A NEW METHOD FOR ESTIMATION OF SOIL MOISTURE FROM PALSAR POLARIZATION DATA IN HIGH DENSITY VEGETATED AREA

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ABSTRACT: Changes in the distribution of *Pinus pumila*, *Sasa kurilensis* and the alpine flora over the past 30 years in the Taisetsu Mountains study area in Hokkaido were quantified in order to calculate the expansion and contraction of *Pinus pumila*, *Sasa kurilensis* and alpine flora. The physical and geographical factors in the change mechanism were then analyzed. In order to quantify the dehydration mechanism in changing vegetation areas, an algorithm was developed using the linear model between different microwave backscatter coefficients (dB), based on the volumetric soil moisture (VSM) (%) measured on site and satellite data. In the development of the algorithm, the fact that the seasonal changes of a dwarf bamboo grass and *Pinus pumila* are much smaller than the seasonal changes in other alpine plants and soil moisture content was used to develop a model which uses differences in microwave backscattering coefficients while taking into consideration the phenology. The moisture content in the soil under specific vegetation in Goshikigahara on Taisetsu Mountains was then identified. The study discovered that the area under *Sasa kurilensis* increased by 25.9% (13,689 m^2) over a 32 year period from 1977 to 2009 and the area under *Pinus pumila* increased by 14.4% (12,707 m^2) in total for both plots. When looking at the expanding area of *Sasa kurilensis*, the plants preferred areas facing northeast through to southeast, with gradients of 0-20 degrees and solar radiation of 830,000 Wh/m^2 or more. When looking at the seasonal fluctuations of soil moisture in 2010 in areas under *Pinus pumila*, bamboo grass and alpine plants, the soil moisture content in Goshikigahara increased in general from mid-June to early July, except for a decrease in some areas covered by dense bamboo grass. In August, September and October, there was a clear soil moisture content decrease (dehydration) in most areas under dense bamboo grass. At the edges of some expanding bamboo grass areas (where bamboo grass was invading alpine vegetation areas), increases in soil moisture content were observed. There were no major fluctuations in areas where alpine plants cover a wide area from August to October, but the areas showed slight dehydration.

1. INTRODUCTION

Recently, a dwarf bamboo species, *Sasa kurilensis, Poaceae,* has invaded into alpine snow-meadows in wilderness area of the Taisetsu Mountains, northern Japan (Kudo et al., 2011). It is predicted that the biodiversity of alpine and subalpine ecosystems will be more seriously affected by climate change than that of other ecosystems (Kudo et al., 1992, 2006). The ecotone along the altitudinal gradient is important as a mechanism which creates biodiversity in the plant community. In order to evaluate and predict the vulnerability to climate change of mountain ecosystems, it is essential to understand the ecosystem of the ecotone between the forest zone and the alpine zone (Nagy and Grabherr, 2009). The photoenvironment near the ground changes dramatically after the tree line, therefore it is predicted that the composition of the plant community drastically changes. It is also possible that the diversity of the undergrowth is greatly influenced by the tree species which make up the tree line and the stand structure of the tree line. However, regarding changes in the biodiversity of a plant community along the altitudinal gradient, very little comparative research on different mountain areas has been conducted.

It is predicted that the impact of global warming caused by climate change on terrestrial ecosystems will be particularly prominent in the Polar Regions and alpine belts (Chapin et al., 2000). In recent years, the thaw period has been starting earlier every year in the Taisetsu mountain range (Kudo and Hirao, 2006). This has led to concerns that the early thaw is leading to progressive soil dehydration, which creates an environment where *Sasa kurilensis* (Chishima bamboo grass) can spread more easily and the alpine vegetation will rapidly decline due to the invasion of bamboo grass and dehydration. *Pinus pumila* (Japanese stone pine) has a huge biomass in the alpine zone and its growth trend is having a great impact on other alpine vegetation. However, there is little information about where and to what extent the bamboo grass and *Pinus pumila* have spread. The factors which trigger the expansion have not been identified. In order to identify the environmental factors which cause the expansion of bamboo grass and *Pinus pumila* and the disappearance of alpine plants, it is important to analyze seasonal fluctuations in soil moisture in areas of vegetation change. In particular, it is essential to estimate the soil moisture content situation and analyze seasonal changes over a wide area. However, since mountain areas do not have many days of good weather, it is difficult to monitor vegetation and surface properties using conventional optical satellite sensors (Hoshino et al., 2009; Moran et al., 2004). In addition, the roughness height of *Pinus pumila* and bamboo grass greatly affects the algorithm for the estimation of the soil moisture content when using microwave backscattering data. Therefore, in this study, aerial photographs were analyzed in order to sample the changing vegetation area and analyze the mechanism causing the changes. Then, a model using the phenological differences between different microwave backscattering coefficients was developed by utilizing the characteristics that the seasonal changes of bamboo grass and *Pinus pumila* are much smaller than the seasonal changes of alpine plants and soil moisture content. Based on the model, the seasonal changes in soil moisture content in the changing vegetation area were studied.

2. THE STUDY OBJECTIVES

2.1 The Study Area and time-series spatial data

About 98 ha of land in the central part of Goshikigahara (altitude: 1,700-1,800 meters, 43º33'N, 142º54'E) on Taisetsu Mt, in Hokkaido Japan was selected as a model area and aerial photographs from 1966 and 1977 were digitized and orthorectified. Similar orthorectification was undertaken for aerial photographs taken in 2008 using a hyperspectral camera (NEC) which has a 60-spectral bands, as well as for the aerial high spatial resolution (25 cm) photographs taken in 2009. Change detection analysis was then conducted by overlaying the precisely orthorectified time-series spatial data. The backscattering coefficient data calculated from ALOS PALSAR HH/HV polarization data in June 19, Jull 7, August 4, August 21, September 19 and October 6, 2010. The field measurement of plants species and soil moisture of study area was taken in July, August and September in 2008, 2009, 2010 and 2011.

2.2 Objectives of the Study

The objective of the study is to clarify the mechanism causing the dehydration of soil over large areas of changing vegetation areas (Goshikigahara). When estimating the soil moisture content in a large area which is covered with dense vegetation, it is necessary to take into account the impact of the vegetation. Therefore, the method for identifying seasonal fluctuations of soil moisture content over large areas was developed using microwave backscattering coefficients for densely vegetated areas.

3. METHODOLOGY

3.1 Sampling of the Changing Vegetation Area and Analysis of the Change Detection and Change Mechanism

An alpine meadow with a relatively gentle gradient in Goshikigahara in the Taisetsu Mt. National Park was chosen as the study area. Two quadrats of 500 meters times 500 meters were set up and one was named the northern quadrat and the other was named the southern quadrat. Aerial photographs taken in 1977 (on September 25) and in 2009 (on September 3) were used after being digitized and orthorectified. The Japanese rectangular plane coordinate system was used for all the data created. In order to examine the geographical characteristics of the area where bamboo grass is expanding based on the 50-cm mesh Digital Surface Model (DSM) data created from the 2009 aerial photographs, Esri's ArcMap was used to obtain the slope directions (eight directions), gradients (every 10 degrees) and the solar radiation (the starting date: 120th, the ending date: 270th, the date interval: 15, the hour interval: 0.5). Manley's selectivity index was used to analyze the relationship between the bamboo grass expansion area and the topography (the slope direction, the gradient and the solar radiation).

3.2 Seasonal Fluctuations in the Soil Moisture Content for the Changing Vegetation Area

Three elements are included in the total backscattered light of the microwave (synthetic aperture radar (SAR)) in pixels of the satellite image of a densely vegetated area. The three elements include: diffuse light from the plant layer (σ^0_{dv}), diffuse light from the soil layer (σ^0_s) and multiple diffuse light from both plants and soil (σ^0_{int}) (Moran et al., 2004). The total backscattered light can be obtained with the following formula:

$$\sigma^0_{dB} = \tau^2\sigma^0_s + \sigma^0_{dv} + \sigma^0_{\text{int}} \qquad (1)$$

Where, τ^2 is an attenuation coefficient for the (bidirectional) backscattering from the plant layers. When looking at the correlation between the total backscattering coefficients σ^0_{dB} for a densely vegetated area obtained using formula (1) and the average volumetric soil moisture surveyed (VSM), a close correlation was observed when the satellite data received on September 19, 2010 was used, as shown below.

$$VSM = 0.0357 \times \sigma^0_{dB} + 1.1696 \quad (R^2 = 0.833) \qquad (2)$$

Although a high correlation was observed for the area where soil moisture content was surveyed, the correlation was low for non-surveyed areas when formula (2) was used. The study assumed that the seasonal changes (growth) of the roughness height of bamboo grass and *Pinus pumila* over one month does not affect the backscattering signal, based on the penetration properties of the L-band microwave through the plant layer and the phenological characteristics of bamboo grass and *Pinus pumila*. Based on this assumption, the following formula was created (Hoshino et al., 2010; 2011):

$$\Delta VSM = \Delta f(R, m_s) \approx \Delta\sigma^0_{dB} = (\sigma^{t2}_{dB} - \sigma^{t1}_{dB}) = (\sigma^{t2}_s - \sigma^{t1}_s) \qquad (3)$$

Where, R is roughness; m_s is the VSM surveyed; ΔVSM is seasonal changes in the soil moisture; $\Delta\sigma^0_{dB}$ is the difference between backscattering coefficients; σ^{t2}_s and σ^{t1}_s are backscattering coefficients from soil in season t2 and season t1, respectively.

4. RESULTS

4.1 Sampling of the Changing Vegetation Area and Analysis of the Change Detection and Change Mechanism

As a result of comparison between the area under bamboo grass in 1977 and the area under bamboo grass in 2009, the area increased by 25.9% (13,689 m^2) in the total area of the plots (Fig. 1). In addition, when looking at the percentage of increase in each quadrat, the area under bamboo grass increased by 10.9% in the northern quadrat and by 47.5% in the southern quadrat. Therefore, the southern quadrat showed a more marked increase.

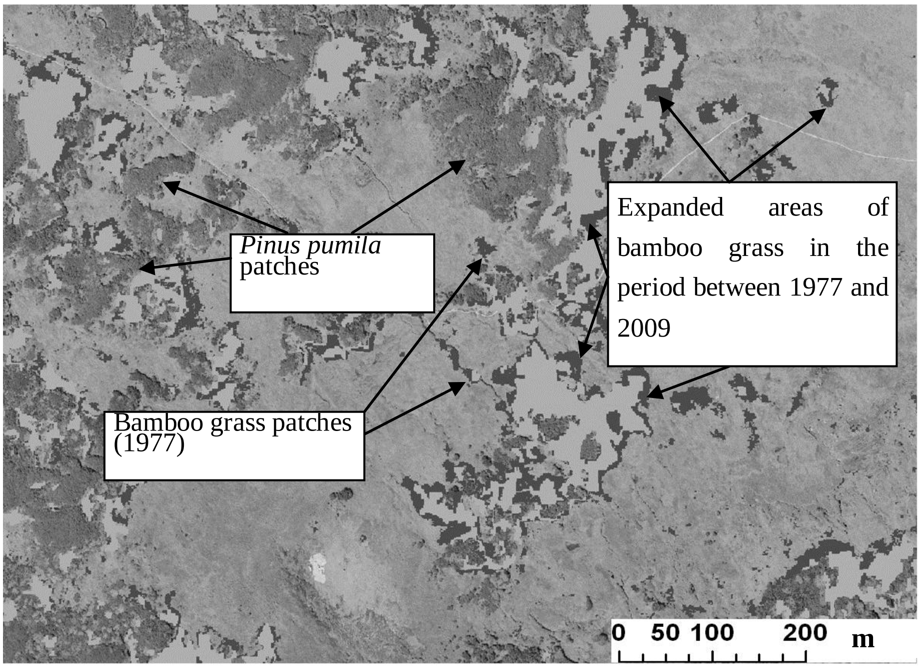

Fig. 1. Distribution of Bamboo Grass and *Pinus pumila* and the Expansion of Bamboo Grass over 32 Years

When looking at the rate of increase in each quadrat, the area covered by *Pinus pumila* increased by 14.6% in the northern quadrat and 13.9% in the southern quadrat. Therefore, there was no large difference between the northern quadrat and the southern quadrat unlike the results for the bamboo grass areas. The result shows the area that the bamboo grass expanded to and the preference of bamboo grass for certain types of topography and solar radiation. Regarding the slope direction, areas which face northeast through to southeast were preferred and areas which face south through to north were avoided. Regarding the gradient, areas with 0-20 degree gradients were preferred and areas with 20 degree gradients or more were avoided. Regarding solar radiation, areas receiving 830,000 W. h/m^2 of solar radiation or more (but excluding 910,000-1,000,000 W. h/m^2) were preferred and areas with 810,000 W. h/m^2 of solar radiation or less were avoided. As a result of the preference analysis, it was found that the bamboo grass preferred slopes which receive less sunshine (areas which face northeast through to southeast) rather than slopes which receive more sunshine (areas which face south through to west).

(2) Seasonal Fluctuations in Soil Moisture Content in the Changing Vegetation Area

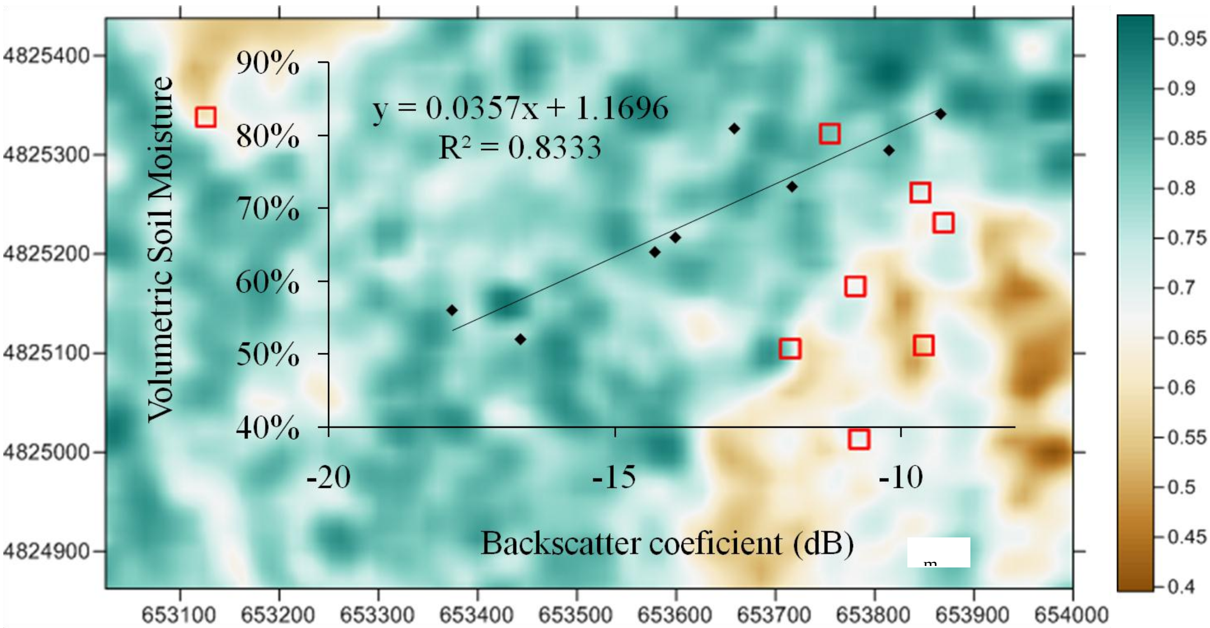

Fig. 2. The estimation map for moisture content in a large area of Goshikigahara created using the linear model which uses the correlation between the microwave backscattering coefficient (dB) and the surveyed VSM data (at measurement points shown as mark (□)). 0.4 (40%)-0.95 (95) in the legend is the soil moisture content.

The microwave satellite data used is high-resolution mode polarization data obtained from ALOS/PALSAR. Data for June 19, July 6, August 4, August 14, September 19 and October 6, 2010 was all obtained at an off-nadir angle of 34.3°, an incidence angle of 38.6° with an ascending orbit direction. For the data for August 4 and 21, the observation mode was FBS (HH: horizontal transmit, horizontal receive) single-polarization with a pixel size of 6.3 meters. For all the other data, the observation mode was FBD mode (HH/HV: HV means horizontal transmit, vertical receive) dual polarization with a pixel size of 12.5 meters. Fig. 2 shows the soil moisture distribution map created using the linear model (formula 2) which uses the correlation between the microwave backscattering coefficient (calculated using formula 1) and the surveyed VSM data. The soil moisture content in many areas around Goshikigahara is between 65% and 80%. The moisture content in areas with steep slopes on the southeast side of the subject area is relatively low. Bamboo grass has expanded into this area. A high correlation was observed ($R^2 = 0.833$) for the areas where soil moisture content was surveyed (measurement points shown as □ in Fig. 2). In order to calculate the seasonal fluctuations in the moisture content of soil over wide areas where VSM was not surveyed, the study developed a new estimation model (see formula 3) which takes into consideration the fact that the fluctuations in the moisture content of the soil is greater than the seasonal changes of bamboo grass and *Pinus pumila*, regarding the impact on backscattering coefficients. Normally, the L-band microwave from PALSAR tends to penetrate herbaceous plants due to its long wavelength (the wavelength: 23.6 cm, the center frequency: 1,270 MHz) (Hoshino et al., 2009). However, in the areas where the vegetation is very dense, bamboo grass and *Pinus pumila* presents roughness which interferes with the microwave backscattering. The influence of the roughness of bamboo grass and the *Pinus pumila* canopies cannot be ignored because ALOS/PARSAR takes photographs with an incidence angle of 38.6°. With the assumption that the degree of growth of bamboo grass and *Pinus pumila* over one month is not large enough to influence backscattered light, the influence of the roughness height of bamboo grass and *Pinus pumila* was successfully removed using subtraction in formula 3.

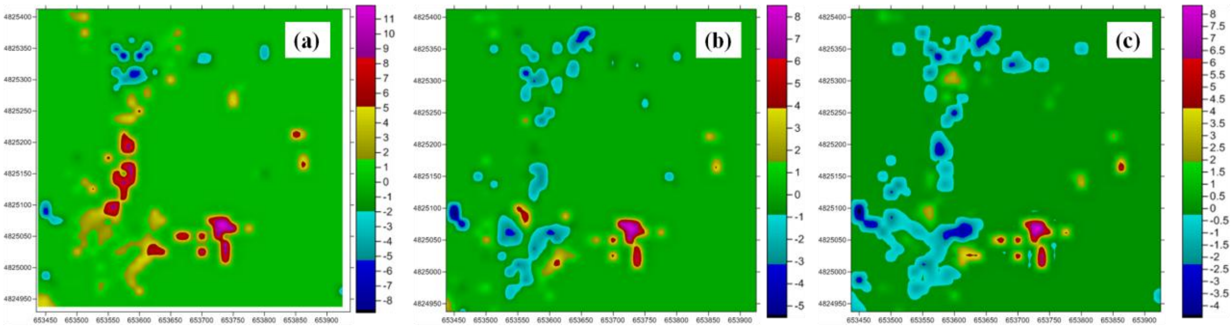

Fig. 3. Differences in backscattering coefficients ($\Delta\sigma^0_{dB}$) of dwarf bamboo distribution area in the Goshikigahara area on Taisetsu Mountains (Where, (a) shows the difference backscattering coefficients ($\Delta\sigma^0_{dB}$) between July 6 and June 19, 2010; (b) shows the difference backscattering coefficients ($\Delta\sigma^0_{dB}$) between August 21 and August 4, 2010; and (c) shows the difference backscattering coefficients ($\Delta\sigma^0_{dB}$) between October 6 and September 19, 2010).

Fig. 3 (a)-(c) show the seasonal changes in backscattering coefficients in the Goshikigahara area calculated using formula 3. Were produced by masking the areas where bamboo grass was found. The positive values indicate an increase in soil moisture, the negative values indicate a decrease in soil moisture, and the values close to zero indicate that the changes were small. It was confirmed that soil moisture decreased in areas where bamboo grass grew densely in mid-June to early July and that soil moisture increased in many areas as the snow melted. However, from early to late August and from September to October, soil moisture clearly decreased (dehydration) in areas under dense bamboo grass over wide areas. There was an exception: soil moisture increased at the edges of bamboo grass expansion areas. It was confirmed that soil moisture was relatively constant from August to October in areas where alpine plants cover a wide area, but the areas showed slight dehydration.

5. CONCLUSION

Estimation of soil moisture in high dense vegetated area is very difficult, because, the microwave backscatter effected by the roughness surface height. Based on the accurate scattering model, both the soil moisture and surface roughness can be retrieved from the polarimetric backscatter measurements with a good accuracy for bare-soil surfaces. This study succeeded in distinguishing different types of vegetation, sampling changing vegetation areas and quantifying tree line changes in mountainous areas which have steep terrain and diverse vegetation structures, using time-series high-resolution aerial photographs from 1977 and 2009. Through re-digitizing and normalizing the old data, complete overlay analysis became possible using the old data and new aerial photographs, which enabled the quantification of long-term changes in vegetation. This method provides an important means of studying changes to forest land in mountainous regions and studying the dynamic state of alpine vegetation through quantification. In addition, satellite microwave backscattering (which is not affected by weather conditions) was used to develop a model for estimating soil moisture in a large area under dense vegetation, which uses differences in microwave backscattering coefficients while taking into consideration the phenology. In the model, the influence of roughness height was successfully removed. This achievement presents significant progress for academic research into estimating soil moisture using microwave backscattering coefficients, as well as for research into mountain areas in general. It is expected that the study results will have practical uses in agriculture, forestry, etc. The study contributed to clarifying changes and the interaction between *Pinus pumila*, bamboo grass and alpine plants in the Taisetsu Mountains area. It succeeded in identifying areas whose vegetation changed from bamboo grass to *Pinus pumila*, from *Pinus pumila* to bamboo grass, from alpine plants to bamboo grass and *Pinus pumila*, as well as quantifying the changes. Discussions about the impact of climate change on alpine ecosystems have mainly focused on rising tree lines. However, in Japan's alpine belts, it was quantitatively shown that the expansion of *Pinus pumila* and bamboo grass is an extremely important factor in addition to changes in tree lines. Based on the study results, it will be possible to create risk maps which forecast the future expansion of *Pinus pumila* and bamboo grass, therefore it is expected that they will be useful for measures to protect vegetation and biodiversity.

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