Effects of Forest Biomass and Stand Consolidation on P-Band Backscatter

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***Abstract*—In previous studies, P-band synthetic aperture radar (SAR) has shown potential for biomass retrieval in forests. However, while measurements show a general agreement that backscatter increases with increasing biomass, different studies show that the backscatter from stands of similar biomass can significantly vary depending on forest structure, hence making biomass retrieval more challenging. In this letter, we show that, while biomass may be the single most important parameter determining the backscatter from a forest, the number density of trees has also a major impact. This can be explained using simple arguments, leading us to propose the use of the biomass-consolidation index to describe P-band HV-polarized backscatter. This is supported by electromagnetic-modeling studies and by a few measurements from boreal forest made with the AIRSAR system over the BOREAS test site in Canada.**

***Index Terms*—Biomass, biomass-consolidation index (BCI), forestry, P-band, synthetic aperture radar (SAR).**

I. Introduction

IN THE light of the recent allocation of 6 MHz for active Earth-observation satellites in P-band (432–438 MHz), there has been a heightened interest in the possibility of using P-band synthetic aperture radar (SAR) for global forest-biomass mapping. This is because of the well-established results that lower frequencies provide better penetration through vegetation canopies, so that backscatter comes from larger structures in the canopy, providing a better correlation between forest biomass and backscatter than using higher frequencies.

Many studies have reported empirical relationships between P-band backscatter (usually measured with the AIRSAR system [1]), and forest above-ground biomass and/or stem volume (for example [2]–[7]). With AIRSAR, many authors have compared data from C-, L-, and P-bands and using the three linear-polarization combinations (HH, HV, and VV). All results agree that P-band shows better correlation with forest properties than the higher frequencies, and in most cases, HV polarization gives the best results. Studies performed over coniferous forests show good correlation between backscatter and biomass, at least until the saturation limit is approached [5]. However, there may be differences between test sites depending on the type of forest studied. In tropical forests, there is a large variation in backscatter for areas with similar biomass, so the study in [8] recommends classifying first forest structure before trying to retrieve biomass.

To develop a globally applicable algorithm for forest-biomass retrieval requires consideration of the differences in structure between different forest types. In a previous work, Imhoff [9] proposed a measure based on the average surface-area-to-volume ratio of the scattering elements to explain differences in backscatter predicted for different forests with the same biomass. Using backscatter models, this was also studied in [10]. In [11], a macroecological model was combined with a scattering model to investigate how the distribution of biomass in a forest affects backscatter concluding that "the trend in number density is a significant influence on the retrieval of biomass density." In this letter, we present physical arguments for combining the number density of trees and their size (biomass) in a single parameter [the biomass-consolidation index (BCI)] that may be able to describe differences in backscatter depending on both biomass and forest structure. To support this, we also give some first indications of its applicability based on a reanalysis of backscatter measurements from different tree species within the BOREAS test site in Canada [12].

II. Importance of Structure

Electromagnetic models have been used to aid understanding of the P-band backscatter from forests (e.g., [4], [7], [9], [10], [13], and [14]). The basic approach used is to model the forest as a collection of dielectric cylinders and discs to represent trunks, branches, twigs and leaves, and then to use electromagnetic theory to calculate the backscatter. Although the models may differ in details, the general approach and conclusions are the same.

In many studies, the work has concentrated on describing the change of backscatter as forests develop with time, where biomass increases as a function of forest age. In these cases, the trees are assumed to grow bigger as they age, while the number density of individuals decreases due to self- and anthropogenic thinning. For example [4], noted from measurements of the Landes forest in France that "Two of the most striking features of the ground data are (1) the linear or quasi-linear increase of tree dimensions (diameter and length of trunk, branches, and needles) with age, while tree density shows a negative exponential behavior due to thinning practices."

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Modeling studies generally agree on the qualitative explanation of P-band backscatter. For HH-polarization, the trunk–ground backscatter usually dominates, giving good sensitivity to trunk biomass. This may be affected by ground properties (such as slope, moisture content, and flooding), and in cases of very dense forest or low ground–trunk interaction (loss of dihedral scattering), the branch scattering may dominate. For VV-polarization, the backscatter is a complex function of branch, trunk–ground, and even direct-ground backscatter. For HV-polarization, the relationship is simplest, with all studies indicating that the branch scattering dominates and that it is relatively insensitive to ground properties because direct backscatter dominates. Branch biomass is usually well correlated with total biomass, and HV-polarization offers the most robust choice for biomass retrieval as it avoids the problems of ground interaction that can confuse the relationship between HH-polarization and biomass. This agrees with the empirical results that HV is the most promising single polarization for retrieving total aboveground biomass, and hence, we will restrict the rest of this letter to this choice of polarization.

Although biomass appears to perform well at explaining results from often monospecific forest stands, this is not the only forest parameter which determines backscatter. Sensitivity analyses with backscatter models show that, since the HV backscatter is dominated by the primary branches, the parameters describing these (orientations and size distributions) are those that affect the total backscatter.

The effect of branch orientation is well illustrated by both Beaudoin *et al.* [4] and Hsu *et al.* [13], where varying the average elevation angle of the branches can cause large changes in backscatter. For a particular set of forest parameters, simply changing the average orientation of the primary branches from 40° to 60° was shown to give about 5 dB difference in backscatter. The importance of branch angle is also related to the radar incidence angle [4], and in both [4] and [13] this was set to 45°.

Differences in the size distribution of branches (with all other parameters fixed) may also give large differences in backscatter. In [13], it was observed that, while changing branch number density to keep the same total branch biomass, "the HV return increases by 7 dB if the radius of the primary branches increases from 0.75 to 1.5 cm." Similar effects have also been noted in [9]–[11]. For a fixed biomass, Imhoff [9] noted that the ratio of the total surface area of the scatterers to their volume was a good descriptor of the backscatter. This was described in terms of structural consolidation, which "may be defined as the relative occurrence of many small components in a unit of space versus fewer and larger ones." Thus, many small scattering elements have a large surface area in comparison to their volume (low consolidation) and, hence, give low backscatter. On the other hand, the same biomass (volume), but composed of fewer larger cylinders (branches), will have a lower surface area and also gives a higher backscatter. This was confirmed by the studies of Quiñones and Hoekman [10] and Woodhouse [11], where many small trees (high surface area) gave lower backscatter than few large trees with the same total biomass.

Given the strong dependence of backscatter on stand structure, it may seem surprising that empirical studies have shown such good correlation between backscatter and biomass. The simplest explanation for this is that, in most studies, the test areas have been limited to one biotope, where both the total biomass and the degree of consolidation increase with age. Hence, these two parameters are well correlated for monospecific plant stands [15].

However, the separate effects of biomass and stand structure on the backscatter represent a possible source of ambiguity in developing a general biomass retrieval algorithm for use over different forest structural types. While this ambiguity cannot be resolved without additional input data, we believe that a refined model to include the effects of both biomass and stand consolidation is of use to clarify their relative importance.

III. Biomass-Consolidation Index

To describe the combined effects of biomass and stand consolidation on the HV-backscatter, we propose the use of a variable that we name the BCI. The basic idea is to combine the important parameters of total biomass density b (e.g., in tons per hectare) and the number density of the trees n (in trees per hectare) in a single measure, which may provide a better quantitative description of backscatter.

The basis for our approach is the observation that the direct backscatter from primary branches dominates. At this wavelength (70 cm—i.e., much larger than the branch diameters for most coniferous trees), the scattering is essentially Rayleigh in character and, thus, the backscatter from an individual branch increases with the square of the branch's volume. Since the branches are randomly positioned in the canopy, the backscatter from many branches is an incoherent addition of their contributions. Thus, the total radar cross section (RCS) from a given volume will be related to the number of branches present and their average volumes (approximately proportional to biomass). This is similar to the argument given in [16]—although, in that case, for the low VHF frequencies considered there, it was argued for tree trunks rather than branches. Converting from total RCS to σ° and from average volumes and number of primary branches to volume (ν_{branch}) and number densities (n_{branch}), it can be shown that

$$\sigma^0 \propto \frac{\nu_{\mathrm{branch}}^2}{n_{\mathrm{branch}}}. \tag{1}$$

Finally, to relate the backscatter to commonly measured forest variables, we assume that the primary branch properties are well correlated with those for the trees as a whole and can replace the volume and number densities in (1) by the total biomass (b) and tree number (n) densities for the forest, i.e.,

$$\sigma^0 \propto \frac{\nu_{\mathrm{branch}}^2}{n_{\mathrm{branch}}} \propto \frac{\{b\}_{\mathrm{tons/ha}}^2}{\{n\}_{\mathrm{trees/ha}}} \equiv \{\mathrm{BCI}\}_{\mathrm{tons^2/(trees\cdot ha)}} \tag{2}$$

where the last term is our definition of the BCI. Note that, in replacing the branch number density by the number of trees, we implicitly assume a fixed number of (primary) branches per tree.

Of course, there are some limitations of this description. First, we ignored the effects of branch-size distributions and simply used the average branch volume—which we, in turn, assume is proportional to tree biomass. We also neglect the effects of attenuation in the forest, which may become significant for high volumes. In addition, the simplified descriptor relies on the assumption of essentially Rayleigh scattering, which assumes thin branches compared to the wavelength. This is generally true at P-band for coniferous forests, but significant departures may occur, particularly in mature broadleaf forests.

Finally, we note that the BCI includes only part of the structural information for the forest, i.e., that depending on the number and sizes of branches, but does not include anything about the orientation of the branches. The relative positions of branches may be of importance through multiple scattering, although the low albedo at P-band for branches suggests that this is less important than at higher frequencies; furthermore, as long as the individual scatterers are in the Rayleigh regime, the form of (2) will be unchanged. Neither have we considered any effects of differences in dielectric properties that may occur with tree species, age, or environment.

IV. Electromagnetic Modeling

In the following section, we present backscatter model results illustrating the usefulness of the BCI. The model is described in detail in [14] and [17] and can be used to calculate the polarimetric backscatter from a collection of dielectric cylinders located above a sloping dielectric ground plane. The cylinders are treated as single scatterers, and the backscattered field from each can be separated into the different mechanisms, direct backscatter, ground–cylinder, and ground–cylinder–ground interactions.

In order to vary the biomass density and number density of the forest independently, the basic input parameters to the model are 1) the average diameter at breast height (dbh)—to define the biomass per tree (based on allometric relationships) and 2) the total biomass density—to determine the number density of trees.

From the tree dbh, we then use allometric equations to derive the distribution of the tree's biomass between branches, needles, and the trunk. Instead of using detailed models for tree structures, we use simple relationships based on observations of coniferous forests in Sweden to estimate average dimensions for cylinders to describe the trunk, branches, and needles. This means that the properties of length, diameter, and number densities in the model are well correlated with dbh and, hence, total forest biomass. However, the average values are perturbed using random distributions, and results presented are the average of at least 100 independent realizations of each forest "stand." The dielectric properties for the branches and their orientations are also selected from random distributions; however, for these parameters, the average values remain fixed for all tree sizes (for exact details of the relationships and random distributions, see [14]).

V. Model Results

The model results agree with other studies on the main scattering mechanisms for different polarizations. For HV, Fig. 1 shows an attempt to use the total biomass density as a descriptor

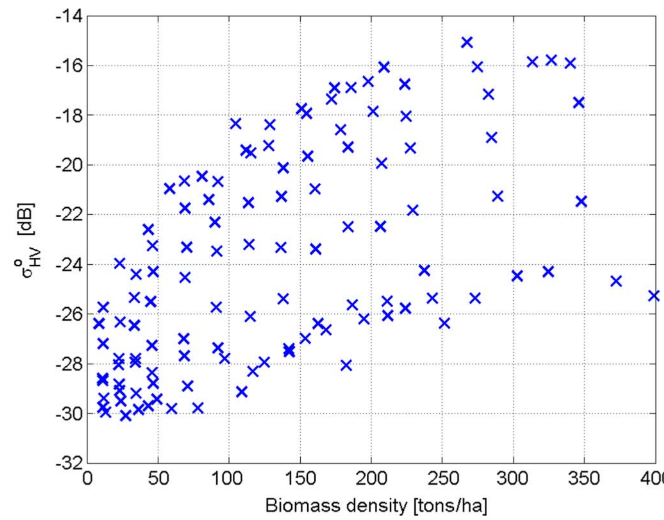

Fig. 1. Model calculations of P-band HV-polarization for different forest biomass densities. For each biomass density, the backscatter can vary significantly depending on the biomass-consolidation level.

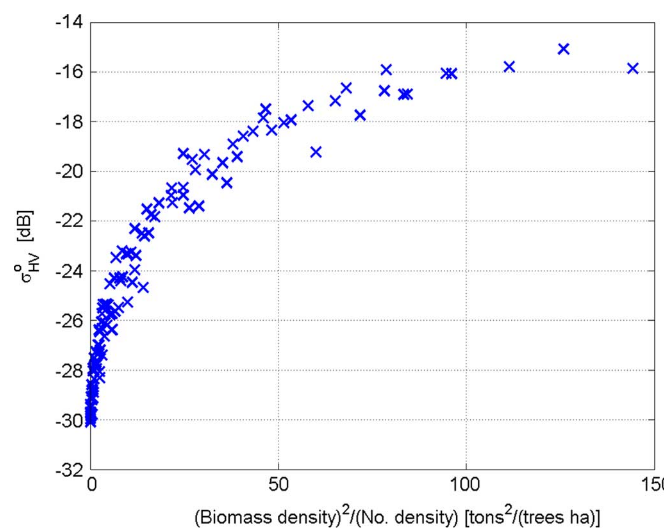

Fig. 2. Model calculations of P-band HV-polarization backscatter plotted as a function of BCI. The data used are the same as in Fig. 1, but BCI is a better parameter to describe the backscatter.

of the total backscatter. For a given biomass, the backscatter can vary significantly. This is due to differences in the stand consolidation—depending of whether there were few large trees or many small ones. An alternative plot is shown in Fig. 2, where the backscatter are shown to be well described by the BCI, although there appears to be a tendency toward saturation for higher biomass levels.

VI. Test on SAR Measurements

To test the BCI on SAR measurements, we have reinvestigated data from the southern study area of the BOREAS campaign in southern Canada [12]. SAR data were acquired by AIRSAR (C-, L-, and P-band polarimetric) and standard processing and calibration performed [18]. The *in situ* data were collected using standard forest measurement techniques [19].

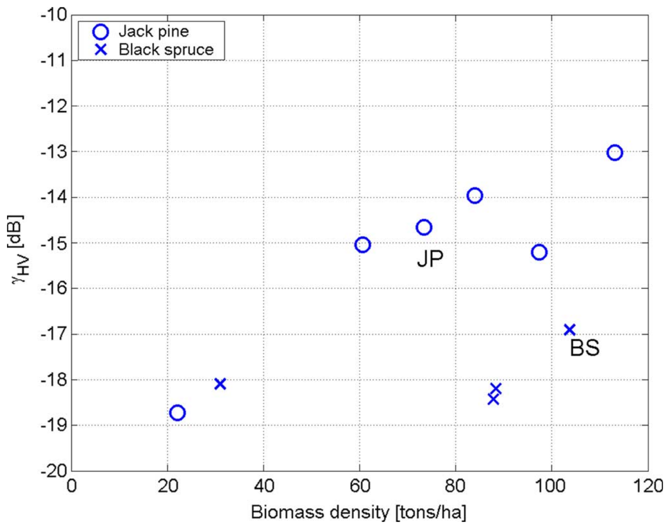

Fig. 3. AIRSAR measured backscatter coefficients for P-band HV-polarization related to *in situ* biomass measurements from BOREAS. Jack Pine and Black Spruce stands are shown with different symbols, showing that, for biomass densities of around 100 tons/ha, the Black Spruce has lower backscatter than Jack Pine.

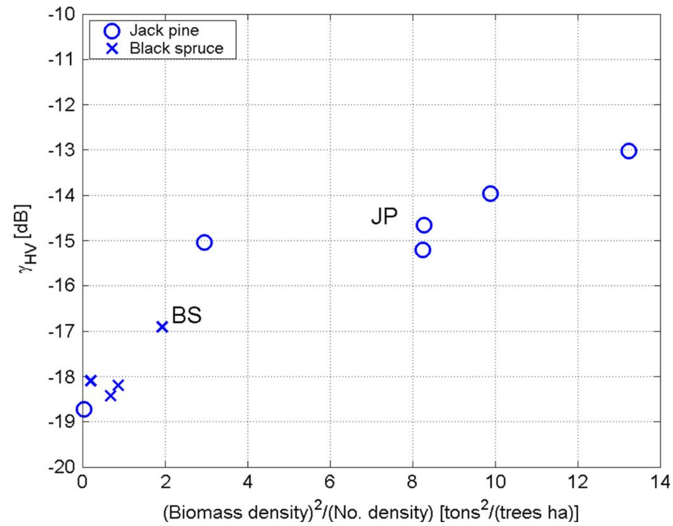

Fig. 4. AIRSAR measured backscatter coefficients for P-band HV-polarization related to *in situ* measurements using BCI. The correlation between backscatter and BCI is better than using biomass density, and the Jack Pine and Black Spruce lie along the same line.

Excellent results from this data, using model-based biomass retrieval, have been published previously [7]. However, the retrieval method relied on the use of a many-parameter scattering model, trained on the measurements and using different parameters for different tree species. In particular, a significant difference between the stands dominated by Jack Pine (*Pinus banksiana*) and Black Spruce (*Picea mariana*) was observed. We believe that observed differences between species in the like polarized backscatter, particularly HH, are related to the different ground and understory properties due to the trunk–ground interaction [14]. However, for the HV backscatter, we will show that the differences between the Jack Pine and Black Spruce measurements may be a result of different stand consolidation for these species.

To illustrate the difference between the Black Spruce and Jack Pine stands, Fig. 3 shows standwise measurements of backscatter plotted against *in situ* measurements of biomass based on three plots of 5 m $\times$ 5 m for each stand. The biomass measurements used are those denoted by Forestry Canada in [7], where the uncertainties in the accuracy of the *in situ* data are discussed in detail. Backscatter measurements are from the AIRSAR image no. 5401 (acquired on July 21, 1994), where we have manually selected homogeneous areas of about 1–5 ha centered on the *in situ* measurements using the AIRSAR images. The backscatter measurements are shown using γ instead of σ°, to provide some compensation for differences in incidence angle, as described in [6].

Although there are few stands available in Fig. 3, it appears that the Black Spruce measurements at biomass levels around 100 t/ha are a few decibels lower than those for Jack Pine with similar biomass. Based on HV backscatter measurements alone, there is confusion between the Black Spruce stands with high biomass and low biomass Jack Pine stands.

To illustrate the differences between the Black Spruce and Jack Pine areas, consider the two stands marked BS and JP, respectively, in Fig. 3, where BS shows a lower backscatter than JP despite a higher biomass density. The *in situ* data shows that the Jack Pine trees are generally larger (dbh ~20 cm, height ~19 m) than the Black Spruce (dbh ~10 cm, height ~11 m). Since the biomass densities are similar, the difference in dbh indicates that there are many more trees in the Black Spruce area, which is also given by the *in situ* data (~5000 trees/ha for the Black Spruce compared to ~700 trees/ha for the Jack Pine area).

To further illustrate the effect of number density, Fig. 4 shows a plot of the backscatter measurements used in Fig. 3 but, in this case, related to the BCI instead of biomass. It can be seen that this appears to give a better description of the backscatter. A measure of the better performance of the BCI can be the modified coefficient of determination $R^2 = 0.9$, compared to $R^2 = 0.1$ using biomass density. Although this is based on very few data points and says little about the possibility of inverting measurements, it does indicate the potential benefit of including both biomass and number density (i.e., stand consolidation) in the analysis of backscatter.

VII. Conclusion and Discussion

In this letter, we have reviewed published results on modeling P-band, HV-polarized backscatter from forests, and its relationship to forest biomass. The importance of stand consolidation is apparent and can describe the observed differences in backscatter between different areas with similar biomass. We have shown how biomass and stem number density can be combined in a single variable that we call the BCI. In model studies, this gives a much better correlation with backscatter than biomass alone. The BCI also shows better correlation than biomass with the measurements from BOREAS, as the BCI includes implicitly the structural differences between the Jack Pine and the Black Spruce stands.

The example from BOREAS is an extreme case, with a large variation in stem number density. In the future, more measurements are required to test BCI more thoroughly with SAR measurements, and we support Woodhouse [11] in his call for researchers to include information of stem number density in publications related to forest backscatter.

This letter suggests that number-density variations may cause ambiguities in forest biomass retrieval from P-band SAR backscatter. To resolve this ambiguity requires an independent measure, such as number density, which may be possible to estimate in the future using high-resolution sensors. Another possibility is to use tree height (e.g., from SAR interferometry or lidar), as described below.

In the case of the stands marked BS and JP in Fig. 3, measurements of tree height (*in situ*) indicate that BS has a height of 11 m, compared to 19 m for JP, despite a higher biomass. In terms of backscatter, BS is about 2 dB lower than JP. Thus, both backscatter and tree-height measurements seem to suggest that BS has lower biomass density, which is diametrically opposite to the *in situ* measurements. However, this apparent inconsistency can be explained by the BS trees being smaller (and hence having lower biomass per tree) but being more densely packed (higher number density). If the relationship between biomass per tree and tree height is known, then remote-sensing measurements of tree height could give an estimate of the average biomass per tree. It would then be possible to use this information together with the backscatter intensity to estimate number density and, finally, combine the two estimates to obtain biomass density. The potential advantage of this is that the relationship between tree height and biomass per tree may have less variability than the relationship between height and biomass density, as the former depends primarily on tree species, whereas the latter depends on the rate of thinning which is determined by a variety of factors including availability of resources and human intervention.

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