Remote Sensing of Environment 115 (2011) 227–232

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Soil moisture limitations on monitoring boreal forest regrowth using spaceborne L-band SAR data

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ARTICLE INFO

Article history:
Received 5 June 2010
Received in revised form 24 August 2010
Accepted 28 August 2010

Keywords:
Synthetic aperture radar
L-band
Biomass
Soil moisture

ABSTRACT

A study was carried out to investigate the utility of L-band SAR data for estimating aboveground biomass in sites with low levels of vegetation regrowth. Data to estimate biomass were collected from 59 sites located in fire-disturbed black spruce forests in interior Alaska. PALSAR L-band data (HH and HV polarizations) collected on two dates in the summer/fall of 2007 and one date in the summer of 2009 were used. Significant linear correlations were found between the log of aboveground biomass (range of 0.02 to 22.2 t ha^{-1}) and $\sigma°$ (L-HH) and $\sigma°$ (L-HV) for the data collected on each of the three dates, with the highest correlation found using the L-HV data collected when soil moisture was highest. Soil moisture, however, did change the correlations between L-band $\sigma°$ and aboveground biomass, and the analyses suggest that the influence of soil moisture is biomass dependent. The results indicate that to use L-band SAR data for mapping aboveground biomass and monitoring forest regrowth will require development of approaches to account for the influence that variations in soil moisture have on L-band microwave backscatter, which can be particularly strong when low levels of aboveground biomass occur.

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1. Introduction

Research by a number of investigators in the 1980s first demonstrated a relationship between pine forest biomass and synthetic aperture radar (SAR) image intensity, providing the impetus for subsequent research using SAR data from airborne and spaceborne platforms (Riom & Le Toan, 1981; Sader, 1987; Wu, 1987). While analyses of data from airborne platforms showed that P-band (64 cm wavelength) radar backscatter provided the strongest correlations to aboveground biomass (Dobson et al., 1992; Kasischke et al., 1995; Le Toan et al., 1992; Rignot et al., 1994; Santos et al., 2003), recent research has focused on L-band (24 cm wavelength) data because of its availability from a number of spaceborne SAR systems (the Japanese JERS SAR, the ALOS-PALSAR, and the Shuttle Imaging Radar SAR-C, or SIR-C).

Research evaluating the potential for spaceborne L-band SAR data to estimate aboveground biomass has taken place using sites located in a number of different forest types, including boreal forests (Harrell et al., 1995; Kurvonen et al., 1999; Pulliainen et al., 1999; Rauste, 2005; Tsolmon et al., 2002), temperate forests (Dobson et al., 1992; Harrell et al., 1997; Kasischke et al., 1995), savanna woodlands (Austin et al., 2003; Lucas et al., 2000; Mitchard et al., 2009; Santos et al., 2002), and tropical forests (Kuplich et al., 2000; Luckman et al., 1997, 1998; Salas et al., 2002; Takeuchi et al., 2000). The consensus emerging from these studies was that at L-band: (1) HV-polarized microwave backscatter was the most sensitive to variations in aboveground biomass; and (2) across all forest types, the sensitivity to biomass reached saturation at biomass levels of 80 to 120 t ha^{-1} (dry weight).

Very few studies have been carried out to examine L-band SAR backscatter/biomass relationships under low biomass situations (<20 t ha^{-1}) (see, e.g., Tsolmon et al., 2002), where microwave backscatter from the earth's surface will also be sensitive to variations in soil moisture as well as differences in biomass (Wang et al., 1994). For example, using data from the ERS C-band (6 cm wavelength) SAR, both French et al. (1996) and Bourgeau-Chavez et al. (2007) found strong correlations between SAR backscatter and soil moisture in young (6 to 12 years) boreal forests regenerating following fires. While detailed studies of the relationship between L-band SAR backscatter and soil moisture in non-agricultural landscapes have yet to occur, surface scatterometer measurements by Ulaby et al. (1978) showed that backscatter at L-band frequencies was strongly correlated to soil moisture. In addition, Pulliainen et al. (1999) showed that the L-band backscatter obtained by the JERS SAR over mature boreal forests differed by 1 dB between wet and dry conditions. Research using SIR-C L-band data showed that the relationship between biomass and backscatter in pine forests was sensitive to variations in soil moisture (Harrell et al., 1997). Finally,

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doi:10.1016/j.rse.2010.08.022

Salas et al. (2002) noted considerable temporal variation in JERS SAR backscatter in regenerating tropical forest sites that they attributed to variations in soil and vegetation moisture.

Here, we investigated the relationship between L-band SAR backscatter and aboveground biomass in sites located in fire-disturbed black spruce forests in interior Alaska using ALOS PALSAR data. The sites used in this study were located in areas that had burned between 9 and 21 years prior to the data collections and had lower biomass levels than typically found in regrowing temperate and tropical forests. Variations in precipitation in the days preceding the PALSAR data collections resulted in differences in soil moisture on the three dates that SAR data were available. This data set was analyzed to determine if: (1) L-band SAR backscatter is sensitive to lower biomass variations typically found in regenerating boreal forests; and (2) variations in soil moisture resulted in a systematic shift in the relationship between biomass and L-band SAR backscatter.

2. Study site and methods

The 59 sites used for this research were located within the perimeters of three fire events near Delta Junction, Alaska, including: (a) the 20,000 ha Granite Creek Fire that burned in the spring of 1987 (center of fire: 63° 53.1' N Lat., 145° 30.5' W Long.); (b) the 8,900 ha Hajdukovich Creek Fire that burned in the summer of 1994 (center of fire: 63° 48.9' N Lat., 145° 7.6' W Long.); and (c) the 7,900 ha Donnelly Flats Fire that burned in the early summer of 1999 (center of fire: 63° 55.4' N Lat., 145° 43.8' W Long.). These three fire events occurred on relatively flat terrain (<2° slope) on a broad alluvial outwash plain located between the Alaskan Range to the north and the Tanana River to the south. The elevation of the sites ranged between 385 and 520 m ASL. More detailed descriptions of these study sites can be found in O'Neill et al. (2003) and Kasischke and Johnstone (2005).

The study sites were located in areas that had been occupied by mature black spruce (*Picea mariana*) forests prior to burning, where the depth of the pre-fire surface organic layer ranged between 10 and 25 cm (Kasischke & Johnstone, 2005). In Alaskan black spruce forests, depth of burning strongly regulates patterns of post-fire succession (Johnstone & Kasischke, 2005; Johnstone et al., 2010). In sites where a deep organic layer remains after the fire, succession is driven by vegetative reproduction of shrubs and recruitment of black spruce seedlings. In sites experiencing deep burning of the surface organic layer, the exposure of dense humic and mineral soils provides the opportunity for aspen (*Populous tremuloides*) seedling recruitment and growth, initiating a pattern of relay floristics that is more common to post-fire succession in white spruce (*P. glauca*) forests in interior Alaska (Viereck et al., 1983) (Fig. 1).

Each of the fire events used in this study contained areas that experienced shallow and deep burning of the surface organic layers. These differences in the depth of burning were the result of variations in organic layer moisture driven by mineral soil texture and seasonal thawing of frozen ground layers (Harden et al., 2006; Kasischke & Johnstone, 2005). The data collected in the study areas provided the opportunity to simultaneously investigate how fire severity influences post fire succession and biomass regeneration (Shenoy et al., in review), and the sensitivity of L-band backscatter to variations in biomass.

During the summers of 2008 and 2009, data were collected to estimate aboveground biomass of black spruce and aspen seedlings as well as for willow (*Salix sp*.), the dominant understory shrub component in the regenerating forests in the study region. A field reconnaissance was first undertaken to identify areas with different patterns and levels of post-fire regeneration. For specific sites, we first identified an area that had a uniform vegetation cover over a 100 by 100 m (1 ha) area, and then placed the plot at the center. Vegetation

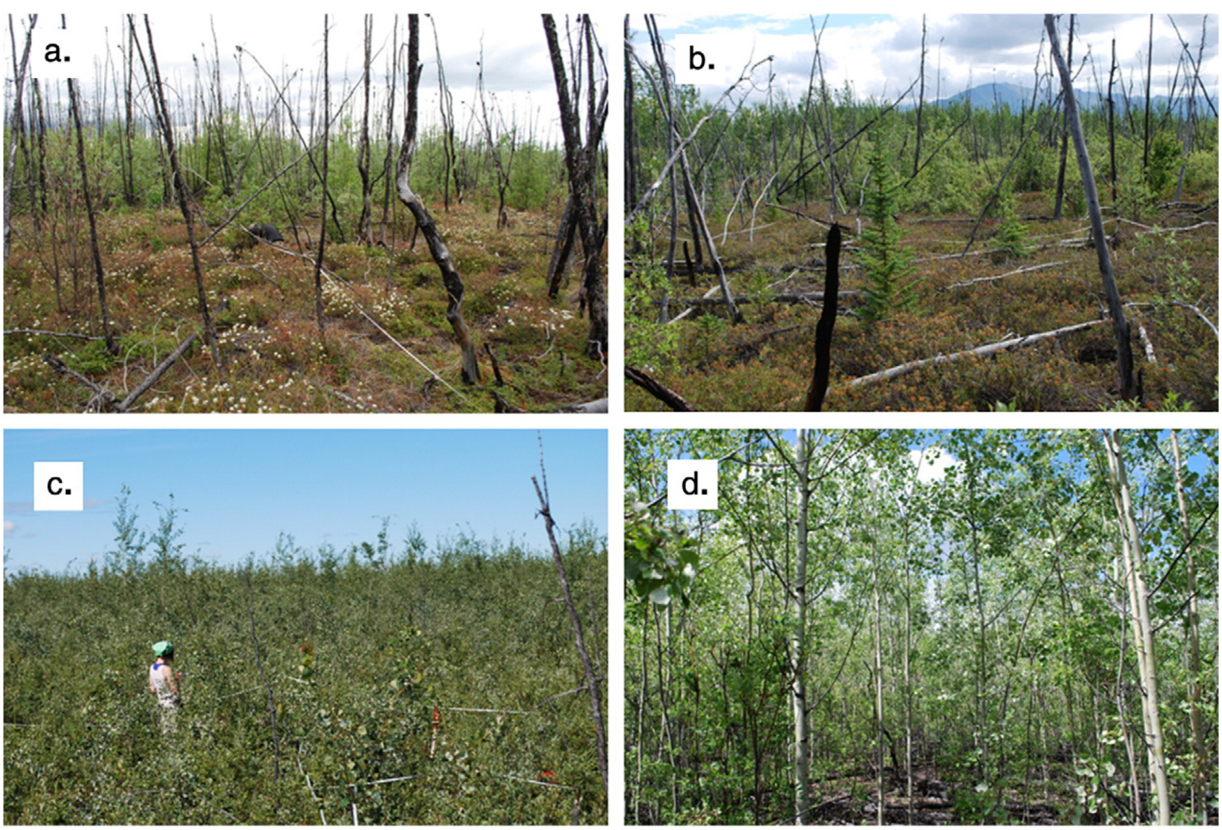

Fig. 1. Ground photographs showing differences in post-fire regeneration occurring in study sites used for this study. (a) 1994 burn site dominated by willow shrubs and black spruce seedlings; (b) 1987 burn site dominated by black spruce saplings and willow shrubs; (c) 1994 burn site dominated by aspen seedlings and willow shrubs; and (d) 1994 burn site dominated by aspen saplings. All photographs taken by E. Kasischke in the summer of 2008.

and organic layer sampling was accomplished by locating a baseline (40 m) oriented in a random direction at the plot center. One sample transect (30 m) was located perpendicular to the baseline at plot center and an additional sample transect was located at a random distance between 5 and 15 m from the plot center in each direction (3 sample transects total). All black spruce and aspen seedlings within a distance of ±1 m of the sample transects were counted to determine seedling density. The diameter distribution of black spruce and aspen seedlings was determined by measuring all seedlings within a 1 by 10 m belt transect located at a random distance along each sample transect. The diameters of all willow stems were also measured in these 1 by 10 m sample areas. Finally, depth of the surface organic layer was measured every 5 m along each sample transects.

Biomass of the black spruce, aspen and willow seedlings were determined using allometric equations from Johnstone and Kasischke (2005), with the exception of aspen, where additional trees were harvested and combined with the data from Johnstone and Kasischke (2005) and Mack et al. (2008) to create a single biomass equation (Shenoy et al., in review).

The SAR data used in this study were collected by the Advanced Land Observing Satellite (ALOS) Phased Array type L-band SAR (PALSAR) sensor. The PALSAR data were received and processed by the Alaska Satellite Facility (ASF). The PALSAR data were collected in the dual polarization (FBD) mode (HH and HV polarizations), where the local incidence angle near swath center was 39°. PALSAR data were collected over the study sites on three separate occasions (15 August 2007, 30 September 2007, and 20 August 2009). The ASF PALSAR data were provided as single look complex images (Level 1.1 product) with a pixel spacing of 9.4 m in slant range and 3.1 m in azimuth. The images were multi-looked (2 range and 10 azimuth) in order to obtain a ground pixel spacing around 30 m in both directions. Prior to geocoding, the PALSAR image intensity values were calibrated using radiometric correction coefficients provided by ASF.

The three PALSAR images were geocoded to within ±30 m using a 60 m spatial resolution digital elevation model and a UTM projection. Geocoding of the SAR data was based on a lookup table describing the transformation between the radar and the map geometry (Wegmüller et al., 2002) which was generated using a digital elevation model (DEM) and the orbital information of the PALSAR images. To correct for possible inaccuracies in the input data a refinement of the lookup table was applied in the form of offsets estimation between the SAR images and a reference image (e.g. a DEM based simulated SAR image) transformed to the radar geometry. The locations of each study site within the PALSAR scenes were determined using GPS data that had been collected during the field observations. Average radar image intensity (I) from the PALSAR data was based on all pixels within a 55 m radius (approximately 10 pixels) of the center of the site. The image intensity values were converted to a radar backscatter coefficient (σ°) using the following relationship

$$\sigma^\circ = 10\ \log(I/A) \tag{1}$$

where A is the area (m^2) of the pixels used to generate the average image intensity.

While soil moisture data were not available for this study, variations in the relative ground moisture conditions were inferred from precipitation records collected at Delta Junction, Alaska. Previous studies (Bourgeau-Chavez et al., 2007) determined that variations in the time and amount of precipitation were the primary drivers of near-surface soil moisture in the burned sites being used in this study. The highest levels of precipitation occurred prior to the 30 September 2007 and the lowest occurred prior to the 20 August 2009 (Table 1). The soil moisture levels during the 30 September 2007 collection were likely higher than those on 15 August 2007 for several additional reasons. First, the rates of surface evaporation would have been lower in late September because the average maximum daytime temperature decreased from August (21.5 °C) to September (12.3 °C). Second, senescence of deciduous foliage occurs in late August in Alaska; thus the removal of soil water via plant transpiration drops significantly in September. Based upon the above assessment, the likely range in soil moisture for the three dates was as follows: 20 August 2009: moderate (best guess of volumetric moisture: 20–40%); 15 August 2007: high (best guess of volumetric moisture: 30–50%); and 30 September 2007: very high (best guess of volumetric moisture: 40–60%).

Table 1
Summary of precipitation (mm) on the 3 dates used in this study. Data are from Delta Junction, Alaska, which is between 10 and 32 km from the sites used in this study.

	15-Aug-07	30-Sep-07	20-Aug-09
	High soil moisture	Very high soil moisture	Moderate soil moisture
Previous 60 days	115	128	82
Previous 30 days	59	68	38
Previous 15 days	53	58	38
Previous 24 hours	9	0	6

To analyze the relationship between radar backscatter and biomass, we performed a linear regression using the log of aboveground biomass as the dependent variable and σ° as the independent variable. To analyze the influence of variations in soil moisture, a backscatter ratio (σ°_r) using the scattering coefficients from two dates was generated using the following relationship

$$\sigma^\circ_r = \sigma^\circ\,(\text{date 1}) - \sigma^\circ\,(\text{date 2})$$

In this analysis we subtracted the site values from the two dates with the lowest backscatter (20 August 2009 and 15 August 2007) from the site values from the date with the highest backscatter (30 September 2009) to produce σ°_r. We evaluated this relationship by using σ°_r as the dependent variable and log of the aboveground biomass as the independent variable.

3. Results

The aboveground biomass levels for the sites used in this study ranged between 0.02 and 22.4 t ha^{-1}. These values are conservative because some sites did include other low-lying woody shrubs, including blueberry (*Vaccinium* sp.), Labrador tea (*Ledum groenlandicum*), and shrub birch (*Betula glandulosa*). As expected, aboveground biomass was highly correlated with depth of the residual organic layer

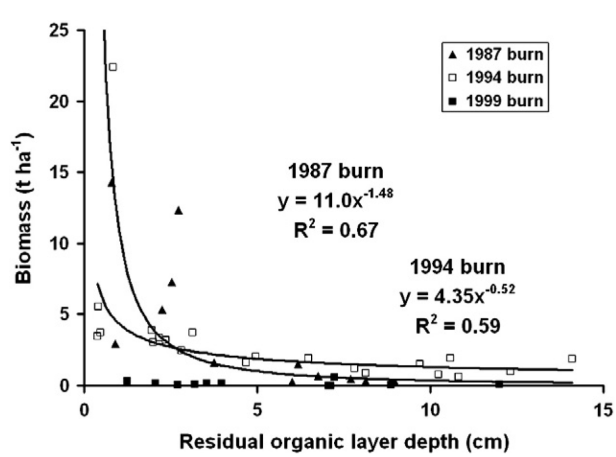

Fig. 2. Relationship between post-fire organic layer depth and aboveground biomass from sites in the 1987, 1994, and 1999 burns. Lines are presented for the 1987 and 1994 data, but not for the 1999, where no significant correlation existed. R^2 values are significant at *p<0.001*.

Table 2
Summary of linear regression of log of aboveground biomass as a function of PALSAR σ° (L-HV).

Date	F-value	r^2	RMSE ($t\ ha^{-1}$)	Intercept	std error	t-statistic	95% CI	Slope	std error	t-statistic	95% CI
15-Aug-07 (high moisture)	55.1	0.49*	2.8	2.11*	0.55	11.1	±1.10	0.221*	0.030	7.4	±0.059
30-Sep-07 (very high moisture)	97.4	0.63*	3.2	4.11*	0.41	14.8	±0.83	0.214*	0.022	9.9	±0.043
20-Aug-09 (moderate moisture)	54.0	0.49*	3.3	5.56*	0.75	10.1	±1.50	0.311*	0.042	7.3	±0.085

*Significant at $p<0.0001$.

in the sites located in the 1987 and 1994 burns, with the biomass levels increasing non-linearly in the sites with the shallowest organic layers (Fig. 2). The reason the biomass levels in the 1999 burn were among the lowest found across all sites and did not vary as a function of organic layer depth is most likely because of the low soil moisture experienced in this burn resulted in low recruitment of tree seedlings (Kasischke et al., 2007).

Overall, the dynamic range in σ° for the 59 sites averaged 5.9 dB at HH polarization and 8.3 dB at HV polarization. The correlation between the log of the aboveground biomass and σ° (L-HH) was very low for all three dates: $R^2=0.20$, 0.32, and 0.15 ($p<0.0005$) for the 15 August 2007, 30 September 2007, and 20 August 2009 data, respectively.

The linear correlations between σ° (L-HV) and the log of the aboveground biomass were much higher (Table 2). The highest R^2 was found for the data collected on the day when the soil moisture was greatest, 30 September 2007 (Fig. 3). The regression equations developed using the 15 August and 30 September 2007 PALSAR data had identical slope and intercepts, but the regression equation developed using the data from 20 August 2009 (the driest date) had a slightly higher intercept and slope. The RMS errors for the three PALSAR data sets ranged between 2.8 and 3.3 $t\ ha^{-1}$ (Table 2).

There was a linear relationship between the log of biomass and the backscatter ratio ($\sigma°_r$), where the ratio decreased as the biomass increased in both comparisons (Fig. 4). The biomass influence was greatest where the differences in soil moisture were the highest (30 September 2007 versus 20 August 2009) (Fig. 4). The analysis showed that both the slope of the regression line and the intercept for regression lines presented in Fig. 4 were significantly different (Table 3). While the L-HH backscatter ratio was correlated to biomass as well, the correlations were not as strong ($R^2=0.27$, $p<0.0001$ for 30 September 2007 versus 20 August 2009 ratio and $R^2=0.16$, $p<0.001$ for 30 September 2007 versus 15 August 2007 ratio).

4. Discussion

While many previous studies have been conducted on the correlation of L-band SAR backscatter to biomass, only one study has investigated this relationship where the measured aboveground biomass for the sites being investigated was low (Tsolmon et al., 2002). The results from our study also showed that the degree of microwave backscattering at L-band from land surfaces was sensitive to variations in biomass in areas where the rate of post-disturbance regrowth was low, such as in many boreal forests, with the highest correlations being obtained using HV polarized data. The results of our study were robust from the standpoint of species composition, where in some sites biomass was dominated by willow shrubs and black spruce saplings, and in others by aspen seedlings and saplings. Thus, these results demonstrate there is the potential for using multi-temporal SAR data for estimating changes in aboveground biomass, a potential that was shown by Takeuchi et al. (2000) in regenerating tree plantations in a tropical region.

The results of our study demonstrated, however, that the sensitivity of L-band backscatter to variations in soil moisture affects the correlation between backscatter and biomass in areas with low levels of forest regrowth. In a modeling study, Wang et al. (2000) found while L-HH backscatter was sensitive to variations in biomass in low biomass situations (biomass = 0 to 3 $t\ ha^{-1}$), that backscatter from the soil surface provided the dominant return. The modeling results of Wang et al. (2000) indicated that at volumetric soil moistures between 5 and 45%, the direct backscatter from the soil surface was so great that variations in backscatter from biomass would not be detected. Our results showed this not to be the case – there was a ~4 dB increase in L-HH backscatter as biomass increased from 0 to 3 $t\ ha^{-1}$.

The highest correlation between L-HV backscatter on biomass occurred when the soil moisture was the highest. This is the opposite of the finding of Harrell et al. (1997), who found that the highest

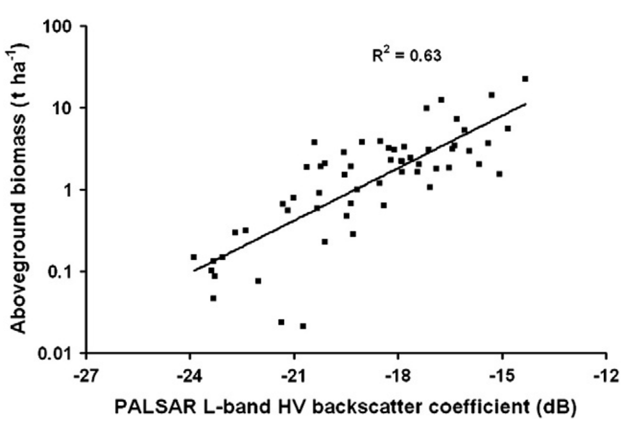

Fig. 3. Aboveground biomass plotted as a function of PALSAR σ° (L-HV) from the date with the highest soil moisture conditions (30 September 2007). R^2 value is significant at $p<0.0001$.

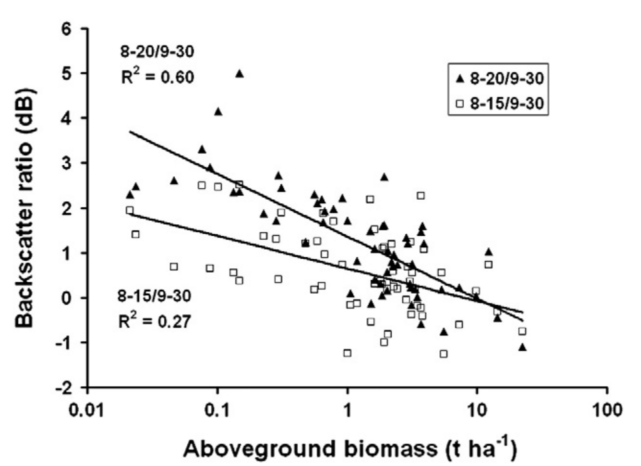

Fig. 4. Variations in the L-HV backscatter ratio ($\sigma°_r$) between wet and dry dates as a function of aboveground biomass. R^2 values are significant at $p<0.0001$. (8-20/9-30 denotes that the backscatter ratio between 20 August 2009 [moderate moisture] and 30 September 2007 [very high moisture]. 8-15/9-30 denotes the backscatter ratio between 15 August 2007 [high moisture] and 30 September 2007 [very high moisture].).

Table 3
Summary of linear regression of the backscatter ratio (σ_r°) (L-HV) as a function of the log of aboveground biomass.

Dates	F-value	r^2	Intercept	std error	t-statistic	95% CI	Slope	std error	t-statistic	95% CI
(20 Aug 09)/(30 Sept 07)	84.9	0.60*	1.37*	0.10	13.6	0.20	-1.39*	0.15	9.2	0.30
(15 Aug 07)/(30 Sept 07)	20.8	0.27*	0.65*	0.11	6.1	0.21	-0.72*	0.16	4.6	0.32

*Significant at $p < 0.0001$.

correlations between biomass and L-band SAR backscatter in mature pine forests occurred when the soils were drier.

5. Conclusions

Variations in L-band SAR backscatter from the sites containing regenerating forests used in this study came from two sources: (a) variations in biomass; and (b) variations in soil moisture. While the changes in L-HV SAR backscatter as a function of biomass (9 dB) were greater than those observed due to the differences in soil moisture (up to 5 dB), there was a systematic shift in backscatter as a function of biomass when data from very high and moderate soil moisture conditions were compared. The sensitivity of L-band backscatter to variations in soil moisture in low biomass settings is supported by modeling results (Wang et al., 2000) and observations made in tropical forest regions (Salas et al., 2002).

The sites used for this research were located in a region that experiences periods of low precipitation during the growing season. The conditions present during the times when the PALSAR data were collected did not represent the driest conditions that can occur during the growing season. Thus, the differences in L-band backscatter between dry and wet conditions in regrowing boreal forests are likely to be higher than observed in this study.

It should be noted that the black spruce ecosystems of interior Alaska used in this study experience extremely low levels of growth, with aboveground biomass reaching 40 to 60 t ha^{-1} in mature black spruce forests that are 100 to 200 years old (Harrell et al., 1995). The maximum biomass levels of 10 to 20 t ha^{-1} that occurred in the sites used in this study were in sites that had been disturbed 14 to 21 years prior to disturbance. Regrowth is much more rapid in temperate and tropical forests. For example, stand biomass in 15 year old pine forests used by Harrell et al. (1997) ranged between 60 and 140 t ha^{-1}. In these situations, large variations in L-band backscatter caused by variations in soil moisture will only occur during the first several years of regrowth following disturbance or planting.

While L-band backscatter is clearly sensitive to variations in low biomass situations, there is also evidence that variations in soil moisture influence the SAR backscatter biomass relationship in higher biomass situations (Harrell et al., 1997; Pulliainen et al., 1999). In a modeling study where forest biomass ranged between 60 and 350 t ha^{-1}, the results of Wang et al. (1998) showed that variations in litter and soil moisture caused greater changes in backscatter at L-HH and L-VV polarizations than backscatter at L-HV polarization at shallow incidence angles (20–40°), but that at steeper incidence angles, the effects were minimal for L-HV polarization.

These results show that using spaceborne SAR systems to monitor forest regrowth will not only require collection of biomass data to establish the relationship between biomass and backscatter, but may also require developing methods to account for variations in soil moisture. While the case for the impacts of soil moisture is compelling at low biomass (<20 t ha^{-1}), the evidence for a systematic change in backscatter due to soil moisture at higher biomass is less clear.

Mitchard et al. (2009) suggested that the influence of soil moisture on approaches to estimate savanna woodland biomass using PALSAR L-HV data could be accounted for through the analysis of data collected over multiple dates. The equations developed by Mitchard et al. (2009), however, had the highest errors in the region with the lowest biomass (for the NCCP Mozambique site the average aboveground biomass was 40.7 t ha^{-1} while the RMSE errors were between 19.2 and 25.2 t ha^{-1}), and unaccounted variations in soil moisture will only increase these uncertainties.

To reduce the errors associated with using L-band SAR data to estimate biomass in regrowing forests, additional research is required. This includes studies where soil moisture is systematically measured in sites with varying levels of aboveground biomass over multiple dates when spaceborne or airborne SAR data are collected. These studies are needed across a range of sites experiencing both fast and slow regrowth. Ideally, similar data would be collected across a range of forest and woodland types in order to understand the influence of tree architecture on soil moisture–biomass–backscatter relationships. These data would provide the basis for the validation of theoretical models, which can then be used to examine the influence of soil moisture on backscatter/biomass relationships across a broad range of conditions. Without such research, it will not be possible to use time-series L-band SAR data to assess changes in forest biomass because of uncertainties introduced by variations in soil moisture.

Acknowledgements

The research was supported by the National Aeronautics and Space Administration through grant number NNG04GR24G to the University of Maryland and by the Spanish Ministry of Science and Education and the European Social Fund: FPI grant BES-2006-11684. The authors would like to thank Aditi Shenoy and Kirsten Barrett for their assistance in the collection of the biomass data used in this study.

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