Multi-sensor Remote Sensing of Forest Dynamics in Central Siberia

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Popular Summary

The forested regions of Siberia, Russia are vast and contain about a quarter of the world's forests that have not experienced harvesting. However, many Siberian forests are facing twin pressures of rapidly changing climate and increasing timber harvest activity. Monitoring the dynamics and mapping the structural parameters of the forest is important for understanding the causes and consequences of changes observed in these areas. Because of the inaccessibility and large extent of this forest, remote sensing data can play an important role for observing forest state and change.

In Central Siberia, multi-sensor remote sensing data have been used to monitor forest disturbances and to map above-ground biomass from the Sayan Mountains in the south to the taiga-tundra boundaries in the north. Radar images from the Shuttle Imaging Radar-C (SIR-C)/XSAR mission were used for forest biomass estimation in the Sayan Mountains. Radar images from the Japanese Earth Resources Satellite -1 (JERS-1), European Remote Sensing satellite-1 (ERS-1) and Canada's RADARSAT-1, and data from ETM+ on-board Landsat-7 were used to characterize forest disturbances from logging, fire, and insect damage in two regions of

central Siberia (Boguchany and Priangar'e areas). The results and recommendations are presented.

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Abstract

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Priangar’e areas.

1. **INTRODUCTION**

In Central Siberia (Fig. 16.1), a vast area between the Yenisey and the Lena Rivers, the character of taiga changes dramatically. The Central Siberian plateau and Sakha-Yakutia are distinguished by their extreme continental and arid climates. The mean January temperature decreases from -17°C in Krasnoyarsk (56°10'N; 93°00'E) to -43°C in Yakutsk (62°10'N; 129°50'E) while the annual precipitation total decreases from 410 mm to 200 mm. The Siberian anticyclone dominates the area throughout winter and, with little winter precipitation (34 mm and 21 mm, respectively); the depth of snow cover is small. A severe climate and continuous permafrost predispose the development of forests composed by cold-resistant species (mainly *Larix gmelinii)* and poor floristic diversity. (www.rusnature.info).

<Fig. 16.1>

It is known that about 70% of the permafrost areas in Siberia are occupied by larch dominated forests, with the remaining 30% composed of tundra. The maximal depth of permafrost is about 30-100 m in north-western Siberia and 500-1500 m in the northern parts of central and eastern Siberia. Depth of thaw in the summer is typically 5 cm to >1.0 m.

Larch dominated forests are an important component of the global circumpolar boreal forest. In Russia, larch is the most widespread species and is found from the tundra zone in the north to the steppes in the south. The zone of larch dominance extends from the Yenisei ridge in the west to the Pacific Ocean and from Lake Baikal in the south to the 73rd parallel in the north, where it forms world’s most northern forested stand, and is called Ary-Mas. In Central Siberia, the southern and western margins of the larch forest come in contact with evergreen conifers (Siberian pine, *Pinus sibirica*, pine, *Pinus silvestris*, spruce, *Picea obovata*, fir, *Abies sibirica*), hardwoods (birch, *Betula pendula*, *B. pubescens*, and aspen, *Populus tremula*). Larch forms high closure stands as well as open forests, and can be found primarily growing over permafrost, in locations where other tree species barely survive. Wildfires are typical for this territory, and they most commonly occur as ground fires due to low crown closure. Due to the surface root system (caused by permafrost) and dense lichen-moss cover, ground fires are primarily stand-replacing fires. The vast area of larch forests, including the forest-tundra ecotone, is generally considered a “carbon sink". However positive long-term temperature trends at higher latitudes result in an increase in fire frequency and an increase of greenhouse gas emissions, and may convert this area to a source for greenhouse gases.

Litter decomposition in the larch communities is reduced by low summer temperatures resulting in increased litter thickness. The thick litter layer, together with moss and lichens, becomes a thermal insulator that promotes permafrost formation at an increasing depth in the soil. In addition, during low-precipitation years, the ground cover layer dries and becomes a fire fuel source. This facilitates the spread of fires over tens to hundreds of kilometers. The burning fires emit greenhouse gases, which in turn can increase temperature and decrease the permafrost depth. The fire return intervals (FRI) within the interior of larch forests were found to be about 82±7 years, and increased to 300 years in the northern extreme of the larch forest. (Kharuk et el, 2008). There is evidence of decreasing FRI (fire frequency increase) in the 20th century compared with the 19th century caused by both natural (air warming) [jch1]and anthropogenic impacts.

Taiga forest in Central Siberia can be divided in northern, middle and southern subzones. Both the northern and middle subzones are dominated by larch forests (*Larix gmelinii* and *Larix sibirica*), while the southern subzone is dominated by Scotch pine (*Pinus sylvestris)* stands.

In the northern subzone of Central Siberia, forest-tundra and open forests reach their largest latitudinal extent. Relatively high (about 13°C) summer temperatures on the lee side of the Putorana plateau, which shelters the region from the northerly winds, allow forests to penetrate further north than anywhere in the world. On the Taymyr peninsula, woodlands (known as 'forest islands' or 'Ary Mas') formed by *Larix gmelinii* extend to the world's northernmost location at 72°30'N in the valley of the river Novaya, the Khatanga's tributary.

The tundra-taiga transition area is dynamic because it is very sensitive to human activity and climate change. During the last 6000 years in northern Eurasia, there has been a general cooling trend of about 2-4^{o} C, and larch and birch stands have retreated between 400 and 500 km southward during this period (Callaghan et al., 2002). Temperatures have warmed by as much as 2^{o} C in the past three decades in parts of the Northern Hemisphere (Hansen et al 1999). Reports on modern changes of the tundra-taiga boundary associated with climate warming are rare (e.g. Kharuk et al, 2004, 2007-2010, Sturm et al. 2001), but observations within the northern most forest stand showed regeneration advance into tundra and stand densification (Kharuk et al, 2004, 2006).

The northward movement of tundra-taiga boundary may be the eventual outcome if climatic warming persists over centuries or millennia (Skre et al. 2002). The situation, however, is complicated by human activities that have led to ecosystem degradation in this area. In some Russian case studies, southward displacement of the taiga-tundra boundary was reported due to human disturbance and increasing waterlogging, which led to paludification and the death of treeline trees (Skre et al., 2002; Vlassova, 2002). Local variations in climate and human activities require continued monitoring and research.

In the middle taiga, forests composed of *Larix sibirica* prevail in the relatively warmer and moister western areas, with some dark taiga species (spruce, Siberian Pine and fir). East of the

Yenisey, much of the taiga is represented by monospecies larch stands with the presence of Siberian pine and spruce along the rivers. Because of the severity of the environment and the remoteness of the area, these forests remain virtually untouched by humans. In the drier eastern part with low seasonal permafrost thawing, *Larix gmelinii* dominates with the sporadic appearance of *Pinus sylvestris*.

For the middle taiga it was shown that "dark needle" coniferous forest (DNC), made up of Siberian pine, spruce and fir, are expanding into the habitat of larch. The age structure of the regeneration (with mortality control) showed that it was 20 to 30 years old. The results obtained indicate climate-driven migration of Siberian pine, spruce and fir into traditional larch habitat. On the western and southern margins of the larch-dominated forest, DNC regeneration formed a second layer in the forest canopies, which could eventually replace the larch in the over story. With stand densification Siberian pine received an additional advantage since larch is a shadow intolerant species (Kharuk et al, 2007).

In the southern taiga, vegetation is more varied because of the higher diversity of climatic and soil conditions. Forests are composed of *Pinus sylvestris* in the west, *Larix gmelinii* in the east and the dark taiga (i.e., fir, spruce and Scotch pine) along the high watersheds which have cool summers and ample precipitation. The Sayan Mountains are a system of deeply eroded ridges. These mountains have an average elevation of 1000-2000 m, but the highest summits, Munku-Sardyk and Mongun-Taiga reached 3,492 and 3976 m, respectively. Permafrost occupies about 50 per cent of the total area of the western Sayan and almost the whole of the eastern Sayan except for its westernmost part. Vertical zonality is well expressed in the distribution of soils and vegetation in the Sayans. Although topographic and climatic variability create differing vertical sequences, all are dominated by taiga vegetation. In the Western Sayan Mountains, there is a considerable difference between the altitudinal sequences of the northern and southern macroslopes. The most prominent feature of the northern Western-Sayan sequence is the large extent of the dark taiga belt. This is composed mainly of Siberian Pine (*Pinus sibirica)* and fir (*Abies sibirica)* with an admixture of *Larix sibirica* in the upper regions. Spruce (*Picea obovata)* is another important dark taiga tree species, especially in river valleys. The lower part of the forest belt has been substantially modified by human activity. In disturbed areas taiga has been replaced by secondary birch-aspen forests and patches of pristine taiga survive only locally. The high mountainous zone is represented by floristically rich subalpine and alpine meadows and mountainous tundra communities. The southern macroslope of the Western Sayan receives more insolation and is much drier. This sequence begins with the steppe (which is intensively cultivated at present) developing on chernozem and in drier regions on southern chernozem and chestnut soils. The steppe zone is succeeded by a narrow belt of birch-aspen forest-steppe. The forest belt is composed mainly of *Larix sibirica* forests with well-developed undergrowth and the herbaceous cover enriched by steppe species. The dark taiga is confined to higher elevations of this belt and reaches highest elevations on south facing slopes. Taiga, the largest biome in Northern Eurasia, accounts for a quarter of the world's pristine forests (Dirk et al. 1997). It has been affected by development, in particular by the production of timber and oil. Although the annual industrial production of timber has declined since the 1980s, many areas experience problems with respect to illegal cutting of forests, fragmentation of mature stands, and unacceptable forest-harvesting practices. Global climate and land use changes have multiple effects on forests worldwide. However, the multi-scaled interactions among climate change, disturbance regimes, and land use change make it difficult to predict key ecosystem characteristics except by coarse, generalized estimates. Many Siberian forests are facing the twin pressures of rapidly changing climate and increasing timber harvest activity. Mean temperatures have risen significantly over the past 40 years, and this trend is expected to continue. The frontier of timber harvest is pushing into previously uncut areas.

Mean temperatures have risen significantly over the past 40 years, and this trend is expected to continue. There are reports showing that Siberian pine and larch growing in the alpine forest-tundra ecotone are strongly responding to warming by an increase of growth increments, stand densification and regeneration density, upward tree line shift, and transformation of krummholz to arboreal forms. Climate-induced waves of upslope and downslope tree migration were reported for the alpine forest-tundra ecotone in the southern Siberian Mountains. Observations show that tree mortality was observed during the Little Ice Age, but lagged behind the initial cooling. Living tree natality dates showed that treeline advance began at the end of the 19th century, but lagged behind the warming temperatures. Larch and Siberian pine regeneration now survive at elevations up to 160 m higher in comparison with the maximum observed treeline recession during the Little Ice Age and surpasses the historical maximum during the last millennium by up to 90 m. A 1°C change promoted an upward shift in the treeline of about 80 m. The treeline advance rate was estimated at 0.90 +/–0.22 m yr^{-1} (Kharuk et al, 2010a). Presently, at high elevation seedlings are still in the vulnerable stage and could be killed by cold winters consisting of low temperatures and strong winds, and this could result in the recession of the treeline.

Studies within Altai-Sayan Mountain sites showed an increase of the dense forest stands of about 1.5 times during the last four decades. An increase of tree growth increment starting in the mid 1980’s was observed, which was strongly correlated with mean summer temperatures. Stand densification was also observed along rivers and streams due to earlier snowmelt which increases the growing period. Substantial densification in tree line populations seems to be a common phenomenon in northern and high-elevation environments and occurs more frequently than actual elevational tree line advance (Kharuk et al, 2008). Forest response to climate variables at high elevations is non-uniform because tree establishment and survival depends on the availability of sheltered (wind protected) areas. The forest spatial distribution is dependent on azimuth, elevation, and slope steepness and this pattern changed over the last decades. A typical upper boundary is a mosaic because tree and regeneration survival depends on the availability of sheltered relief which is provided by rocks or local depressions (Kharuk et al, 2010c).

Milder climate also promotes changes in tree morphology, i.e., transformation of mat and prostrate krummholz into vertical form (Kharuk et al., 2006, 2010a). The last decades of warming caused a wide-spread transformation of larch and Siberian pine mat and krummholz to a vertical form beginning in the 1980s. This date approximately coincides to the period when winter temperatures surpassed the mean value during the 20th century. Larch is much less likely than Siberian pine to be found in krummholz forms. This species surpasses Siberian pine in frost and wind resistance and was observed in arboreal forms where Siberian pine was still prostrate.
In a warming climate, Siberian pine should enjoy a competitive advantage due to its higher temperature response. Stand densification is also beneficial for Siberian pine since larch is a shade intolerant species. Thus, current climate change should lead to an increase the proportion of Siberian pine in the upper canopy. Substitution of “light-needle” deciduous larch by evergreen conifers, decreases albedo and provides positive feedback for even greater warming. The other expected consequence is an increase of biodiversity since Siberian pine dominated communities provide a better food base for the animals and birds. Larch will continue to maintain its advantage

in drier areas and in zones of temperature extremes.

The Siberian forests are the habitat of many insect species. Periodic outbreaks of certain insect pests cause a decrease in growth increment, forest decline or mortality over vast areas. The Siberian silkmoth (*Dendrolimus superans sibiricus,* Tschetw) feeds heavily on needles of certain tree species, defoliating and killing large stands rapidly. This is one of the primary factors of taiga succession. The preferred pest host species are fir and Siberian pine but spruce and larch are also sometimes affected. Outbreaks are encouraged by favorable weather conditions: low summer precipitation, relatively mild winters with stable, dense snow cover and lack of late spring and early autumn frosts. On the contrary, cold, rainy summers and severe low-snow winters are not favorable for the Siberian silkmoth. Outbreaks have a periodicity, occurring about every 15–25 years. Between 1878 and 2004 ten Siberian silkmoth outbreaks were observed in the Yenisey River watershed area. The largest outbreak (1954–1957) resulted in tree damage over about 4 million ha and tree mortality on about 1.5 million ha (Kharuk et al, 2003, 2004). The last catastrophic outbreak occurred in the Priangar'e area and caused about 10.0 million ha damaged and 300 thousands killed stands between1993 and 1995. Outbreaks of insect pests promotes wildfires, because pest-killed stands accumulate combustible material in form of dead wood, grass and bush communities.

Global change is likely to significantly change forest composition of south-central Siberian landscapes, with some changes taking ecosystems outside the historic range of variability. Direct climate effects generally increased tree productivity and modified probability of establishment, but indirect effects on the fire regime generally counteracted the direct effects of climate on forest composition. Harvest and insects significantly changed forest composition, reduced living aboveground biomass, and increased forest fragmentation. Gustafson et al. (2010) studied the relative effects of climate change, timber harvesting, and insect outbreaks on forest composition, biomass (carbon), and landscape pattern in south-central Siberia and found global change is likely to significantly change forest composition of south-central Siberian landscapes, with some changes taking ecosystems outside the historic range of variability. Remote sensing provides a useful tool for monitoring forest disturbances and estimation of forest parameters in Central Siberia, because the area is broad and hard to reach. Twenty years ago two authors of this chapter, Dr. Ranson and Dr. Kharuk committed to collaborate to study the remote forests of Siberia. Since then, with Sukachev Institute of Forests and NASA's support we have been conducting research on forest mapping, disturbance characterization and parameter retrieval using multi-sensor data in Central Siberia. For example, in the Western Sayan Mountain, radar data was used to map forest aboveground biomass (Sun, Ranson, and Kharuk, 2002). In the middle subzone of Central Siberia, around Boguchany and Priangerʼe, multi-sensor data including LANDSAT ETM+ data, radar data from the Japanese Earth Resources Satellite (JERS-1), European Remote Sensing satellite (ERS-1) and Canada's RADARSAT-1, were used to detect fire scars, logging and insect damage in the boreal forest (Ranson et al., 2003). From July 10 to 25, 2008, a team of American and Russian scientists conducted an expedition to study an extremely remote and harsh section of northernmost central Siberia. The expedition started from a flat spot near the headwaters of the Kotuykan River, above the Arctic Circle, and the team, using three inflatable rubber boats packed with survival gear and scientific instruments, traveled the river, stopped frequently to make observations and collect data in support of several ongoing studies. Data from the field, collected by Geoscience Laser Altimeter System (GLAS), Phased Array type L-band Synthetic Aperture Radar (PALSAR) and LANDSAT MSS, TM and ETM+ were used for monitoring changes of forest cover, and estimation of above-ground biomass. The following sections will describe these studies in detail.

2. Forest Biomass Estimation from SAR data in The Western Sayan Mountains

2.1. INTRODUCTION

Methods and algorithms have been developed for mapping above ground biomass in the boreal forest (Saatchi and Moghaddam, 2000; Kurvonen et al., 1999; Paloscia, et al., 1999; Bergen et al., 1998; Ranson and Sun, 1997a; Dobson et al., 1995; Ranson et al., 1995; Saatchi et al., 1995; Rignot, et al., 1994; Beaudoin, et al., 1994; Le Toan et al., 1992; Dobson et al., 1992). These studies concentrated on relatively flat areas, where terrain effects were not significant. Estimation of forest biomass using synthetic aperture radar (SAR) data can be complicated by topography that influences radar backscatter (Luckman, 1998; van Zyl, 1993; Bayer et al., 1991; Rauste, 1990), particularly through local incidence angle and shadowing. Changes in radar incidence angle caused by terrain slope can have several effects on radar image data. For example, radar backscattering varies with incidence angle, which varies with terrain slope and aspect. Foreshortening is also a terrain-induced effect where a smaller incidence angle results in more ground surface area being illuminated. Another effect of terrain on the backscatter is the apparent change of the forest spatial structure in the radar field of view. For example, when trees of a relatively uniform stand grow on a slope, a portion of the sides of these trees will be directly exposed to the radar beam.

Terrain correction techniques are designed to reduce effects of incidence angle and illuminated target area. For correction of the illuminated pixel area, simple algorithms can be used if a suitable digital elevation model (DEM) exists (Kellndorfer et al. 1998). Correction of the backscattering dependence on incidence angle requires knowledge of the land cover type within a pixel. A few attempts have been made to correct terrain effects by using simple radar backscattering models and a DEM. For example, Goering et al. (1995) used a DEM and empirical radar backscatter models to reduce terrain effects from ERS-1 SAR images. However, Goyal et al., (1998) found that the small-scale topographic features resolved by SAR couldn't be resolved by a DEM in rugged terrain. Periodic artifacts due to the terrain model generation methodology were observed in the derived variables (e.g., slopes). Other methods, such as image ratios were used to reduce the effects of radar incidence angle caused by topography (Ranson et al., 1995; Shi and Dozier, 1997; Wever and Bodechtel 1998, Ranson et al, 2000). Wever and Bodechtel (1998) proposed the use of L-band hv (Lhv) and X-band VV (Xvv) ratio or difference images for radiometric rectification.

A method was developed to correct for the backscatter dependence on terrain using an algorithm derived from simulated radar backscattering of a forest stand on various slopes. The derived dependence of the L band hh (Lhh) and Lhv backscattering on radar local incidence angle was used to remove the terrain effect from the Lhv data. Finally, a biomass map was produced from the corrected Lhv data.

2.2. STUDY AREA and DATA

The study area, in the Western Sayan Mountains covers a 50 x 25 km area with center coordinates of 53^{o} 4.2' N latitude and 93^{o} 14.3' E longitude (Fig. 16.1). The area is the site of the Ermakovsky Permanent Study Area established in 1959 and used for research by the Sukachev Institute of the Siberian Branch of the Russian Academy of Sciences.

The Western Sayan Mountains are a complex of ridges dissected by a widespread drainage network. Topographically, the territory is very heterogeneous and therefore climatic conditions and ecosystems are very diverse. The elevation varies from 2400 m above sea level to 1300–1500 m in the basins. The slopes are covered by dark needle coniferous forest with a predominance of

Siberian pine (*Pinus sibirica* Du Tour) and fir (*Abies sibirica* Ledeb.); spruce (*Picea obovata* Ledeb.) is an admixture within the drainage network. In a southward direction, with the decrease in precipitation, larch (*Larix sibirica* Ledeb.) appeared within canopy (mostly on the south-facing slopes). Within the study site, forest types are arranged in elevational belts including pine-birch forest-steppe (up to 250–300 m), a narrow belt of light coniferous and mixed stands (up to 400–450 m) and dark needle coniferous stands (up to 1600–1700 m) which gradually transform into a sub-alpine belt of meadows and sparse fir-Siberian pine stands (1600–1800 m). At higher elevations, there are very sparse stands mixed with mountain tundra, bushes, alpine meadows and stony areas. The mean annual, summer and winter temperatures are -3°C, +12°C, and -16°C, respectively. Precipitation totaled about 1200 mm/yr which mainly falls May-September.

<Fig. 16.2>

A Russian forest inventory map (1:50,000) compiled from aerial photographs and site visits between 1993 and 1995 was used as ground truth information (Fig. 16.2). The map is typical of forest inventory maps with forest units related to economic value of the stands. Total 56 biomass plots ranging from 1.16 to 24.0 Kg/m^2 were prepared from field measurements and forests inventory data. The field plots were sorted according to biomass values. Even numbered plots were used for developing biomass estimation model and the odd numbered plots were used for validation.

Shuttle Imaging Radar-C (SIR-C) data were used in this study. The SIR-C/X-SAR missions were flown during April 9-19, 1994 and September 30-October 10, 1994 (Stofan et al., 1995). The instrument had quad-polarized (hh, hv, vv, vh) L-band (wavelength =23 cm) and C-band (5.6 cm) and a vv polarized X-band (3 cm) radar channels. The mission was a cooperative experiment between NASA's Jet Propulsion Laboratory (JPL), the German Space Agency, and the Italian Space Agency. The SIR-C image data used in this study were acquired on April 16, 1994 with an image center incidence angle of 46.4^o. The original image is single look complex (SLC) data with line spacing (azimuth) of 5.8 m and pixel spacing (slant range) of 13.3 m. The images were processed with 6 looks in azimuth and 2 looks in range direction resulting in images with a pixel size of ~35 m.

Since previous work (Ranson et al., 1995; Dobson et al., 1995; Ranson and Sun, 1997b) had shown that Lhv data is especially sensitive to forest above ground biomass, only L band data were used in this study. Figure 16.3A is the Lhv image of the study area. In the image, the Sayan Mountains can be seen on the left side of the image. Forested mountains appear bright or dark depending on the slope and aspect with respect to the radar illuminating direction (from right of this image). Some deforested areas can be seen in the center of the image. A broad level plain to the right has large wetland areas such as the dark object in the lower right corner and bare agricultural fields. The village of Ermakovsky and the Sukachev Institute of Forest field camp are located at the upper right in this image.

<Fig. 16.3>

2.3. METHODS

2.3.1. Terrain Effects Correction Using a Digital elevation Model

Slope and aspect were be generated from elevations and used to calculate the local incidence angle for a pixel of the radar image:

$$\cos(\vartheta) = \sin(s)\cos(\alpha)\sin(s+\varphi) + \cos(\vartheta_0)\sin(\alpha) \qquad (16.1)$$

where θ is the local incidence angle, s is local slope, θ_0 is radar incidence angle at the center of the image, φ is aspect of the slope, and α is azimuth angle of the radar look direction.

Radiometric distortion due to the illumination areas was corrected using the local incidence angle with an equation of the form used by Kellndorfer et al. (1998).

$$\sigma^0_{corr} = \sigma^0 \sin(\vartheta)/\sin(\vartheta_0) \qquad (16.2)$$

where: σ^o_{corr} is radar backscatter coefficient after correction, σ^o is original backscatter coefficient.

Kellndorfer et al (1998) found that this correction was adequate for land cover classification purpose. However, for estimation of biomass from radar backscattering, the effect of terrain on scattering mechanisms needs to be considered. The radar backscattering is a function of incidence angle even in flat area. With a fixed radar looking direction, terrain changes the local illumination direction (both zenith and azimuth, see Fig. 16.4) of radar beam interactions with the forest canopy. Radar backscattering models may be used to model the dependence of backscattering on local radar incidence angle if the detailed knowledge of the forest types and their structure information are known.

<Fig. 16.4>

2.3.2. Modeling Radar Backscatter Of Forest Stands On Slopes

The three-dimensional radar backscatter model (Sun and Ranson, 1995) was modified for this study to include the effect of slopes on backscatter. The modified model accepts a stem map (with location, diameter breast height (dbh), height, species and crown shape for each tree), an elevation map (height for each surface pixel), and a soil surface roughness and dielectric constant map as inputs to simulate high-resolution polarimetric radar images of the forest stand. The scattering components are also available from the modeling outputs. Detailed measurements of the forest structure were not available for the Western Sayan Mountain study area. A 100X100 m stem map of conifer stand was made during the Boreal Ecosystem-Atmosphere (BOREAS) Study (Sellers et al., 1997) in 1994. The measurements included the stem locations and diameter at breast height (dbh) for every tree in the stand. This stand is a typical boreal conifer forest with above ground dry biomass of about 10 Kg/m^2. In addition to the stem map, total height, crown length and crown width were measured. The relationships between these parameters and dbh were developed from the field measurements. These relationships were then used to infer tree crown characteristics for each tree from its dbh. When a slope was introduced, the horizontal position of a tree was not changed, but the tree was vertically moved depending on its position within the stand. Tree crowns were modeled as cones. The backscattering from the ground surface was calculated using the IEM (integral equation model) model (Fung, 1994). The parameters for the simulation are listed in Table 16.1.

High-resolution radar images of the stand on various slopes and azimuth directions were simulated. The radar backscattering coefficients were obtained by averaging the simulated images. Three slopes (10^o, 20^o and 30^o) and eight azimuth directions (45^o increment from 0 to 360^o) for each slope were simulated. Local incidence angle was calculated for each case.

Since Lhh backscatter is more sensitive to slope (because of greater canopy penetration and seeing more ground), it was used to estimate the local incidence angle (θ) from the LHH image. Then it was used to correct the Lhv image. To do so, a simple analytical relationship between backscattering coefficients and incidence angle needed to be established for both hh and hv polarizations.

The simple backscattering models for vegetation-like media take the form of (Ulaby et al., 1982):

$$\sigma^0 (\theta) = \sigma_0 \cos^p \theta \qquad (16.3)$$

where θ is the local incidence angle. Both σ_0 and p are polarization dependent. When p=1, the model means that the scattering coefficient (scattering per unit surface area) is dependent on cos θ, which is the ratio of projected area (normal to the incoming rays) to the surface area. When *p*=2, the model is based on the Lambert's law for optics. Ulaby et al. (1982) pointed out that although either *p*=1 or 2 seldom closely approximate the real scattering, sometimes *p*=1 or 2, or a value between 1 and 2 may be used to represent scattering from vegetation. The model simulation results were fit to this simple model to estimate σ_0 and p for both L-band hh and hv polarizations.

2.3.3. Biomass Estimation

The biomass parameters of 56 stands were defined from forest inventory tables based on age and site index. These tables and methods are in operational use for Russian forest inventory and management. Positions of these stands were located on corrected Lhv radar images and the backscattering signatures were extracted. These stands were sorted according to biomass and selected alternately for either model development or testing. Regression relationships were developed between the cube root of total biomass and the averaged radar signature similarly to the method described by Ranson and Sun (1997a). The derived equation was used to convert the Lhv images to biomass maps.

2.4. RESULTS

2.4.1. Terrain Correction with a DEM

In this study, we first corrected the dependence of illuminated pixel area within the SIR-C image on incidence angle using the DEM available from NIMA. We found that the spatial resolution and accuracy of this DEM was not suitable for terrain-effect correction of SIR-C imagery. Figure 16.3B is the Lhv image that was corrected using the local incidence angle derived from the DEM. While the correction for large slopes appears to be appropriate, the smaller slopes have not been corrected due to the lower resolution of the DEM data than that of the SIR-C image.

Consequently, the method of using backscatter modeling to account for terrain effects on backscatter was used.

2.4.2. Modeling of the Terrain Effect

Figure 16.5 shows simulated radar images of the stand on a 20^o slope with four different azimuth directions. The one on the upperleft represents a stand on a 20^o slope facing the radar. The radar looks from left to right. The image on upperright represents the same scene, but the surface is facing to the right and away from radar. Trees are still growing vertically, so the images of the tree crowns did not change, but crowns project longer shadows upon the ground surface. The backscattering from the ground (a rough surface) decreases when the slope faces away from the radar (resulting in a larger local incidence angle effect).

<Fig. 16.5>

The pixel size of these images in Figure 16.5 is 0.5m by 0.5m. The radar incidence angle used was 46.4^o (illumination from left) the same as the SIR-C image used for the modeling. The observed change of the backscattering coefficient (the brightness of the images) with changing slope was caused by three major factors. First, is the change of the illuminated area per pixel. This is easily seen in Fig. 16.5 as the increase in the number of range pixels (resulting in less area illuminated by a pixel) of the scenes. The second major factor is the change in tree shadowing. There are more shadows cast by trees visible in the images for slopes facing away from the radar. The third major factor is change in contribution of surface backscattering because of local incidence angle.

<Fig. 16.6>

The simulated dependence of radar backscatter on local incidence angle shown in Figure 16.6 were used to correct terrain effects. The best fits of the simulated data yield the following two equations of the form suggested by Ulaby et al. (1982):

$$\sigma^0_{hh}(\theta) = 0.361 * \cos^{1.78}\theta \quad r^2 = 0.93 \qquad (16.4)$$

$$\sigma^0_{hv}(\theta) = 0.203 * \cos^{1.50}\theta \quad r^2 = 0.95 \qquad (16.5)$$

Ideally, equations of this form should be developed for different kind of land cover types, which will be part of our future modeling efforts. For this study, we used the pair of equations to make the terrain correction of the L-band hv (Lhv) image. Here, we assume that Equation 16.4 is applicable to the SIR-C Lhh image.

2.4.3. **Terrain Correction from Modeling**

For each pixel, Equation 16.4 was used to estimate cosθ from the Lhh image data:

$$\cos\theta = (\sigma^0_{hh}(\theta) / 0.361)^{1/1.78} \qquad (16.6)$$

If the actual SAR data is different than the simulated data and gives a different value for σ^0_i other than the 0.361, the resulting cosθ will be:

$$\cos\theta = (\sigma^0_{hh}(\theta) / \sigma^0_i)^{1/1.78} = (\sigma^0_{hh}(\theta) / 0.361)^{1/1.78} a \qquad (16.7)$$

Where $a = (0.361 / \sigma^0_i)^{1/1.78}$ and accounts for the difference between σ_0's from the simulation (0.361) and radar image (σ^0_i).

The purpose of the terrain correction is to bring the Lhv backscattering coefficients at incidence angle θ to a reference incidence angle θ_0. Using Equation (16.5) for both θ and θ_0, and taking ratio of the two result in the following Equation:

$$\sigma^0_{hv}(\theta_0) = \sigma^0_{hv}(\theta)(\cos\theta_0 / \cos\theta)^{1.50} \qquad (16.8)$$

The reference incidence angle θ_0 can be any value, but the natural choice will be the SIR-C radar incidence angel at the image center (46.4^o). It can be seen that the uncertainty of cosθ caused by the factor *a* (Eq. 16.7) only causes a relative scaling to the corrected Lhv image (Eq. 16.8).

The corrected Lhv image using this method (Fig. 16.7A) shows that the terrain pattern was removed (compared with Figure 16.3A, uncorrected data and Figure 16.3B corrected with the DEM). The low biomass areas, such as clear cuts, top of high mountains, and bare valleys are still identifiable. A threshold limit for Lhv backscattering was set in the correction, so the pixels with Lhv backscattering lower than this limit (shadowing, water surface, or other very low backscattering targets) will not be 'corrected'.

<Fig. 16.7>

2.4.4. Biomass Estimation

The equation developed from corrected LHV data is:

$$B^{1/3} = 8.45 + 0.67\,\sigma^{o}, \quad r^2 = 0.78, N=28 \qquad (16.9)$$

Figure 16.7B is the biomass map developed from corrected data. Biomass differences shown are mostly related to logging, disturbance or natural vegetation communities, such as wetlands. The biomass map has a continuous level of biomass ranging from 0 to $\geq$25kg/m^2. This upper value range was specified since a small number of points in the image exceeded the maximum biomass levels in the training and testing data.

The comparison between field biomass test data and predicted biomass developed from the terrain corrected LHV data is shown in Figure 16.8. The accuracy for the independent set of validation points, given as the root mean square error, was acceptable at 1.81 kg/m^2. The r^2 of 0.91 was also very good, but the predicted values did not follow a one-to-one relationship with the field measurements. Statistical tests performed on the regression coefficients showed that the slope (0.77) was significantly different from 1.00 and the intercept (1.84) was significantly different from 0.00. Consequently, the prediction model over-estimated areas with low biomass levels and under estimated areas with higher biomass levels.

<Fig. 16.8>

2.5. CONCLUSIONS

The effect of terrain on SAR backscatter and subsequent biomass estimation was discussed. We have demonstrated a model-based method for terrain-effect correction of SAR images without using a DEM. However, this method requires multiple polarization SAR data. It seems that if general information on forest structure is available, this method could be used in other areas.

The terrain slope changes the local radar incidence angle, as well as the forest structure perceived by the radar. The dependence of radar backscattering on the slope and aspect (azimuth of the slope) is very complex. Regardless of the methods to be used for terrain effect correction (using DEM or not), certain assumptions have to be made about the nature of the backscatter. The 3D radar model used in this study provides a tool to simulate complex structure of the forest stand in mountainous areas. If land cover information is available, this method can be applied to reduce the terrain effect for different cover type using different equations. If a very good DEM is available, the 3D model can be used to simulate radar backscattering dependence on terrain, and then it can be used to correct single polarization SAR data.

In this work we based our correction on the model results from a biomass stand of 10 kg/m^2, which resulted in better estimates of midrange biomass values. Methods to improve the biomass estimates over the full range by simulation of low and high biomass cases need to be explored.

3. DISTURBANCE DETECTION USING RADAR AND LANDSAT

3.1. Introduction

Disturbance is an important factor in determining the carbon balance and succession of forests. Fires and resulting scars can be detected using measured changes in temperature during the fire and the vegetation changes immediately after the burn (Kasischke et al. 1993, Martin 1993). Michalek et al. 2000 also reported on the utility of TM data for assessing stand density and fire severity in Alaska. Woodcock et al. 2001, showed that Landsat 7 could be used over large areas to detect change, especially logging in the western United States. Defoliation of forest stands results in changes in reflectance and can also be used to detect insect damage in forests. Early work by Dottavio and Williams (1983) and Nelson (1983) demonstrated the utility of Landsat data for gypsy moth and spruce budworm damage in US forests. Landsat has also been studied to provide information on other insect outbreaks (Royle and Lathrop 1997, and Radeloff et al. 1999). A number of papers in the Russian literature describe successful use of airborne and satellite systems to monitor insect outbreaks (e.g., Peretyagin et al. 1986, Kharuk, et al. 1989, 2003, 2004, 2009a).

A problem with optical systems for northern forest studies was a lack of available data caused by cloud cover and low solar illumination in winter. The launch of the synthetic aperture radar (SAR) systems: European Resource Satellite (ERS) -1 and 2, Japanese Earth Resources Satellite and Canada’s Radarsat provided the availability of data in all weather conditions. Kasischke et al. (1992) found ERS data could be used to detect fire scars in the boreal forest because the fire scars were 3-6 decibels (dB) brighter than the rest of the landscape. This brightness is a result of physical changes that occur due to fire including increased surface roughness, removal of tree canopies, and alteration of soil moisture patterns (Bourgeau-Chavez et al., 1993). While optical and thermal sensors are sensitive to the initial changes in temperature and vegetative cover, SAR is sensitive to the longer-term roughness and moisture patterns that occur post-fire.

Landsat has provided long term, high-resolution optical data (30 m). The high-resolution data available from orbiting SARs also provides a closer look at disturbance patterns. While large area frequent coverage may not be practical, the detailed reflectance and backscatter can provide information useful for identifying type and extent of disturbances on a local to regional scale. This information can then be used with the coarser resolution systems to identify disturbance over large remote areas such as Siberia. This section describes work towards understanding the use of remote sensing to detect important disturbance factors (fire scars and insect damage) in Siberia and explore the use of combined data from Landsat and SAR systems.

3.2. Study Sites

The study area is located in central Siberia within 88-92 degrees East longitude and 50 to 70 degrees North latitude (Figure 16.1). Within this larger site are Landsat image sized (~180 X180 km) intensive study sites identified by their predominant disturbance. The Boguchany wild fire test site was selected because of the presence of large fire scars and logged areas. The site is located at 97^o 25' E and 59^o 2' N, 75 km North of the Angara River and 350 km east of the Yenisey River in Eastern Siberia. The Priangar'e Insect site is located to the west of the Boguchany site 94° 30' E and 57° 30' N, and was plagued by a severe insect outbreak between 1992 and 1995.

The Boguchany test area, named after the nearby town, is located within an important region for timber logging in Siberia (Kharuk and Ranson 2000). The elevation of the study site ranges from 300 to 500 m. The growing season in the region is short, ranging from late May to early September. In the summer, smoke plumes from burning wild fires obscure the sky; fire is the principal factor that determines ecosystem dynamics in this region and therefore most of the stands are of pyrogenic origin (Kharuk and Ranson, 2000). Scotch pine (*Pinus silvestris*) and larch (*Larix siberica*) cover most of this landscape. However other conifers, such as Siberian pine (*Pinus siberica*), Spruces (*Picea obovata*) and fir (*Abies siberica*), can also be found in patches in the area. Deciduous stands such as birch (*Betula pendula*) and aspen (*Populus tremula*) cover the areas of lower elevation in this region. Several methods of logging are practiced in the area including the Finland technique (logging with seedlings preserved), and complete clearing where no vegetation is left on the site. These sites are covered with live grasses in the summer and covered with dry, dead grasses in the fall.

<Fig. 16.9>

The fires that caused the burn scars in this study were ignited by lightening and extinguished by rainfall. This study will focus on the two largest fire scars in the area (See Fig. 16.9). Fire scar 1 is the product of two fires that were detected on the July 16 and 19, 1996 and merged into one fire the 21st of the same month. One of the two fires is known to have started on a 1979 clear-cut in an area of regenerating pine, birch and aspen when a large volume of dead wood ignited. The fire was a strong surface and crown fire and by the time it was extinguished on August 8, 1996, 32 thousand hectares of forest, old clear cuts and dense regenerating stands were burned. The second fire contributing to fire scar 1 started in an approximately 100 year old pine-larch stand that also included some regenerating pine and larch trees. Fire scar 2 burned in an undisturbed coniferous forest 60 km northwest from fire scar 1 also in 1996. The fire scars were located using satellite imagery and verified by field surveys in the fall of 1999 conducted by scientists from the Sukachev Institute of Forests. Ground location was determined and survey plot measurements and digital on-ground photos were taken. IKONOS Carterra imagery was also available from the summer of 2001 for field checking.

<Fig. 16.10>

The insect damage study site, as shown on Figure 16.10, is within the Niznee Priangar'e region where a severe Siberian silkmoth (*Dendrolimus sibiricus)* outbreak occurred between 1993 and 1995 (Kharuk et al, 2003). The topography of the area consists of a plateau with low hills. Soils are mainly spodosols (podzols). Climate is continental with cold dry winters and warm moist summers. Annual precipitation is 400-450 mm. Mean annual temperature is +2.6˚C with an absolute minimum of -54˚ C recorded during December and maximum of +36˚ C recorded in July. Vegetative growth period is about 100 days. Forests cover 95% of area. The dominant species are fir (*Abies sibirica*); other species included by Siberian pine (*Pinus sibirica*) also known locally as Siberian cedar, Siberian spruce (*Picea obovata*), Scotch pine (*Pinus silvestris*), larch (*Larix sibirica*), aspen (*Populus tremula*), and birch (*Betula pendula*). Stands are of average productivity with a wood stocking density of 200-230 m^3/hectare and mean age of 135 years. Typical insect damage is characterized by complete defoliation and death of conifer stands, or death of only conifer trees within mixed stands.

3.3. Data and Preprocessing

Available JERS, ERS-1, Radarsat and Landsat-7 satellite data were analyzed to determine to what extent these sensors could detect the presence of fire scars, clear cuts and insect damage. Table 1 summarizes important parameters of the sensors used.

The JERS data were resampled to 25 m pixel size, reoriented, and filtered using a 3 by 3 Frost filter (Frost *et al.* 1982). The ERS-1 data were received from the Alaska SAR Facility (ASF). These data were then multilooked to 25 m pixel size, reoriented, converted to ground range, wrapped onto a longitude/latitude grid using corner coordinates and, filtered using a 3 by 3 Frost filter. The Radarsat standard beam data received from ASF were previously converted to ground range. The data then were ingested, resampled to 25 m pixel size, wrapped into a longitude/latitude grid using corner coordinates and filtered using a 3 by 3 Frost filter. The Landsat 7 scenes were ordered and received from the EOSDIS EROS Data Center Distributed Active Archive Center (DAAC). There was no radiometric terrain correction applied to the images because neither area had a steep topographic gradient (the elevation difference was less than 250 m). No additional atmospheric corrections were applied to the Landsat 7 data.

To attain greater geometric accuracy and to ensure that the data sets were co-registered with the highest possible accuracy, the JERS, ERS, and Radarsat data were registered to the Landsat 7 scene. Landsat 7 data were selected as geometric ground information for this site because these data have good geometric calibration. Ideally, orthorectification of radar images using a DEM should be performed before registration, but there was no high resolution DEM available. Instead we used a large number of control points to register the images. Because of the low terrain relief, the results seem satisfactory.

The SAR images were manually registered to the Landsat 7 scene. To accomplish this, points at the intersection of linear features were selected such as on roads, rivers, and clear cuts when applicable. In Boguchany, 103 points were used to register the ERS data, 74 to register JERS and 65 to register the Radarsat data. In Priangar'e 70 control points were used to register the JERS data and 90 to register the Radarsat data. The same procedure was used for both sites. After registration, images were subset to the area covered by each of the 4 sensors. Figures 16.9 and 16.10 show the SAR and Landsat 7 images used for the analysis.

3.4. Methods

3.4.1. Vegetation classes

The following land cover classes were identified for the two sites: *coniferous forest (CF), broadleaf deciduous forest (DF), regeneration/sparse forest (RS), bare surfaces (BS) and clear cut (CC)*. For the Boguchany site the following disturbance classes were added: *burned coniferous forest (BC), burned deciduous forest (BD), and burned logged areas (BL)*. Additionally, two classes of insect damage were identified in the Priangar'e area: *severely damaged (SD)* with complete defoliation of a stand and *moderately damaged (MD*) with only conifer trees defoliated. Since the insect outbreak had occurred in 1996 and subsequently subsided the two classes represent severity of damage rather than stage of insect attack. Table 16.2 provides a list of classes and descriptions for the two study sites.

3.4.2. Training site selection

Field campaigns were conducted in the Boguchany area in the fall of 1999 and Priangar'e area in the summer of 2000. During this field campaigns, tree species were identified. GPS measurements were acquired and in Boguchany, plot measurements pertaining to the successional stages of the burned and logged areas were obtained. Fig. 16.11-A shows the burned area in Boguchany. A field visit to Priangar'e included aerial overflights to obtain photography of damaged areas (Fig. 16.11-B). Information gathered during these field campaigns along with the existing local ecological knowledge of the staff at the Sukachev Institute of Forest provided a good basis for determining and locating the different vegetation classes on the Landsat and radar images.

<Fig. 16.11>

The training sites for the classes mentioned above were determined based on the information gathered in the field, the multi-year and multi-season coverage provided by other Landsat scenes and the contextual information provided by the individual Landsat scenes. Once the training sites were so determined, histograms were examined for each class in each radar band. If the data was normally distributed, the class was left intact. If however the histogram showed a multimodal distribution, these training sites were displayed using the radar bands and training sites assigned to a more or less homogeneous subclass. Then the histograms for these subclasses were once again reviewed to make sure that the distribution of the values was normal. This way, the deciduous forest and bare ground classes was split into three subclasses on the Priangar’e site, and the burned-logged class was split into two subclasses on the Boguchany site. Approximately one-third of the training sites were set aside for testing the classification and two-thirds were used for training the classifier.

The clear cuts in both Boguchany and Priangar'e sites appear as rectangles with straight edges cut out of the forest cover in a checkerboard fashion revealing their man-made nature. The older clear cuts are clearly overgrown with deciduous trees, whereas the most recent ones have exposed bare soil. Because of the time difference between JERS and Landsat 7 data, only those logged sites were included in the clear cut class that were at least three years old and had grasses and seedlings growing on them. Based on *a priori* work, it was determined that the older, now tree covered clear cuts could not be separated from the natural deciduous forest cover. The fire scars in the Boguchany area are spatially quite distinct from the clear cuts. The fire scars have lobe-like edges that are at times discrete and at other times more transitional.

It is worth noting that if an unburned area is spectrally, structurally and texturally heterogeneous, it is likely that the fire scar visible in the landscape after burning will also be spectrally, structurally and texturally heterogeneous. This is to say that fire scars are not monolithic features at a 30 m resolution. The patterns observable within a fire scar provide valuable information of the history of the site. When anthropogenic disturbance (such a logging) has occurred in the area prior to the burn, the burned area will be a patchwork of spectral, structural and textural features shaped by a combination of anthropogenic and natural disturbance factors. This texture information was used to identify these sites but was not explicitly included in the classification.

On the Priangar'e site the logged areas do not appear in juxtaposition with the insect damage.

In this case the anthropogenic (logging) and natural disturbances (insect infestation) are spatially separate. Insect damage appears on the landscape as patchy “thinned out” forested areas since insect only damaged the needles of the coniferous trees and left the leaves of other trees intact. The degree of the damage they caused partly depends on the species composition of the stands: if a stand was composed of coniferous species (food species), the stand was severely damaged. If the stand consisted of a mix of food and non-food species, then the damage was more moderate. It is important to mention that severely and moderately damaged classes are not thematically distinct. Instead they are two, somewhat arbitrarily defined overlapping areas on a thematic continuum between completely healthy and completely damaged forest stands.

Training sites for each class were chosen, keeping in mind that the radar data available was acquired over a period of three years. The changes that have occurred within the landscape during this period had to be eliminated or at least minimized within the training sets. For example some of the Boguchany training sites were eliminated from the training set because on a 1991 Landsat 5 images they appeared as coniferous forest, and by the time the 1999 Landsat 7 scene was taken, the site became a clear cut. Since there was no additional information available on this particular site, it could not be determined at what point between the two dates the site was logged and whether or not the date of its logging fell within the three year period the radar data was acquired.

3.4.3 Data Analysis

The purpose of this analysis was to determine whether or not and how each sensor was detecting each land cover class and whether or not the radar sensors were capable of separating the classes from one another based on backscatter information alone. Once the training sites were carefully selected and split into subclasses as described above, backscatter values were extracted from each class for each radar sensor, and descriptive statistics were generated. The analysis procedure consisted of two parts 1) Transformed Divergence (Richards and Jia, 1999) analysis and 2) maximum likelihood classification. Transformed Divergence (TDM) is a measure of separability between classes and may therefore be used to assess the quality of the class spectral mean vectors and covariance matrices. A high TDM (> 1.80) indicates good statistical separation of the classes and indicates how well each sensor or sensor combination detected each land cover class. Maximum likelihood classification provides the means to examine the separability of classes in a mapping or thematic sense. After classification, the subclasses were merged into their original parent class.

3.5. Results and Discussion

3.5.1. Radar Data Analysis

Burned Site

Figure 16.12a presents the average backscatter and standard deviations for each radar sensor for the 7 classes from the Boguchany fire scar study area. For JERS data the coniferous and deciduous forest classes, as well as the burned deciduous and coniferous forest classes have very similar backscattering coefficients. This is probably because at L band (0.23 m wavelength), larger tree branches and trunks are the primary scatterers. After surface and crown fires, many of the tree trunks still remained standing as seen on the images of the burned forest sites. This might explain why the returns are so bright for both unburned and burned forest types in the L band. It is also clear that the regeneration sparse, clear cut and burned logged areas classes all have lower backscattering coefficients, which is likely due to the absence of large branches and trunks. Classes with little or no tree cover (RS, CC and BL) also have similar backscatter and, as a group, have lower backscatter than the classes with standing trees.

<Fig. 16.12>

In Figure 16.12a it can also be seen that the unburned classes (CF, DF, RS, and CC) all have lower ERS-1 brightness values than the burned classes (BC, BD, RS). The post-fire regeneration class seems to have intermediate values. C band radar is scattered by structures in about 5 cm in size such as leaves and small twigs on trees or grasses. Field observations revealed that small structures such as leaves and twigs were no longer present on burned trees, however grasses having leaves of similar sizes are abundant on the fire scar during the summer months. Based on this, the burned and unburned vegetation should be difficult to distinguish. There must be some other factor such as soil moisture (Bourgeau-Chavez et al., 1993) influencing the CVV backscatter that causes the burned areas to be brighter than the unburned ones.

The plotted Radarsat backscatter shows very little difference between any of these classes (Figure 16.12a). Only the clear-cut class has backscatter values that are a bit lower than the others. These areas also appear dark on the radar image (Figure 16.12b). There is not an obvious explanation as to why burned and unburned classes are so clearly separable using CVV ERS data and why the CHH Radarsat backscatter for these same classes are so similar. Only one year passed between the acquisition of the two data sets, therefore land cover change is unlikely be the answer. There is an 11^{o} difference in incidence angle between the two sensors, (ERS = 23^{o}, Radarsat = 34^{o}), but it is not well understood exactly how incidence angle influences radar backscatter from burned areas. Soil moisture could have changed over the one-year period and it is also possible that at a larger incidence angle, the differences in soil moisture between burned and unburned areas are less pronounced.

The separability of classes using the radar data was quantitatively examined with the use of the Transformed Divergence Measure (TDM). For JERS data, high TDM values exist between logged classes (CC and BL) and unburned and burned conifer (CF, BC, respectively) and unburned and burned deciduous stands (DF, BD, respectively). In this case, unburned forest stands are not separable from burned forest stands. High TDMs also exist between RS and BD classes. This indicates that forested classes and classes lacking tree cover are easily separable from each other using JERS data regardless of their burned state. ERS and Radarsat TDM values were generally lower than those for JERS. The exceptions were for ERS data which had much higher separability values for burned forest (BC and BD) and unburned forest (CF and DF). From these results it is clear that any single radar sensor used alone cannot be used to discriminate between burned and unburned forest classes, between deciduous and coniferous forest classes, and between unburned and burned non-forested classes. However, JERS data can be used to discriminate between forest and non-forest classes regardless of burning, and between post-logging regeneration and forest classes also regardless of burning.

ERS data appears most useful for discriminating between burned forest areas and unburned forest, regeneration and clearings. Other class pairs with relatively high TDMs include RS and BC (1.49), and BD (1.73). This indicates that post-cutting regeneration is easily separable from the burned forest classes. However, the separability between the RS and the unburned forest classes (CF and DF) is very poor ($\leq$ 0.20). Low TDMs were found between CF and DF classes indicating that CVV data cannot be used to distinguish between coniferous and deciduous forest classes. TDM values were also minimal between CF and CC.

From these data it is clear that the CVV band alone cannot be used to discriminate between coniferous and deciduous stands, clear cuts and forest classes, and between clear cuts and post fire regeneration classes. However, ERS data can be used to discriminate between the burned and unburned land cover classes, regardless of other characteristics of the site, and between post cutting regeneration classes and burned forest classes. JERS data at the L-band seems to detect larger structural differences between forest types that are caused by logging (i.e. removal of large trunks). At the same time ERS C-band data seem to detect soil moisture differences and perhaps structural and moisture differences at a leaf level associated with burning. This indicates that the combination of the two sensors should provide improved results in discriminating logged and burned areas. The maximum separability from the Radarsat data is 0.72 and occurs between the CF and the CC classes. This value is quite low and indicates that the Radarsat data alone is not suitable for distinguishing any of these classes from each other.

For the TDM values generated based on the three sensor data combined, the average separability increased to 1.55. Although this is an increase from using each sensor alone (JERS average separability: 1.23, ERS: 0.64, and Radarsat: 0.16), on the whole, combining the three sensors does not provide very good distinction between these eight classes since TDM values under 1.8 are considered poor. Combining the radars provided the greatest increases in useful separability ($\geq$ 1.80) over individual radars between burned classes (BC, BD, BL) and regenerating forest (RS). Overall, forest (CF, DF) could be separated from disturbance classes (RS, CC, and BL), but not from burned forest (BC, BD). Burned forest could be separated from regeneration and clear cut. The common theme among class pairs is that classes can be separated successfully that have different structural characteristics determined by the presence or absence of large trunks and branches, such as forest and non-forest classes. This is mostly due to the LHH band JERS data, since these class pairs had reasonably high TDM values (around 1.7) using JERS data alone. ERS contributes the most in separating burned forest from other classes; however, TDMs never reached 1.80 for any class pair.

Table 16.3 lists the maximum likelihood classification results of the combined radar data for the Boguchany site. Only the burned logged class (BL) was identified with accuracy greater than

80%. Forest classes were confused with each other as were burned forest classes. Regeneration and clear cut classes were mostly confused with each other. These classification results indicate that using this combination of radars might provide useful classification of forest classes (CF + DF), logging (CC + RS), burned forest (BD + BD) and burned logged areas (BL). The overall classification accuracy for all classes was about 66%.

Insect Damage Site

Figure 16.12b presents the average backscatter and standard deviations for the insect damaged site. Neither JERS nor Radarsat backscatter differs much across the forested sites (CF, DF, IS, IM). JERS backscatter decreases slightly for clear cuts and drops off for the bare surface class and water. Radarsat does not show this decrease in backscatter except for the water class. Apparently CC and BS surfaces are sufficiently rough to the C-band radar beam to maintain backscatter levels similar to forested sites.

Two trends in the radar separability values for the Priangar'e site are obvious that both JERS and Radarsat can distinguish water from the land cover classes very successfully, including the bare surface sub classes. JERS and, for the most part, Radarsat are also successful at distinguishing bare surfaces from the vegetated classes (1.92-2.00). Radarsat has low TDM values between bare surfaces and clear cuts and fails to separate the BA-2 class from all the vegetated classes. For JERS, TDM values are very low between coniferous forest (CF) and insect damage classes (IS, IM) and the deciduous forest subclasses and the moderate insect damage class. This might be because the insects only damage the leaves of the trees and the L band radar does not detect leaves, only major branches and trunks. Radarsat values are low for these classes, but higher than JERS for separating conifer forest from disturbance classes (IS, IM and CC).

Radarsat separability of the forests classes was poor ($\leq$ 1.31), as was separability of damaged forest classes from each other and with undamaged conifer forest ($\leq$ 0.97). The TDM values between deciduous subclasses and both damaged classes were also extremely low ($\leq$ 0.28). However the separability between coniferous forest and clear cuts was higher (1.77). This may be because there is volume scattering occurring within the tree canopies while volume scattering back to the radar is absent from the grassy clear cuts.

With the combined use of the two radars the distinction between the clear cuts and coniferous forest (TDM=1.96) and clear cuts and severe insect damage (1.86) increased. There was no large increase in the separabilities between the other classes. In addition, there was good separability of conifer forest and the deciduous subclass (DF3). Low TDMs were found for CF and the other two deciduous subclasses suggesting a possible mixture of conifer and deciduous trees or forest density differences among these deciduous classes. Overall, the combination of JERS and Radarsat may be useful for separating clear cuts from other forest types, but is not useful for separating insect damaged stands from undisturbed forest.

The results of classification of the training sites using the JERS and Radarsat backscatter show 61% correct classification of conifer forest and 77% correct classification of the deciduous forest (combined subclasses). Reasonable classification results (> 80%) were obtained for clear cuts and bare areas and water (Table 16.4). Only 29% of the severely insect damaged, and 46% of the moderately damaged classes were classified correctly. Misclassifications were primarily with deciduous forest (51% and 41% respectively) indicating the combination of JERS and Radarsat is not useful for recognizing this disturbance.

3.5.2. Landsat and Combined SAR

Burned Site

Mean spectral reflectance digital numbers (DN) from burned area training sites are shown in Figure 16.13a. Only Bands 3 (0.63-0.69μm), 4 (0.76-0.90μm) and 5 (1.55-1.75 μm) are shown for illustration. Because of the post-senescence timing of the acquisition deciduous trees are bare and ground vegetation is dead reducing near-infrared (NIR) reflectance. Conifer forest has higher NIR response than burned conifer forest. Deciduous forest and burned deciduous forest exhibit a similar trend but with higher responses. Clear cuts have unique spectral characteristics in this fall image with overall higher responses, especially in the SWIR (band 5).

The TDMs from Landsat ETM+ data are greater than 1.80 for all classes except between burned forest classes (BC and BD) and between burned logged (BL-1 and BL-2) and clear cut (CC) classes. Regeneration (RS) and BL-1 TDM was slightly less than 1.80. Even though this Landsat 7 image was acquired in 1999, three years after the burn, many dead, burned trees still remained standing on the burned forested sites casting their shadows on the regenerating vegetation forest floor. This is why there is good distinction between the live and burned forest classes. One exception to this good separation between live and burned vegetation classes are the clear cut (CC) and the burned logged (BL) classes (TDM ≤ 1.45). The burned logged sites were logged prior to the burn in 1996. When the burn occurred, there were no trees standing on these sites, only grasses and seedlings. Since there were no mature trees on the site, there were no burned trunks left standing either, therefore no trunks could cast their shadows on the regenerating grasses and seedlings after the burn and lower the site's reflectance in the NIR. This is why three years after the fire the burned logged site seems spectrally similar to a clear cut class and the regenerating/sparse class.

<Fig. 16.13>

Using the Landsat spectral statistics to classify the Boguchany burned area produced generally good accuracy. As shown in Table 16.5 conifer and deciduous forest classes, regeneration and the two burned forest classes had classification accuracies greater than 89%. Clear cut and burned logged areas were confused with each other resulting in lower classification accuracies of 83% and 84%, respectively. Overall accuracy was 90% and Kappa coefficient was 0.88 indicating Landsat reflective bands should perform well in discriminating the burned area classes.

Combining the three radars and Landsat data increased the TDM values for those classes that the optical and microwave sensors alone could not distinguish well. The largest increase occurred in the case of the burned logged and burned deciduous class where TDM increased from 1.35 to 1.97 when the spectral and structural information was combined. However, there was only a minor increase in the TDM values between the clear cut and burned logged subclassess since in this case both classes were both spectrally (regenerating grasses and seedlings) and structurally (lack of trunks) similar.

In summary, L band radar data provided structural information of the vegetation such as the presence of absence of large trunks and C band radar data seems to provide information on soil moisture conditions while Landsat data provides spectral information on the vegetation cover such as whether or not the vegetation is reflective in the NIR. This synergistic interaction between the optical and microwave sensor is key to distinguishing disturbed sites from non-disturbed ones since they might look extremely similar using one or the other type of data alone.

Classification with combined data sets of Landsat, JERS, ERS and Radarsat resulted in classification accuracies above 90% for all classes (tables not shown for brevity). The overall classification accuracy was nearly 94% with a Kappa coefficient of 0.93. The classes with the most improvement were the burned logged class (BL) from 84% to 93% and the CC class from 83% to 90%. The reduction of confusion between these two classes resulted in the higher classification accuracies. The added information on surface roughness condition available with the radar likely contributed here.

Insect Damage Site

Figure 16.13b shows that NIR reflectance are high for broad leaf trees and ground vegetation for the midsummer acquisition of the insect damaged area. The shorter wavelength reflectance (bands 1, 2 and 3, *vis* 3) did not vary much across the classes with vegetation in them. NIR and SWIR reflectance (Bands 4, 5 and 7, *vis* 4 and 5) however, are quite different and appear suited for discriminating forest classes from disturbed classes. Notice the overlapping spectral responses for the three deciduous subclasses. This is also apparent for the bare surface subclasses except for TM band 4, suggesting a sparse vegetation cover on BA1 (more than on BA1 and BA2, but less than the clear cut (CC).

The widely varying spectral reflectance shown indicate that Landsat data can be used very successfully to distinguish among water, bare ground, clear cuts and all of the vegetation classes. Very high TDM values were observed between all class combinations from Landsat data indicating good separation of the forest classes and disturbances. Even TDM values between severe and moderate insect damaged classes were high (1.83). The only low TDM values were found among subclasses of deciduous or among bare surface subclasses.

TDM results obtained after combining JERS, Radarsat and Landsat 7 for the insect disturbance area shown that there was only modest improvement in TDM adding the radar data with the Landsat over the Landsat alone for most of the classes. However, combining the radar data with the Landsat data increased the separability between the severe and the moderately severe insect damaged classes from 1.83 to 1.93. Of interest is the increase in separability between DF-1 and DF-3 deciduous forest subclasses. Recall that the subclasses were selected from training sets originally selected from Landsat data, but yielded multimodal histograms with radar backscatter. DF-3 then is spectrally similar to DF-2 in the Landsat bands but apparently structurally dissimilar as inferred from the JERS backscatter. Based on this, DF-3 is likely a deciduous conifer or larch (*Larix sibirica*).

The classification results with Landsat 7 data were excellent as shown in Table 16.6. Every class had at least 95% classification accuracy. Overall accuracy was 98.6% with a Kappa coefficient of 0.98. Adding the additional radar channels (results table not shown) offered only slight improvement in class accuracy with an overall 99% correct and kappa coefficient of 0.99.

3.6. Conclusions

This study was designed to examine the utility of using different radar systems and Landsat 7 for identifying forest landscape classes, especially those related to disturbance. We found that the results were limited when using each single channel radar alone, however JERS and ERS were found to be useful for identifying certain classes. JERS was most useful for separating forest from disturbed classes with no standing trees. ERS was more useful for separating forest classes from disturbed classes where trees are left standing. Radarsat, on the other hand, was the least effective individual radar for this study. Combining the radars improved the identification of classes over results obtained with any single radar. Generally, if one radar sensor was found to have high separability for a pair of classes, adding additional radars did not greatly increase the separability. If all radars had low separability, combining the radars had very little benefit. In both sites the low separabilities found between CF and DF and burned forest and insect damaged forest classes indicates that classes that have both large trunks and leaves present on them are not possible to separate using even combined radar sensor data.

Regarding the detection of disturbance, the available data was acquired over a two-year period therefore careful comparison of radars for burn scar detection was not possible. Changes in surface soil moisture can greatly change the backscatter from burn scars as shown and verified by other researchers (e.g. Kasischke et al., 2011). Landsat 7 data proved the most useful of any single remote sensing system for recognizing forest type and discriminating between disturbance types. Even with non-growing season images, as was the case for the fire damaged site, the results were very promising. Combining the Landsat data with the available radar data improved the separability of classes and the overall classifications. The results also indicate that the combination of radar and Landsat 7 may be especially useful for recognizing other forest types by utilizing the structural information of radar and spectral information of Landsat 7. As radar and Landsat 7 data becomes more widely available combining these data sets should improve the accuracy of forest mapping activities. However, there is extra effort and cost involved in registering different image types.

This work underscores the importance of using multichannel SAR data for forest studies. When combined with optical data the SAR appears to offer potential for improving classification. The future multichannel systems may contribute greatly to improved results in forest analysis and disturbance mapping.

4. Characterization of forest-tundra in the North of Central Siberia

4.1. Introduction

Northern Siberia is a climatic hot spot—an area that is warming faster than the rest of the planet. In the past 30 years, average temperatures across the region have risen 1-3°C, while the worldwide average increase in that time is about 0.6 °C. The region remains fiercely cold. The average winter time low in Khatanga, a small village in Northern Siberia, is -37 degrees C and can drop to -59 ° C. Yet the warming trend is so rapid here that scientists are curious to watch the effects on the land. Scientists from all over the world are now looking at Siberia.

Starting July 10, 2008, authors Ranson and Kharuk led a team of American and Russian scientists (Fig. 16.14) to study an extremely remote and harsh section of northernmost central Siberia. A Russian MI 8 helicopter flew the team from Khatanga above the Arctic Circle, and landed at a flat spot (70^{o}41’34”N, 105^{o}38’46”E) near the headwaters of the Kotuykan River and the team made a rapid exit from the helicopter (Fig. 16.15) into the rain. In the following two weeks, the team used three rubber boats to travel the river, stopping frequently to make observations and collected data in support of several ongoing studies.

<Figs. 16.14, 16.15>

4.2. Study Region and Data

The study area is located around 70^o 20’-71^{o}15’N, 102^{o}40’-105^{o}50’E (Fig. 16.16). The river flowing from south to north in the western part of the area is the Kotuy and it flows northward into the Kheta River, and then flows north into Arctic Ocean. Fig. 16.17 shows the lower reach of the Kotuy River as seen from the helicopter (the upper-left corner of Fig. 16.16). In the middle of the Fig. 16.16 it is the Kotuykan River. The white triangle near the lower right of the image was the landing place of the Russian MI 8 helicopter. Fig. 16.18 shows a scene where the Kotuykan River joins with the Kotuy River. The mountains, the Siberian Traps, were formed from basaltic lava flows during massive eruptions about 250 million years ago. The freeze/thaw cycle cracks and crumbles the rocks. The weather and the river have eroded the mountains into spectacular formations and sheer drop-offs.

<Fig. 16.16>

<Figs. 16.17-20>

From the bank across from the camp site (Fig. 16.19), there are larch trees growing along the river, these are gradually replaced by tundra and bare rocks as elevation increases. In the background are the flat-topped mountains known as the Siberian Traps. The slope in the foreground is littered with basaltic rocks formed from lava flows about 250 million years ago. Fig. 16.20 is a picture taken on the top of a trap at one side of the river looking across to the one on the opposite river bank. At the top of these traps, few trees can survive.

The harsh climate of Siberia is a challenging one for larch trees. The photo (Fig. 16.21) shows the fates of several trees. A tree without bark or branches leans across the center of the photo. This tree died centuries ago, but the frigid and arid climate has kept it from decaying. In the foreground, a tree that broke at the trunk and toppled managed to survive when a side branch grew into a vigorous new tree. In front and to the right of the “reborn” tree is a small dead tree that still has branches and bark. It is an ancient tree that died recently. In its last years, it put energy into making seed. Pinecones from the previous two years still cling to its branches. Forest ecologist and author titled the photo (Fig. 16.22) as Siberia’s “bones and flesh.” The “bones” are the skeletons of fossil trees that died prior to the extremely frigid climate of the Little Ice Age, during the 14^{th} to 18^{th} centuries. Although they died hundreds of years ago, the frigid climate has prevented them from decaying. The “flesh” is the new trees that are colonizing the area as the climate warms. These trees are growing far above the “fossil” tree line, which is evidence that the current warming trend is very strong. These data on the ages of both old and new trees— will be used in future analysis to create a timeline of climate change in this part of Siberia.

<Figs. 16.21-22>

Landsat data (MSS, TM and ETM+) from 1973 to 2009 were acquired for this study. These images were used for classification and comparisons of vegetation status. Japan’s Phased-Array L-Band Synthetic Aperture Radar (PALSAR) on the Advanced Land Observing Satellite (ALOS)

(Shimoda et al., 2009), data acquired in 2007 by JAXA's ALOS mission was used for showing the vegetation cover and information related to above-ground biomass. The lidar waveform data acquired by Geoscience Laser Altimeter System (GLAS) on board NASA's ICESat satellite were used to predict biomass.

Table 16.7 lists the PALSAR and Landsat data acquired for this study. Landsat data (MSS, TM and ETM+) were acquired in 1973, 2002 and 2009 and these images were used for classification and comparisons of the vegetation status. Dual-pol PALSAR data acquired in 2008 by JAXA's ALOS mission (http://www.eorc.jaxa.jp/ALOS/en/obs/palsar_strat.htm) were acquired to study the vegetation cover and information related to above-ground biomass. The lidar waveform data acquired by the Geoscience Laser Altimeter System (GLAS) on board NASA's ICESat satellite were used to predict biomass from waveform data. Though it is not ideal from a vegetation measurement standpoint, GLAS data have been used for forest studies (e.g., Lefsky et al. 2005; Harding and Carabajal 2005; Ranson et al. 2007; Sun et al. 2008, Boudreau et al. 2008). GLAS systematically samples the forest vertical structure and provides top canopy height in addition to the surface elevation. GLAS illuminates/measures an area on the ground ~65m in diameter, though the footprint size and degree of circularity changed significantly over the course of the mission (Abshire et al. 2005). Sequential GLAS footprints are spaced 172 m apart (Schutz et al. 2005). GLAS waveform data (GLA01), land products (GLA14), and associated documentation are available through the National Snow and Ice Data Center (NSIDC) website (http://nsidc.org/data/icesat/data.html).

4.3. **Data Processing**

4.3.1. PALSAR Data Processing

The L-band dual-polarization (HH/HV) ALOS PALSAR data in Level 1.1 were converted from digital number to sigma0 using the revised calibration coefficients (Shimada, et al., 2009). The Repeat Orbit Interferometry Package (ROI_PAC) version 3.0 released on Oct. 4th, 2007 was used to geo-locate the SAR data. After the image data were imported into ENVI, these images were geographically mosaicked. Figure 16.23 shows the mosaic of PALSAR L-band HV data for the region. A ration of HV to HH was also generated.

<Fig. 16.23>

4.3.2 Landsat Image Processing and Classification

A dark-object subtraction technique was used to correct for varying atmospheric conditions for each sub-scene; subsequently, Landsat digital number (DN) was converted to top of atmosphere (TOA) radiance in W/(m^2 sr μm) and then to surface reflectance. The DN to reflectance conversion is important because DN is an inappropriate index of change over time given differences in sensor calibration, solar zenith angle, and sensor viewing angle, among others (Slater, 1980). The Normalized Difference Vegetation Index (NDVI) has been in use for many years to measure and monitor plant growth (vigor), vegetation cover, and biomass production from multispectral satellite data (Tucker, 1979). NDVI were calculated from Landsat data acquired in 1973, 2002 and 2009.

The Landsat data acquired on July 23, 2009 were classified using the unsupervised method (isodata) of ENVI package. The clusters were then combined into 7 classes based on field observations.

4.3.3. GLAS Data Processing

The GLAS data used in this study were the level-1 product GLA01 (waveform) and level-2 product GLA14 (Land/Canopy Elevation). Among the elevations reported in the GLA14 products are the heights of up to 6 Gaussian peaks fit sequentially to a given waveform. The last, i.e., lowest fitted Gaussian peak included in GLA14 data is assumed to be the ground peak. The difference between signal beginning and this peak will be the top or maximum canopy height. From the waveform data many additional variables were generated (Sun, et al., 2008) that captured characteristics of the canopy structure. The indices derived from GLAS waveform and used in the study include the total extent of waveform (wlen) and top canopy height (h14) from GLA14 data; the ratio of waveform energies returned from canopy to ground (eratio), the heights of four energy quartiles (rh25, rh50, rh75, rh100) and additional eight heights (rh10, rh20, rh30, rh40, rh60, rh70, rh80, rh90) where 10% - 90% of total waveform energy were cumulated above ground surface, calculated from waveform.

4.3.4. Field timber volume data

The Equations use to estimate stem volume of larch trees was:

V=0.00001*H*(3.24*D^2+6.601*D+3.361) (16.10)

where D is the diameter at breast height (DBH) in cm. H is the height of the tree (m), and V is the volume of the tree (m^3). This equation is based on the data at Lucunskoe of the Ary-Mas Reserve ($72^0$34’) (Bondarev, 1989).

During the two-week field campaign, one hundred GLAS footprints were sampled. The stem volume was calculated for all of these footprints using the above equation. It was found that the rh50 of some footprints was less than zero, which was probably caused by noisy signal. Also a few footprints had rh50 greater than 15 m, which was problematic because the highest tree we measured in the field was less than 15 m. After excluding these abnormal points, a total of fifty-three points were left for development of a prediction model using the step-wise regression in S-plus.

4.4. Results and Discussions

4.4.1. Landsat Data Classification and NDVI comparisons

Fig. 16.24 is the classification from Landsat-5 TM data acquired on July 23, 2009. These classes are: water (blue), larch forests with three levels of densities (bright green, green, dark green), grass tundra (yellow), wet tundra (maroon) and bare surface (pink). Dense larch forests are growing in the south or along the valley.

Fig. 16.25 is a false color composite using NDVI of July 23, 2009, June 26, 2002 and July 23, 1973 as Red, Green and Blue. It can be seen that in the area of know larch forests, the NDVI was stable across imaging period so the composite color is white or light gray. The red color in the grass-covered areas indicates that NDVI on July 23, 2009 was higher than on other dates.

<Figs. 16.24-25>

4.4.2. Timber Volume Assessment

The regression model was created by step-wise regression in S-plus. The procedure picked nine indices (h14, rh10, rh20, rh25, rh30, rh40, rh70, rh80 and rh100). The relation between field stem volume and GLAS predicted volume is (Fig. 16.26):

$$Y = .26 + 0.75 * X \qquad (16.11)$$

With a R^2 of 0.75, residual standard error of 4.89 m^3, F-statistic is 159 and p-value is zero.

Fig. 16.27 shows GLAS orbits for the data acquired in one data-take period. The background image is composed of 3 channels of PALSAR L-HH (red), L-HV (green) and the ratio of HV to HH (blue). The GLAS data of L3F (May-June, 2006) and L3G (Oct-Nov, 2006) were used in this study. The stem volume prediction model was applied to the footprints with the rh50 between zero and 15 m. Then the footprints falling in the larch forests were compiled, and the mean stem volumes were calculated. The mean stem volume was 17.88 m^3/ha (standard deviation 11.10 m^3/ha) derived from L3F data (n=185), and 21.61 m^3/ha (standard deviation 13.47 m^3/ha) from L3G data. Most GLAS footprints sampled in the field were from L3G data.

<Figs. 16.26-27>

4.5. Conclusion

Landsat multi-spectral data, PALSAR L-band SAR data and GLAS lidar waveform data along with the field sampling data were used to characterize the land cover and stem volume in the area along the Kotuykan River in the extreme north of the central Siberia. The analysis shows some capabilities of long term observations with Landsat and the capability of observing forest structure with lidar and forest cover type with SAR. The data sets used herein represent the state of the technology available to measure frontier lands. The US National Research Council advised NASA on the important measurements and technologies for answering pressing science questions. Among the several missions recommended is the Deformation, Ecosystem Structure and Dynamics of Ice or DESDynI. This mission will orbit a multi-beam lidar and a multi-polarization SAR on separate platforms to provide the best data ever for quantifying forest height and above ground biomass (Hall et al., 2011).

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Table 16.1. Parameters used in radar backscatter simulations.

Geometry									
	Radius			Length			Probability		
Needle	0.3 mm			2.7 cm			100%		
Branch	0.2 cm			15 cm			90%		
	0.8 cm			50 cm			8%		
	1.6 cm			150 cm			2%		
Orientation									
Needle	Vertical preferred ($p(\theta) = 4\sin^2\theta/\pi$, $\theta \in (0^o, 90^o)$ is the zenith angle of the long axis)								
Branch zenith angle	10^o	20^o	30^o	40^o	50^o	60^o	70^o	80^o	90^o
Probability	1.5%	2%	1.5%	3%	14%	25%	22%	14%	17%
Density									
Needle - $23000/m^3$ Branch - $120/m^3$									
Dielectric constants (real, imaginary)									
Needle	(18.03, 6.10)								
Branch	(15.38,5.29)								
Trunk	(6.68, 2.07)								
Soil surface	(10.0, 2.0) Roughness: Standard deviation of surface height σ=2.5 cm, Surface correlation length l = 18 cm								

Table 16.2. Radarsat and Landsat data used for Boguchany and Priangar’e Sites.

Site	Boguchany			Priangar’e	
Sensor	JERS	ERS-1	Radarsat ST4	JERS	Radarsat ST4
Frequency (GHz)	L band (1.275)	C band (5.3)	C band (5.3)	L band (1.275)	C band (5.3)
Wavelength (cm)	23.5	5.66	5.66	23.5	5.66
Polarization	HH	VV	HH	HH	HH
Inc. angle (deg)	38.9^o	23^o	34^o	38.9	34
Image Center	58.01^{o}N, 97.43^{o}E	59.49^{o}N, 97.55^{o}N	59.10^{o}N, 97.33^o E	57.27^o N, 94.16^o E	58.01^o N, 93.86^o E
Orbital Direction	Descending	Descending	Ascending	Descending	Ascending
Image Swath (km)	75	100	100	75	100
Altitude (km)	580	785	798	580	798
Data take date	31 March 1997	7 June 1998	21 Aug. 1999	19 May 1997	18 Aug20 00
Pixel size (m)	12.5	12.5	12.5	12.5	12.5

Site	Boguchany	Priangar’e
Sensor	Landsat 7	
Data Take Date	3 Oct.1999	22 July 2000
Image Center	58.71N, 96.81 E	57.31^o N, 94.36^o E
Path and Row	P141 R19	P140 R20
Resolution (m)	30	30
Sensor	ETM+	ETM+
Cloud cover (%)	0	9%
Bands	7 + pan	7 + pan

Table 16.3. Vegetation class and training set information. a) Boguchany Site, b) Priangar'e site

a).

Class	Training pixel #	Testing pixel #	Class name	Description
CF	4184	1723	coniferous forest	Predominantly needle leaf species including larch
DF	4544	1361	deciduous forest	Predominantly broadleaf leaf species
RS	3593	1797	Regeneration/sparse	Site logged over 10 years ago, mixture of pine and deciduous seedlings
CC	3371	1210	Clear cuts	Recently logged stands with low vegetation cover of grasses and forbs.
BC	3679	1810	burned coniferous	Burned needle leaf species including larch
BD	3754	1675	burned deciduous	Burned broadleaf leaf species
BL	7459	1889	burned logged	Burned logged stands

b).

Class	Train pixel #	Test pixel #	Class name	Description
CF	7934	3836	Coniferous forest	Predominantly needle leaf species including larch
DF	7119	2663	Deciduous forest	Predominantly broadleaf leaf species
IS	6774	4082	Severe insect damage	Defoliated stands, few live trees
IM	3373	1809	Moderate insect damage	Stand with defoliated and undamaged trees.
CC	6191	3864	Clear cut	Recently logged stands with low vegetation cover of grasses and forbs.
BS	3384	1154	Bare surface	Non-vegetated areas may include roads, bare soil, fresh clear cuts, rock outcropping, bogs
WR	975	467	Water	Taseyeva River, tributary of the Angara river

Table 16.4. Classification confusion table for Boguchany area classes and combined JERS. ERS, and Radarsat data. Average accuracy = 63.7, overall accuracy = 65.8%

Percent Classified As

Name	CF	DF	RS	CC	BC	BD	BL
CF	62.21	26.94	1.65	0.00	1.60	7.60	0.00
DF	46.96	45.69	2.29	0.00	0.11	4.78	0.18
RS	3.79	1.36	72.25	10.97	0.39	0.58	10.66
CC	0.09	0.18	19.25	52.65	0.00	0.00	27.82
BC	7.23	0.68	0.52	0.00	52.35	36.99	2.23
BD	3.76	2.53	0.03	0.00	17.05	76.27	0.37
BL	0.20	0.20	4.95	9.40	1.03	0.00	84.22

Table 16.5. Classification confusion table for Priangar’e area classes and JERS and Radarsat combined data. Average Accuracy = 62.48%, Overall accuracy = 70.71

Percent Classified As

Name	NULL	CF	DF	IS	IM	CC	BA	WR
CF	0.00	61.44	36.50	0.52	1.54	0.00	0.00	0.00
DF	0.00	4.77	77.42	4.09	8.51	5.21	0.00	0.00
IS	0.00	9.71	51.34	29.57	9.24	0.13	0.00	0.00
IM	0.00	0.80	40.76	10.91	46.13	1.39	0.00	0.00
CC	0.00	0.08	14.00	0.19	4.28	81.39	0.05	0.00
BA	0.09	0.00	0.00	0.00	0.00	0.89	99.03	0.00
WR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00

Table 16.6. Classification confusion table for Boguchany area classes and Landsat 7 data. Average accuracy = 91.10, overall accuracy = 90.55%

Percent Classified As

Name	CF	DF	RS	CC	BC	BD	BL
CF	98.35%	1.60%	0.05%	0.00%	0.00%	0.00%	0.00%
DF	1.01%	94.89%	2.68%	0.00%	0.04%	0.07%	1.30%
RS	0.22%	2.59%	92.32%	3.73%	0.00%	0.00%	1.14%
CC	0.00%	0.12%	2.17%	83.06%	0.00%	0.00%	14.65%
BC	0.03%	0.49%	0.16%	0.00%	95.90%	2.58%	0.85%
BD	0.00%	0.32%	0.43%	0.00%	3.30%	89.00%	6.95%
BL	0.00%	0.44%	0.87%	8.48%	1.56%	4.45%	84.21%

Table 16.7. Classification confusion table for Priangar'e area classes Landsat 7data. Average Accuracy = 98.18%, Overall accuracy = 98.14%

Percent Classified As

Name	CF	DF	IS	IM	CC	BA	WR
CF	99.04%	0.03%	0.53%	0.40%	0.00%	0.00%	0.00%
DF	0.01%	99.61%	0.00%	0.32%	0.06%	0.00%	0.00%
IS	0.52%	0.00%	96.22%	2.23%	0.01%	1.02%	0.00%
IM	0.06%	1.46%	1.87%	95.61%	0.03%	0.98%	0.00%
CC	0.00%	0.02%	0.00%	0.00%	98.34%	1.65%	0.00%
BA	0.00%	0.00%	0.03%	0.00%	1.45%	98.43%	0.00%
WR	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%

Table 16.8 PALSAR data used for the study

ALPSRP132821410/1420	7/22/2008	HH, HV
ALPSRP131071410/1420	7/10/2008	HH, HV
ALPSRP129321410/1420	6/28/2008	HH, HV
ALPSRP127571410/1420	6/16/2008	HH, HV
LANDSAT-1 MSS	7/23/1973	Bands 4,5,6,7
LANDSAT-7 ETM+	6/26/2002	Bands 1,2,3,4,5,7
LANDSAT-5 TM	7/23/2009	Bands 1,2,3,4,5,7

Figure Captions

Fig. 16.1. Study sites in Central Siberia, Russia from south to north: Western Sayan; Boguchany & Priangar'e; and Kotuykan.

Fig. 16.2. (A) Western Sayan Mountains and (B) authors (From left, Guoqing Sun, K. Jon Ranson, and V. I. Kharuk) in the field.

Fig 16.3. A – original L-band HV radar image; B – Corrected using DEM of coarser resolution

Fig. 16.4. Terrain changes illumination area of a pixel and the spatial structure of the canopy.

Fig. 16.5. Simulation of radar images of a forest stand on various slopes.

Fig 16.6. Relation between backscattering coefficient and local incidence angle for L-band.

Fig. 16.7. A – corrected L-band HV image; B – Biomass map from corrected LHV image.

Fig. 16.8. Comparison of SAR derived biomass with field biomass: SAR Biomass = 1.84 + 0.77*Field Biomass, r2 = 0.91, n = 28, RSE =1.81Kg/m^2.

Fig. 16.9. The JERS (LHH), b. ERS (CVV) c. Radarsat (CHH) and d. Landsat 7 images (Red = (NIR, 0.75 - 0.90 mm), Green = (Red, 0.63 - 0.69 mm), Blue= (Green, 0.525 - 0.605 mm) over the Boguchany site.

Fig. 16.10. The JERS (LHH), b. Radarsat (CHH) and c. Landsat 7 images (Red = (NIR, 0.75 - 0.90 mm), Green = (Red, 0.63 - 0.69 mm), Blue= (Green, 0.525 - 0.605 mm) over the Priangar'e site. ERS data was not available for this site.

Fig. 16.11. (A) Fireweed growing on a burn site at Boguchany (B) Aftermath of Logging in Boguchany Area (C) Trees (fir and pine) killed by Siberian silkworm (*Dendrolimus sibericus*) outbreak (D) insect damaged forest at Priangar'e seen from air.

Figure 16.12: Mean and standard deviation backscatter coefficient for land cover classes at a.) Boguchany burn scar site and b.) Priangar'e Insect Damage site.

Figure 16.13: Means and standard deviations of Landsat 7 spectral digital numbers (DN) for land cover classes at a) Boguchany burn scar site and b.) Priangar'e Insect Damage site.

Fig. 16.14. At their first campsite, the team assembles for a group photo in front of one of the not-yet-inflated rafts. Back row from left to right: Guoqing Sun, Ross Nelson, Slava Kharuk, Jon Ranson, Mukhtar Naurzbaev, and Sergei Im. Front row from left to right: Pasha Oskorbin and Paul Montesano.

Fig. 16.15. In steady rain, a Russian M-8 helicopter drops the scientists off on the banks of the Kotuykan River (70^{o}41'34"N, 105^{o}38'46"E) in northern Siberia. In the foreground, scientists cover gear with plastic. This is the first campsite of the expedition, and it will not be a soft one. The beach is covered with marble- to microwave-sized stones.

Fig. 16.16. Bands 7 (red), 4 (green) and 2 (blue) of Landsat TM image acquired on July 23, 2009.

Fig. 16.17. The low reach of Kotuy River seen from the helicopter, near Khatanga.

Fig. 16.18. A nice spot for lunch, overlooking the Kotuy River. The mountains, the Siberian Traps, were formed from basaltic lava flows during massive eruptions about 250 million years ago. The freeze/thaw cycle cracks and crumbles the rocks. The weather and the river have eroded the mountains into spectacular formations and sheer drop-offs.

Fig. 16.19. A view of the campsite taken from across the Kotuykan River. In the background are the flat-topped mountains known as the Siberian Traps. The slope in the foreground is littered with basaltic rocks formed from lava flows about 250 million years ago. The campsite was originally set up next to the riverbank. It is now on high ground; the river dropped about 2 meters overnight.

Fig. 16.20. Tundra on the top of the mountains with few trees.

Fig. 16.21. The harsh climate of Siberia is a challenging one for Larch trees. The photo shows the fates of several trees. A tree without bark or branches leans across the center of the photo. This tree died centuries ago, but the frigid climate has kept it from decaying. In the foreground, a tree that broke at the trunk and toppled managed to survive: a side branch grew into a vigorous new tree. In front and to the right of the "reborn" tree is a small dead tree that still has branches and bark. It is an ancient tree that died recently. In its last years, it put energy into making seed. Pinecones from the previous two years still cling to its branches.

Fig. 16.22. Forest ecologist Slava Kharuk called this a photo of Siberia's "bones and flesh." The "bones" are the skeletons of fossil trees that died in the extremely frigid climate of the Little Ice Age, during the 14th to 18th centuries. Although they died hundreds of years ago, the frigid climate has prevented them from decaying. The "flesh" is the new trees that are colonizing the area as the climate warms. These trees are growing above the "fossil" tree line, which is evidence that the current warming trend is very strong. Scientists will use data on the ages of both old and new trees—the bones and flesh—to create a timeline of climate change in this part of Siberia.

Fig. 16.23. Mosaic of PALSAR L-Band HV images (7 scenes) of the study site. The SRA data were acquired during the summer of 2008. Tiny red crosses show the places the team collected data.

Fig. 16.24. Classification of Landsat images: larch forests with three levels of densities - bright green, green, and dark green; grassy tundra - yellow, wet tundra – maroon, bare surface - pink, and water body - blue.

Fig. 16.25. NDVI image derived from Landsat data: red – from TM on July 23, 2009; green – from

ETM+ on June 26, 2002, and blue – from MSS on July 23, 1973.

Fig. 16.26. The comparison of GLAS predicted timber volume with field data: B_{pred} = 4.26 + 0.75 B_{field}, R^2 = 0.75, RSE = 4.89 M^3/ha. F-statistic: 159 on 1 and 52 degrees of freedom, the p-value is 0.

Fig. 16.27. GLAS footprints overlaid on a false image from PALSAR data: red – HH, green – HV, and blue – the ratio of HV to HH.