Influence of forest disturbances on backscatter of the airborne L-band synthetic-aperture radar in a larch forest in northern Japan

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Abstract:

This paper is a case study on the detection of forest disturbances in airborne synthetic-aperture radar (SAR) data. We investigated changes in the L-band SAR backscattering coefficient (σ^0) following thinning and a typhoon in a larch forest in northern Japan. The thinning caused changes of intermediate magnitude in the above-ground biomass (AGB), whereas the typhoon broke or uprooted most of the trees, thereby significantly changing the forest structure without changing the biomass. Thinning led to backscattering coefficients change of less than about 1 dB; HV polarization was most sensitive to the change in AGB, and HH was insensitive to it. In the case of the typhoon, VV was sensitive to the change in forest structure, whereas HH and HV were insensitive to it, suggesting that the tree trunks, which were felled in one direction by the typhoon, enhanced the backscattering signal of the polarisation that accorded with the trunk direction.

KEYWORDS Forest disturbances; synthetic-aperture radar; biomass

INTRODUCTION

Water yield in a forest is intimately connected to changes in vegetation cover (Bosch and Hewlett, 1982). Deforestation and forest degradation are worldwide problems affecting carbon emissions and water cycles. In forests in Japan, the proportion of aged trees has increased owing to decreased logging, and such old forests are vulnerable to natural disturbances such as wind storms, which lead to the fall of trees (Kuboyama *et al.*, 2003). Monitoring of forests is increasingly necessary to predict changes in the hydrological cycle and prevent disasters such as landslides in forests.

Recently, polarimetric observations of microwaves using airborne and space-borne SAR have shown the potential of SAR for monitoring land surfaces under all weather conditions. Many studies have demonstrated that the microwave backscattering coefficient (σ^0) is positively correlated with the AGB of a forest (e.g., Watanabe *et al.*, 2006). The geometric properties of trees, such as tree

architecture (Dobson *et al.*, 1995), stand density (Watanabe *et al.*, 2006), and gaps due to windthrow (trees uprooted or broken by wind) (Green, 1998), also influence σ^0 . However, few studies have examined the effects of intermediate-magnitude changes in a forest, such as those due to thinning, on σ^0 (e.g., Champion *et al.*, 1998). Further research on such intermediate disturbances is needed to provide information for forest management, and it is also an urgent topic for detecting illegal tree cutting, especially in tropical forests.

As a case study, we investigated the relationship between forest disturbances and σ^0 in a larch forest in Japan. This plantation forest research site is managed as an integral observation site for monitoring energy and carbon fluxes (Hirano *et al.*, 2003; Hirata *et al.*, 2007). Within the short period from December 2003 to September 2004, planned thinning was carried out, and it was subsequently struck by a typhoon. These events provided a unique opportunity to study intermediate and strong disturbances in the same forest for which both multi-temporal ground-truthed AGB data and an airborne L-band SAR data are available.

MATERIALS AND METHODS

Site description

The observation site is in the Tomakomai forest (42°44'N, 141°31'E) in northern Japan (Figure 1). The dominant species is Japanese larch (*Larix kaempferi*), which was planted from 1957 to 1959. The mean canopy height was approximately 15 m, and the average diameter at breast height (DBH) was 18 cm. The topography is fairly flat, with a gradient of 1–2°. The annual mean temperature and annual precipitation were 6.5°C and 1055 mm, respectively, from 2001 to 2003. From September 2000 to August 2001, evapotranspiration was 367 mm, which corresponds to 29% of the precipitation (Hirano *et al.*, 2003). Other details of the site are described by Hirano *et al.* (2003).

The study area comprises three compartments of the experimental forest, each of which was divided into nine subareas, one side of which was about 150 m (Figure 1). The areas of compartments 1196, 1197, and 1198 are 28.36, 27.80, and 34.64 ha, respectively. Volumetric soil water content was measured using a time domain reflectometry

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probe (CS616, Campbell Scientific, Inc., USA) at a depth of 5 cm at two positions in compartment 1197.

Observational data

SAR data

The fully polarimetric L-band backscatter was measured using Pi-SAR, the airborne SAR operated by the Japan Aerospace Exploration Agency (JAXA). The frequency of the L-band microwave was 1.27 GHz. Four sets of images were analyzed in this study. Data obtained during flights on 20th August 2003 (L0803) and 3rd August 2004 (L0804) were used for analysis of thinning, and those on 7th November 2002 (L1102) and 3rd November 2004 (L1104) were used for analysis of disturbance due to the typhoon. Each data set was obtained at a cruising altitude of 12 km, with high spatial resolution (2-m pixel spacing). Averages of σ^0 were estimated in each subarea in three compartments.

The annual change in AGB in compartment 1198 was small compared to total AGB (Hirata *et al.*, 2007) when no disturbances occurred (i.e., before the typhoon). Nevertheless, we found an apparent difference in σ^0 between L0803 and L0804 in the compartment, which might have been due to a difference in the microwave incidence angle caused by slight differences in the position and posture of the airplane. Therefore, we adjusted the σ^0 values of L0803 to account for the difference in compartment 1198. The amplitudes of the corrections were +0.28 dB for HH, +0.46 dB for HV, and +0.86 dB for VV. The values shown in Figure 2 reflect these corrections.

Distribution of the above-ground biomass (AGB)

Extensive biometric surveys were conducted annually from 1999 to 2004. The horizontal distribution of canopy heights was estimated using airborne lidar based on a tree census for larch and an accurate tree distribution map. The AGB in the upper canopy layer, composed of the dominant taller trees, ranged from 96.1 to 119.1 t ha⁻¹ before any disturbance, and from 82.2 to 108.2 t ha⁻¹ after the disturbances. The AGB in the lower canopy layer, composed

of trees with diameters of less than 5 cm and heights greater than 1 m, was about 4.88 t ha⁻¹, and the AGB of the understory (non woody plants) was 1.24 t ha⁻¹ in 2000.

Figure 1. Location of the observation site (left), and an HH polarization image of L0804 obtained using Pi-SAR (©Pi-SAR/JAXA/NICT 2004) (right). The locations of compartments 1196, 1197, and 1198 are shown. The upper right inset shows how each compartment is divided into subareas.

Figure 2. Relationships between σ^0 and AGB: (a) HH, (b) HV, and (c) VV. Large open symbols are the data for L0803, and small open symbols are the data for L0804. Large solid symbols are the data for L1102, and small solid symbols are the data for L1104. The shapes of symbols indicate the forest compartments: circles, No. 1196; triangles, No. 1197; squares, No. 1198. The dotted lines show the relationship determined empirically in the same forest by Watanabe *et al.* (2006). Data from subareas 4, 5, 8, and 9 in compartment 1196 (Figure 1) are excluded owing to the large influence of the sloping terrain on σ^0 .

Changes in the forest due to thinning and the typhoon

Thinning was conducted in compartments 1196 and 1197 from December 2003 to January 2004, whereas no thinning was conducted in compartment 1198. During thinning, 1588 trees, amounting to about 26% of all trees in the two compartments, corresponding to about 22% of the AGB, were cut. The mean DBH of the thinned trees was close to the mean of all trees before cutting. The thinned trees were distributed almost uniformly in the two compartments.

Typhoon Songda passed near the observation site on 8th September 2004. The strong south winds of the typhoon caused severe damage to an estimated 37 000 ha of forest in Hokkaido (Hokkaido Forestry Research Institute, 2004), and the observation site was damaged severely. Most trees composing the upper canopy were uprooted.

RESULTS AND DISCUSSION

Changes in σ^0 due to the disturbance events

The change in σ^0 due to the thinning was at most 1 dB, which was close to the measurement error, about 0.5 dB (Wakabayashi and Uratsuka, 2004). Therefore, the statistical significance of the change was tested. Sample numbers equal numbers of subareas in a compartment (Figure 1). For the thinning event, the change in σ^0 was significant at the 5% level except σ^0_{HH} in compartment 1196. For the thinning and typhoon events, the change in σ^0 was also significant at the 5% level except σ^0_{HV} in compartment 1198, and moreover, the amplitudes of the changes in σ^0_{HH} and σ^0_{HV} in compartment 1197 and that in σ^0_{VV} in compartment 1198 were statistically larger than 0.5 dB (Table I).

Influence of forest structure change due to the typhoon

To evaluate the influence of the typhoon on σ^0 , we compared the σ^0 data between L1102 and L1104 (Table II, solid black symbols in Figure 2). Note that between these dates, the forest was disturbed by both thinning and the typhoon. For L1102 and L1104, both σ^0_{HH} and σ^0_{HV} were smaller than the curve constructed empirically by Watanabe *et al.* (2006) using summer data (Figure 2). This discrepancy may reflect differences in the dielectric properties, possibly due to seasonal differences in moisture and temperature conditions in the canopy. Other than this seasonal effect, the changes in σ^0_{HH} and σ^0_{HV} between L1102 and L1104 are similar to those caused by the thinning between L0803 and L0804. Although the typhoon changed the forest structure

significantly, changes in σ^0_{HH} and σ^0_{HV} were <0.7 dB. This result suggests that σ^0_{HH} and σ^0_{HV} were determined mainly by the AGB at the site, since the change in AGB due to the typhoon was negligible. Conversely, the change in σ^0_{VV} was obviously different from that caused by thinning. Unlike σ^0_{HH} and σ^0_{HV} , σ^0_{VV} showed a large increase of more than 1.4 dB from L1102 to L1104 (Figure 2 and Table II). This unexpected change in σ^0_{VV} was likely related to the orientation of the trunks of the trees felled by the strong winds of the typhoon. Rignot *et al.* (1997) reported that single scattering increased in an area where trees had fallen but had not been removed and also that randomly oriented, horizontal dielectric cylinders such as tree stems can enhance horizontally polarized radar backscattering. At our site, almost all of the trees were uprooted and fell down toward the north (Figure 3), because at the site, the tremendous typhoon winds were from the southwest. As a result, the V polarization of the incident microwave radiation was nearly parallel to the trunk direction, which likely enhanced the VV polarization signal by increasing the backscattering cross-section. Also, due to the enhancement in VV polarization, decrease in σ^0_{VV} from summer to autumn (Fig. 2c) was smaller than those in σ^0_{HH} and σ^0_{HV} (Fig. 2a and 2b) in 2004.

After removal of the fallen trees from the site, the amount of vegetation cover and the volumetric soil water content decreased by 97% and 11%, respectively (Sano *et al.*, 2010). Cutting down all the trees causes possibly an increase in water yield of roughly 20%, although the amount of the increase depends significantly on the experimental catchment studied (Bosch and Hewlett, 1982). Presumably, the amount of evapotranspiration also decreased after the typhoon, because the decrease in vegetation probably decreased both transpiration and the capacity of the root zone to hold water.

Influence of the change in AGB due to thinning

Thinning decreased the AGB in compartments 1196 and 1197 from 119 to 92 t ha⁻¹ and from 107 to 84 t ha⁻¹, respectively. Soil moisture at a depth of 5 cm was similar before and after thinning: 33.2% in L0803 and 35.4% in L0804. Therefore, soil moisture had a negligible influence on the data, and the differences between the two flights can be used to estimate just the effect of thinning. To evaluate the effect of thinning on σ^0 , we compared the data between

Table I. Changes in σ^0 (dB) after thinning. Data from subareas 4, 5, 8, and 9 in compartment 1196 (Figure 1) were excluded from the calculations because the sloping terrain in those subareas greatly affected σ^0 .

Pol	No.	L0803	L0804	Difference
HH	1196	-7.31	-7.34	-0.03
	1197	-6.93	-7.36	-0.43
HV	1196	-12.13	-12.67	-0.54
	1197	-12.12	-12.72	-0.60
VV	1196	-7.58	-8.13	-0.55
	1197	-7.86	-8.34	-0.48

Table II. Changes in σ^0 (dB) after both thinning and the typhoon. Data from subareas 4, 5, 8, and 9 in compartment 1196 (Figure 1) were excluded from the calculations because the sloping terrain in those subareas greatly affected σ^0 .

Pol	No.	L1102	L1104	Difference
HH	1196	-7.93	-8.29	-0.36
	1197	-7.69	-8.38	-0.69
	1198	-7.73	-8.12	-0.39
HV	1196	-12.79	-13.38	-0.59
	1197	-12.74	-13.37	-0.63
	1198	-12.82	-12.85	-0.03
VV	1196	-9.23	-8.63	+0.60
	1197	-9.26	-8.56	+0.70
	1198	-9.39	-7.98	+1.41

Figure 3. (a) Histogram and (b) rose diagram of the azimuths of the felled trees in compartment 1197. North is 0° and the angle increases clockwise. The sample size was 429, corresponding to about 1.34% of all trees. The length of bars in both (a) and (b) reflects the number of trees. The black vector in (b) indicates the mean azimuth of the felled trees (19.9° clockwise from the North), and the white vector indicates the transmission direction of the microwaves from SAR (5.055°).

L0804 and L0803 (Table I). We examined the relationships between σ^0 and AGB for the HH, HV, and VV polarizations (Figure 2), and compared them with the empirical relationship reported by Watanabe *et al.* (2006) for the same forest stand in August 2004. The HH polarization apparently reached saturation at an AGB of about 100 t ha^{-1} , whereas the HV and VV polarizations increased linearly with AGB. The HV polarization showed the highest correlation ($R^2 = 0.44$) with AGB among the three polarizations (VV, $R^2 = 0.41$; HH, $R^2 = 0.05$). Low correlation for HH was due to small changes in σ^0 . H polarization can penetrate the forest canopy layer more than V polarization. Therefore, the scattering component such as double bounce was possibly enhanced in the sparse forest after thinning. This might have compensated for the decrease in the other scattering components, and resulted in small changes in total σ^0_{HH} after thinning.

The amplitudes of the changes in σ^0 , though statistically significant, were small (less than 1 dB; Table I). We observed smaller changes in σ^0 than those observed by Champion *et al.* (1998), who reported a decrease in σ^0 of 3 to 4 dB at a 25% level of thinning, similar to the thinning level in this study, in a maritime pine forest in France. The small change in σ^0 of less than 1 dB at our study site may be due to the presence of a lower canopy and understory vegetation. Champion *et al.* (1998) also reported that a numerical

simulation predicted a smaller value (1 dB or less) than the value they observed and attributed the discrepancy between their observations and the numerical simulation results to the simple treatment of forest structure and a lack of consideration of a change in vegetation below the canopy in the numerical model.

SUMMARY AND CONCLUSIONS

We investigated changes in σ^0 as a result of thinning and typhoon disturbances in a larch forest in northern Japan. The thinning caused a change in AGB of intermediate magnitude, reducing it by approximately 26.7% at the site. By contrast, the typhoon caused a significant change in the forest structure, mainly by uprooting trees, without changing the AGB. We summarize our conclusions as follows:

- The change in σ^0 due to thinning was less than 1 dB. σ^0_{HV} was most sensitive to the change in AGB, and σ^0_{HH} was insensitive to it.
- σ^0_{VV} , but not σ^0_{HH} or σ^0_{HV} , was sensitive to the forest structure change caused by the typhoon. The significant change in σ^0_{VV} might be due to the orientation of the felled trees.

More study is needed to improve the accuracy of detection of intermediate changes in a forest such as those caused by thinning. On the other hand, L-band SAR data can potentially be used for the sensitive detection of changes in forest structure due to catastrophic disturbances. Investigations of various instances of forest disturbances are needed to clarify how microwave backscattering data change with respect to the nature of the change in forest structure.

Remote sensing using space-borne SAR such as ALOS/PALSAR is being increasingly used as a technique for detection of forested areas and forest disturbances at regional and global scales. Utilization of SAR-retrieved forest data in hydrological and land-surface models will be useful for prediction of future changes in evapotranspiration, water discharge, and carbon dioxide fluxes.

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