE of the parameters, root mean square error RMSE of the predictions, RMSE related to the mean stem volume and the coefficient of determination \(R^2\). The models are based on scattering center height or modeled top height from winter (09.01.2012) or summer (18.05.2013) acquisitions.

Table 8

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Linear model</th>
<th>Extended linear model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RMSE ([\text{m}^3 \text{ha}^{-1}])</td>
<td>RMSE [%]</td>
</tr>
<tr>
<td>Scattering center height</td>
<td>164.30</td>
<td>44.40</td>
</tr>
<tr>
<td>Modeled top height (winter)</td>
<td>180.00</td>
<td>48.64</td>
</tr>
<tr>
<td>Scattering center height</td>
<td>175.81</td>
<td>48.59</td>
</tr>
<tr>
<td>Modeled top height (summer)</td>
<td>181.22</td>
<td>48.97</td>
</tr>
</tbody>
</table>
accuracies compared with the estimations based on modeled top height. The results could be improved substantially by extending the linear regression model with the co-occurrence parameters representing forest structure.

5. Discussion

The current study presented the potential of stem volume estimation in a complex temperate forest consisting of unevenly aged mixed forest stands with high range in stem volume (Table 4) and high species richness (Table 1) in different development stages (Table 2) based on X-band SAR data. In contrast, other studies which investigate biomass or stem volume retrieval based on interferometric X-band SAR data are mostly carried out in boreal (e.g. Karila et al., 2015; Rahlf et al., 2014; Solberg et al., 2013) and tropical (e.g. Gama et al., 2010; Schlund et al., 2015; Treuhaft et al., 2015) forest stands. Table 11 shows the generalized characteristics of global forest biomes according to Apps et al. (1993); Fischer (2003); Montagnini and Jordan (2005) and Thomas and Baltzer (2002). Boreal forests are rather homogeneous concerning species diversity and vertical structure (Malhi, Baldocchi, & Jarvis, 1999). Temperate forests are characterized by a higher tree species diversity and productivity compared with boreal forests (Fischer, 2003; Pretzsch, 2003). Due to the favorable climatic conditions in tropical forests, the diversity of tree species is very high and the stands are multi-layered (Malhi et al., 1999; Montagnini & Jordan, 2005). Taking account of these differences in complexity of forest stands, the abovementioned studies are not completely comparable with the current study. Stem volume per unit area and thus its estimation is strongly influenced by the complexity of the forest stands. Consequently, stand diversity defined by stand density, vertical structure or tree species composition, among others, is not as crucial for stem volume retrieval performed in boreal forest test sites as for heterogeneous temperate and tropical forests. In the case of the temperate forest of Traunstein, the targeted reversion from homogeneous even-aged pure forests to close-to-nature, structurally rich, heterogeneous forests is far advanced. Hence, the stands are rich in tree species composition and highly structured and thus essentially more heterogeneous compared with forest areas investigated in most other studies performing stem volume estimation based on interferometric X-band SAR data.

However, the obtained estimations of stem volume yield similar results at plot level and at stand level compared with the other studies using interferometric X-band SAR data for biomass or stem volume estimation. At plot level (plot size 500 m²) simple linear regression based on height information achieved stem volume predictions with R² ranging from 56% to 60% and RMSE between 164.30 m³ ha⁻¹ and 181.22 m³ ha⁻¹ (relative RMSE between 44.40% and 48.97%). The multiple linear regression model employing the height information and the co-occurrence parameters led to the best results with R² of about 70% and RMSE of 155 m³ ha⁻¹ (relative RMSE of 41.90%). In comparison Karila et al. (2015) obtained stem volume estimations at plot level (plot size about 300 m²) in the best case with RMSE of about 67.2 m³ ha⁻¹ (relative RMSE = 32.2%) and R² of about 0.65 in spruce and pine dominated boreal forest stands using a nearest neighbor prediction model for stem volume estimation based on InSAR heights from TanDEM-X data. Rahlf et al. (2014) also predicted stem volume in spruce and pine dominated forest stands based on 250 m² plots by means of a linear mixed model based on interferometric TanDEM-X data with RMSE of 77.56 m³ ha⁻¹ (relative RMSE of 41.60%). Solberg et al. (2013) obtained stem volume estimations at plot level (plot size 250 m²) with RMSE of about 94 m³ ha⁻¹ (relative RMSE = 44%) in spruce dominated boreal forest stands using linear regression based on height information derived from TanDEM-X data. Gama et al. (2010) estimated stem volume by linear regression in tropical Eucalyptus plantations using interferometric airborne SAR data at plot level (size of about 400 m²) and achieved best results with RMSE of 33.56 m³ ha⁻¹ (relative RMSE = 10.55%) and R² of about 84%. However, airborne data with considerable higher spatial resolution were used in this study.

At stand level (areas of 1.5 to 6.4 ha) stem volume estimation could be improved with R² between 68% and 88% and RMSE ranging from 72.35 m³ ha⁻¹ to 91.20 m³ ha⁻¹ (relative RMSE 27.03%–34.08%) using the linear regression model based on height information. The extension of the model with the co-occurrence parameters led to the best results at stand level with R² of 94% and RMSE of 44.25 m³ ha⁻¹ (relative RMSE of 16.53%). These results are similar or even better compared with the stem volume estimations at stand level (stand size 1–3 ha) in spruce and pine dominated boreal forest reported by Rahlf et al. (2014) with RMSE of about 33.74 m³ ha⁻¹ (relative RMSE = 18.10%) and Solberg et al. (2013) with R² of 81% and RMSE of about 44 m³ ha⁻¹ (relative RMSE = 20%). Schlund et al. (2015) and Treuhaft et al. (2015) achieved biomass estimations based on interferometric TanDEM-X data in tropical forest stands (stand size <1 ha) with RMSE of 53 t ha⁻¹ (relative RMSE of about 20%) and 52–62 m³ ha⁻¹ (relative RMSE of about 29%–35%) respectively. In Solberg et al. (2010) biomass retrievals with R² ranging from 0.45 to 0.81 and RMSE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Intercept (lnha)</th>
<th>SE₀</th>
<th>a₀</th>
<th>SE₀</th>
<th>RMSE [m³ ha⁻¹]</th>
<th>RMSE [%]</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scattering center height (winter)***</td>
<td>4.25***</td>
<td>0.21</td>
<td>0.58</td>
<td>0.09</td>
<td>77.02</td>
<td>28.78</td>
<td>0.68</td>
</tr>
<tr>
<td>Modeled top height (winter)***</td>
<td>0.27</td>
<td>0.78</td>
<td>1.74</td>
<td>0.24</td>
<td>73.35</td>
<td>27.41</td>
<td>0.73</td>
</tr>
<tr>
<td>Scattering center height (summer)***</td>
<td>2.64***</td>
<td>0.23</td>
<td>1.11</td>
<td>0.09</td>
<td>72.35</td>
<td>27.03</td>
<td>0.88</td>
</tr>
<tr>
<td>Modeled top height (summer)***</td>
<td>1.79</td>
<td>0.94</td>
<td>2.21</td>
<td>0.29</td>
<td>91.20</td>
<td>34.08</td>
<td>0.75</td>
</tr>
</tbody>
</table>
of about 17 t ha\(^{-1}\) to 36 t ha\(^{-1}\) (relative RMSE of 21% to 36%) in boreal forest stands (stand size \(>2\) ha) dominated by spruce and pine were achieved using a linear regression model based on interferometric height information from SRTM.

Compared with these studies carried out in boreal and tropical forests, the results of the current study are very viable in view of the fact that the volume estimations obtain similar or even better accuracies in the complex temperate forest stands of Traunstein. Also compared with stand-wise biomass prediction with \(R^2\) of 0.883 and RMSE of 39.98 t ha\(^{-1}\) (relative RMSE of 13.15%) based on L-band airborne data in Traunstein reported by Li et al. (2015), the results are similar. Nevertheless, the results show seasonal differences between the predictions based on the winter and the summer acquisitions. Especially the estimates based on scattering center height are much better for the summer data. In areas dominated by deciduous tree species the scattering center height is situated rather far below the canopy due to lack of foliage in winter. In contrast, the modeled top height is less affected by the off-leaf effect. Therefore, the scattering center height from the summer acquisition is more appropriate for stem volume estimation. The modeled top height is related to the silvicultural parameter top height H100 (Kugler et al., 2011). In contrast, the scattering center height captures the spatial variations in height much better despite the penetration of the signal resulting underestimation of the actual tree height. For this reason, integration of the co-occurrence parameters is performed based on the summer acquisition of scattering center height. It was shown that the co-occurrence parameters improve stem

### Table 10
Comparison of the results from the simple linear regression model and the extended linear regression model at stand level described by the standard error SE of the parameters, root mean square error RMSE of the predictions, RMSE related to the mean stem volume and the coefficient of determination \(R^2\). The models are based on scattering center height or modeled top height from winter (09.01.2012) or summer (18.05.2013) acquisitions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Linear model</th>
<th>Extended linear model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RMSE [m(^3) ha(^{-1})]</td>
<td>RMSE [%]</td>
</tr>
<tr>
<td>Scattering center height (winter)</td>
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<tr>
<td>Modeled top height (summer)</td>
<td>91.20</td>
<td>34.08</td>
</tr>
</tbody>
</table>
volume estimation substantially, i.e. the coefficient of determination was enhanced by 10% to 14% at plot level and 6% to 26% at stand level, respectively. The results at stand level are generally much better compared with the estimations at plot level. At plot level the limiting factor is the spatial resolution of scattering center height and modeled top height. With respect to inventory plots of 500 m², each plot contains only 3 to 13 real height measurements at maximum. Consequently, slight saturation effects occur at about 400 m³ ha⁻¹ at plot level due to the insufficient spatial resolution of height information and thus missing sensitivity for high stand densities.

6. Conclusions

The aims of this study were defined as (i) estimation of stem volume per unit area at plot (circular plots of 500 m²) and stand level (areas of 1.5 to 6.4 ha) based on height information derived from TanDEM-X data and (ii) improvement of the predictions by integration of novel texture parameters representing horizontal stand structure.

A positive linear correlation between stem volume deduced from inventory data and height information derived from polarimetric interferometric TanDEM-X acquisitions was obvious. Stem volume per unit area was estimated by a linear regression model at plot and stand level based on scattering center height and modeled top height respectively. The prediction results showed that the scattering center height based on the summer acquisition was most suitable to predict stem volume per unit area. The results could be improved substantially by extending the linear regression model by parameters derived from the Co-occurrence Matrix. The prediction results are very reliable considering that the study area consists of very complex, heterogeneous, temperate forest stands using X-band satellite radar data.

The study shows the high potential of polarimetric interferometric X-band SAR data for the derivation of reliable stem volume estimations. To make a contribution to global sustainable forest management planning, the approach should be applied to other test sites regarding different concepts of silvicultural land use and forest biomes. By detecting and defining the homogeneous stands concerning forest structure by means of remote sensing, this approach could be extended and potentially deployed worldwide.

Acknowledgments

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References


Table 11

<table>
<thead>
<tr>
<th>Boreal forests</th>
<th>Temperate forests</th>
<th>Tropical forests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Circumpolar belt in high northern latitudes</td>
<td>Between 25° and 50° on both hemispheres</td>
</tr>
<tr>
<td>Climate</td>
<td>Short vegetation due to extreme weather conditions concerning temperature, precipitation and sunshine duration</td>
<td>Oceanic, sub-continental and semi-arid and arid</td>
</tr>
<tr>
<td>Tree species</td>
<td>Limited number of tree species such as spruce, fir and pine</td>
<td>Deciduous and evergreen species</td>
</tr>
<tr>
<td>Vertical structure</td>
<td>Closed canopy and low understory</td>
<td>Less dense canopy and more developed understory</td>
</tr>
</tbody>
</table>

Fig. 13. Scatterplot comparing measured stem volume (on the x-axis) predicted stem volume based on model (11) (on the y-axis) per stand.