Vertical forest structure characterization for the estimation of Above Ground Biomass. Potential and limitations for Radar Remote Sensing

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Abstract

One common method to estimate biomass is measuring forest height and applying allometric equations to get forest biomass; however, conditions like changing forest density or forest structure bias the allometric relations. Remote sensing systems like SAR or LIDAR allow to measure vertical structure of forests. In this paper it is investigated whether vertical structure is sensitive to biomass. For this purpose vertical biomass profiles are calculated using forest inventory data. A structure descriptor based on Legendre polynomials is tested, a biomass inversion based on vertical structure is proposed and the influences of the horizontal integration area and impacts of forest dynamics are studied. This is a case study based on inventory data from the Traunstein test site, a temperate mixed forest, located in the southeast of Germany.

1 Introduction

Forest above-ground biomass (AGB) stores an essential part of the terrestrial carbon and is, therefore, a key element in the global carbon cycle. Mapping of forest total biomass and change are needed for understanding the development of the carbon fluxes [1]; however, biomass stock and spatial distribution are for many forest regions of the world rather poorly quantified. Therefore, methodologies capable to retrieve biomass and forest dynamics at a global scale are highly demanded.

Remote sensing (RS) systems are capable to measure some forest parameters, like forest height and vertical forest structure over large areas with high spatial and temporal resolution. Forestry science aims to reduce the effort of measuring biomass with the help of allometric functions which deduce biomass from easier measurable variables. However, the allometric functions derived for single trees are only partly valid for forest variables derived from RS, because these systems cannot retrieve single tree variables with sufficient accuracy. Thus, other allometric relations need to be developed. As a first step, an innovative approach shown in [2] proposes a height to biomass allometric relation which allows biomass estimation from RS systems capable of resolving forest height (LIDAR and polarimetric SAR interferometry (Pol-InSAR)) [3][4]:

$$B = 1.3\mathrm{H}^{1.58} \tag{1}$$

where B is above-ground biomass and H forest height.

Despite that height allometries show a reduced variability for most temperate forest species [2], changing conditions, not only in tree species composition, but also in terms of density, and forest management limit the accuracy of equation (1) to estimate biomass from height measurements from remote sensing techniques. Thus, forest structure and especially vertical biomass distribution need to be characterized and their relation to AGB needs to be further investigated.

This work is organized as following: first vertical biomass distribution is modelled, then a vertical structure to biomass allometry is derived, spatial scale effects will be studied and finally the influence of forest dynamics into forest vertical structure and biomass will be analysed. These investigations rely on data from for the forest test site Traunstein, located in the South-east of Germany. This dataset consists of 221 inventory plots with tree height measurements, diameter at breast height (dbh) measurements and tree species information together with a full-waveform LiDAR and multi-frequency/multi-baseline SAR datasets. Permanent research areas where all trees are measured are also available for detailed growth and forest dynamic studies.

2 Structure characterization for biomass estimations

2.1 Vertical biomass profiles

Forest vertical structure can be investigated using vertical biomass profiles. In this study we model these profiles from ground inventory data. First, profiles are calculated summing up the biomass of all trees within a measurement plot (0.05ha) in 1m steps along height, and then normalized to the total profile area, to obtain the final vertical biomass distribution.

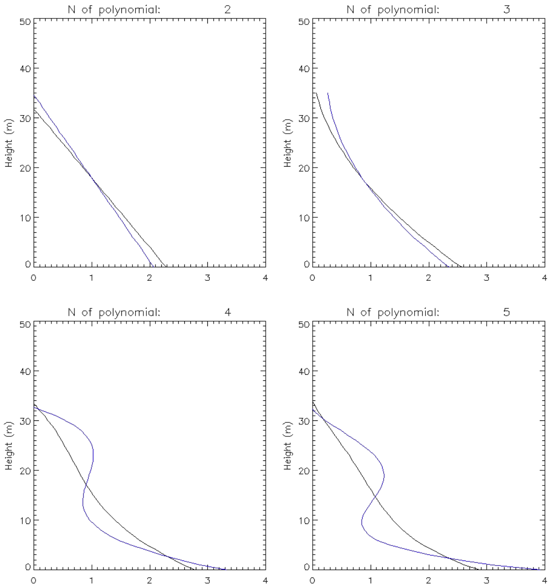

Figure 1: Maximum (black) and minimum (blue) biomass profile reconstruction at 35 m. 4 Legendre polynomials are sufficient to detect differences in between profiles profile.

The Legendre decomposition is used as a structure descriptor. Legendre coefficients are calculated according to (2).

$$B(z) = \sum_n a_n P_n(z) \;\text{ ; where:}$$

$$a_n = \frac{2n+1}{2}\int_{-1}^{1} B(z)P(z)dz \qquad (2)$$

where a_n are the Legendre coefficients and P_n the Legendre polynomials.

In [5] it was shown that a low number of Legendre polynomials (4) is enough to distinguish between different levels of biomass. In **Figure 1** the reconstruction with a 1 to 5 Legendre polynomials is displayed for two profiles with the same height but with a maximum (black) and a minimum biomass (blue). When 4 or more polynomials are used, it is possible to clearly identify the two levels of biomass with the profile shape: the high biomass profile shows a smoothed shape while the low biomass profile presents a sharper shape.

2.2 Structure ratio and biomass inversion

The structure characterization developed in this study is based on the following principle: high biomass profiles are characterized by low frequency components, as a mature stand approaches a homogeneous biomass distribution; however, for the same dominant height (H100) a stand with less biomass presents more gaps with a higher heterogeneity and therefore, it is characterized by a higher frequency components. Using the Legendre decomposition we propose a structure ratio which is sensitive to the frequency of the vertical biomass profile. The structure ratio S_{rat} is calculated as fraction between low (a_{01}) and high frequency Legendre coefficients ($a_{02}, a_{03}, a_{04},$):

$$S_{rat} = \frac{|a_{01}|}{|a_{02}| + |a_{03}| + |a_{04}|} \qquad (3)$$

where $a_{0n}$are the normalized Legendre coefficients.

In **Figure 2 – right**, the height to biomass relation for Traunstein is displayed. Every point is colour coded according to the value of the S_{rat}. Blue colours indicate a low ratio while red indicates a high ratio value. Above 20 m, when forest structure is developed, for a fixed height, points with low biomass (blue) present a lower value of S_{rat} when points with high biomass (red) present a higher value. S_{rat} can then be used to modify the height to biomass allometry. S_{rat} adapts the measured forest height to a virtual height at the allometric curve, reducing the bias and improving the biomass estimation. A linear combination between the structure ratio and forest height has shown the best inversion results:

$$B = 0.77 S_{rat}^{0.4} H^{1.7} \qquad (4)$$

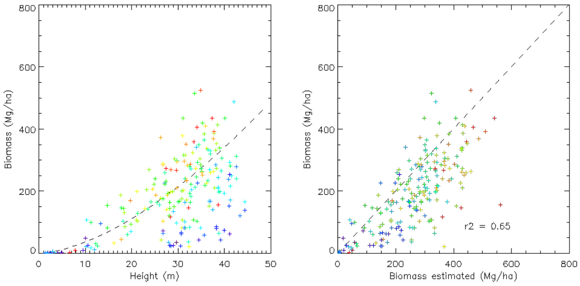

Figure 2: On the left biomass vs. height the dashed curve represents the allometric equation ($B = 1.3H^{1.58}$); and on the right biomass inversion using equation (3). Points are colour coded according to the structure ratio S_{rat} from 0 (blue) to 3 (red).

In **Figure 2 – left**, results from the biomass inversion using equation (3) are displayed. A correlation factor R^2 of 0.65 is obtained.

3 Vertical Structure interpretation

3.1 Horizontal scale

Vertical structure is also sensitive to the horizontal scale used in the estimation of the biomass profile. Vertical structure profiles are generated by aggregating tree biomass within a defined surface. The size of this integration area affects the shape of the profile shape and, therefore, has an impact in the profile interpretation as well as in the structure to biomass relations.

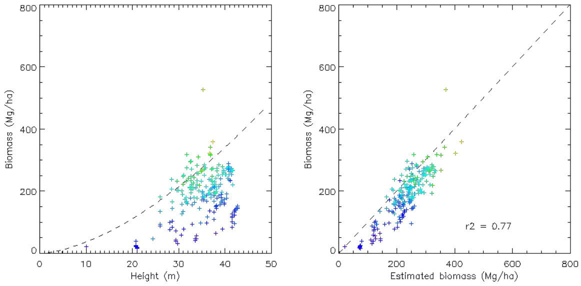

Figure 3: On the left, biomass vs. height represents the allometric equation ($B = 1.3H^{1.58}$); on the right, biomass inversion using equation (3) for an integration distance of 150m and a structure combination with a structure ration (S_{rat}) threshold of 0.5. Points are colour coded according to the structure ratio S_{rat} from 0 (blue) to 3 (red).

Inventory plots available from Traunstein site data set are spaced in a 100x100 m grid and have an area of 0.05 ha. Part of the deviation present in the biomass inversion (Figure 2 – left) may be noise induced by the small area of the inventory plot (0.05 ha). If the inventory area is too small, the characterization of forest structure is highly affected by small changes in the forest composition, for example, the inclusion of one big tree would have a big impact in the shape and the height of the profile. Adjacent plots can be then averaged, according to a distance radius, to simulate larger integration areas. However, if only a distance criterion is used, plots that represent different structural stands might be combined together and, as consequence, the relation of structure to biomass can be lost. For this reason a structure difference criterion between plots can be also used. It is still needed to consider that, if the integration area is too small, small changes in the forest distribution severely impact the structure profile but if the averaging is too large, the sensitivity to biomass will be degraded.

In this study, the integration is done as follows: first the structure ratio S_{rat} is calculated for every plot, then using a moving window of 150 m, those plots with a ratio difference with respect to the central plot below a threshold of 0.5 are averaged; finally a new profile is generated and new heights and S_{rat} are calculated. Results from the new inversion are shown in **Figure 3**. The higher averaging window decreases the allometric level and reduces the structure ratio range (Figure 3 – left), but the sensitivity of structure to biomass increases and the inversion performance increases (Figure 3 – right). The new inversion presents a correlation factor R^2 of 0.77.

3.2 Structure sensitivity in time

In this section we perform a test in order to identify the impact of forest processes and dynamics, natural or anthropic, into the development of forest vertical structure. These processes can modify the allometric relations and the connection between vertical structure and biomass. Moreover a characterization of vertical structure responses to these processes can be used, in SAR reflectivity profiles, to discriminate between natural forest processes and other disturbances, e.g. system or weather.

Two forest management processes have been investigated and modelled: thinning form below and thinning from above. In the thinning from below the trees with the smallest diameter will be removed in steps of 5% of the total remaining basal area (sum of the surfaces of all the tree sections at 1.3m). In the thinning from above the trees with the largest diameters are removed in also steps of 5% of the total basal area. For each step, biomass and the structure ratio S_{rat} are calculated. Inventory data from a permanent growth research area of 25*25 m for an old mature spruce stand are used to initialize these models.

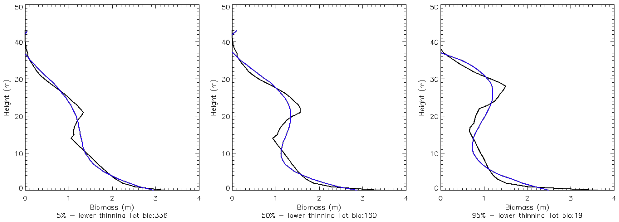

Figure 4: Profile changes under a thinning from below management for a 5%, 50% and 95% basal area removal. The original profile is represented in black and the reconstructed profile with 1-4 polynomials in blue.

Changes in the biomass profile during the thinning process can be shown in **Figure 4** (thinning from below) and in **Figure 5** (thinning from above). Two main differences between these two thinning processes can be observed: the tree extraction in the thinning from below does not reduce the profile height while in the thinning from above it will decrease as the largest trees are removed; and while in the thinning from below the biomass profile becomes sharper, in a thinning from above they are smoothed.

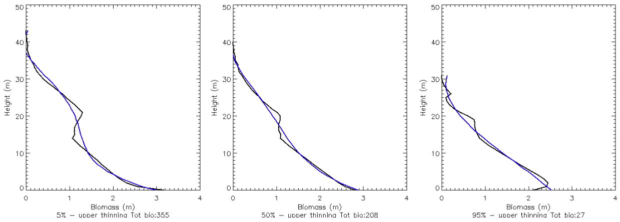

Figure 5 : Profile changes under a thinning from above management for a 5%, 50% and 95% basal area removal. The original profile is represented in black and the reconstructed profile with 1-4 polynomials in blue.

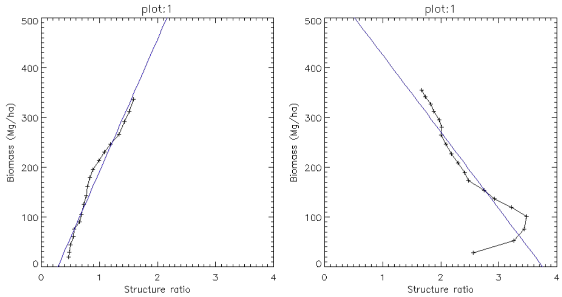

Figure 6: Biomass vs. structure ratio for a thinning from below management (right) and from above (left).

Biomass vs. structure ratio for every thinning step is shown in **Figure 6**, on the left**,** a thinning from below and on right a thinning from above. The tendencies observed in Figure 4 and Figure 5 are confirmed: a direct correlation between the structure a ratio and biomass is observed in case of a thinning from below while an inverse correlation is observed in the case of a thinning from above. This tendency (for a thinning from above), however, does not agree with the assumptions made in section 2, that is, an increase in the structure ratio S_{rat} should be connected with an increase in biomass. Thus, even if this scenario rarely occurs under management, it might be the cause of some ambiguities observed in the biomass inversion. In principle both types of thinnings could be distinguished using a temporal series: a constant forest height between measurements and increase of S_{rat} will indicate a thinning from below while a decrease of S_{rat} will indicate a thinning from above. More investigations in this direction will be done and presented.

4 Conclusions

In this study we show that the structure to biomass allometry is able to improve the estimation of aboveground biomass and a vertical structure descriptor based on low frequency Legendre polynomials is sensitive to it. An adequate integration area must be defined to improve the biomass estimation without sacrificing the spatial resolution. Ambiguities coming from forest management or disturbacnes could be detected with the help of temporal information and used to further improve the biomass inversion.

An understanding of the influences between vertical structure and biomass, as well as the physical interpretation of structure changes will be also useful to advance in the interpreation of SAR reflectivity profiles.

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