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Assessment of radar techniques for regional forest cover mapping over Siberian forests

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SUMMARY

The spatial distribution and characteristics of Russian boreal forests are in general poorly studied. This goal of improved knowledge can be reached only by using earth observation techniques, and application of remote sensing methods for the study of such large and complex areas as the Siberian boreal forests represent a technical challenge. Satellites with optical Earth observation sensors have played the leading role to forest applications. However, the optical sensors have serious limitations: dependence on weather and illumination conditions. In contrast, satellite radar remote sensing provides daytime independence all-weather information. Spaceborne radar remote sensing has become an increasingly important tool for observations of forest ecosystems.

For this study, the region located at the central part of West Siberian Plain, Ob' river basin has been selected. The reasons that this area was chosen are follows: Firstly the West Siberia is weakly studied in natural aspects. To study the local landscape and natural process, such as inundation and swamping, have a scientific as well as an important practical reason. Second Western Siberia in general has become a sort of testing ground to check the results of heavy human impact on the environment. The huge forestland areas have been clear cut or disturbed by fires. This study is dedicated to demonstrate the feasibility of satellite radar remote sensing for boreal forest vegetation mapping by means of satellite Synthetic Aperture Radar (SAR), which could provide a basis for the future activities in this direction. The main objective of this study is to assess the capabilities of SAR data from ERS (C-band) and JERS (L-band) satellites for the regional monitoring of forest cover at the test site in West Siberia including:

- Assessment of existing historical and recent satellite radar data application
- Pre-processing of collected satellite data for the test case area;
- Regional forest mapping using radar data and field data
- Forest change monitoring study using multi-temporal radar data

APPROVAL	
Lasse H. Pettersson	Stein Sandven for Ola M. Johannessen, Director

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INTRODUCTION

The boreal forests have significant global economic and ecological importance as a source of valuable natural resources, as well as performing the regulating function in carbon, water and energy exchange between land-based ecosystems and the atmosphere [Siberia's,1994]. Historically, it was believed that tropical forests are the major players in global cycles. However, the boreal forest contribution to global photochemical cycles is equally important [Isaev et.al., 1995].

The Russian boreal forests are located in the taiga zone and occupy vast areas of the Russian territory, accounting for: 85% of total forested areas, 90% of total growing stock, 80% of coniferous forest. The Russian boreal forests are important both on the national and global scales. For Russia, they constitute one of the basic elements of the national economy and play an important role in terms of ecology and environment protection, as well as in the sense of cultural/recreational resources. On the global scale, they account for about 22% of world forests and account for 40% of all world coniferous stands. [Siberia's, 1994].

The spatial distribution and characteristics of Russian boreal forests are in general poorly studied. One of the main causes of such situation is the vast area of the territory and its inaccessibility. Forest inventories and assessments of the timber resources are the most important parts of assessment and monitoring of the state of Russian boreal forests. This goal can be reached only by using satellite earth observation techniques, and application of remote sensing methods for the study of such large and complex areas as Siberian boreal forests represent a technical challenge.

Satellites with optical sensors have played the leading role to forest application world-wide. However, the optical sensors have serious limitations: dependence on weather and illumination conditions which is in particular critical for the Siberian boreal forests. In contrast, satellite radar remote sensing provides daytime independence and all-weather information. Spaceborne radar remote sensing has become only by combining both ground-based and remote sensing methods. In the case of the Siberian boreal forests, this presents a real technical challenge because of the spatial dimensions and variety of landscapes characteristic of the area.

Over the last decades, satellites with optical sensors have been playing a leading role in forest status/dynamics surveillance. However, optical sensors have serious limitations mostly due to the dependence of their operational efficiency on weather and sun illumination conditions. In contrast, radar remote sensing provides daytime independent all-weather information. Spaceborne radar remote sensing has become an increasingly important tool for observations of forest ecosystems. Synthetic Aperture Radar (SAR) data available from the current generation of satellites have been used in different projects and international programmes to study forests in the tropical, temperate and boreal zones.

ERS-1 and ERS-2 - European Remote Sensing Satellites were launched by the European Space Agency. Launched in the summer of 1991, and in the spring of 1995 respectively, both satellites operate in the SAR C-band (5,6 cm) and vertical (VV) polarisation mode. The sensor system has a 25-m ground resolution and 100-km swath width.

The Japanese Earth Resources Satellite 1 (JERS-1) was launched by NASDA and MITI in February 1992. The satellite operated in the SAR L-band (23,5 cm) with horizontal (HH) polarisation. It's look angle is 35° and the recurrence cycle is only 44 days. The sensor system provides an 18-m ground resolution and a 75–km swath width coverage.

The objective of the present study is to explicitly demonstrate the feasibility of satellite SAR remote sensing for boreal forest vegetation mapping. This will provide a basis for development of future activities in this direction. The research is focused on assessing the capabilities of ERS and JERS SAR data to assist in regional monitoring of forested areas. To meet this goal, a test site in West Siberia was chosen. The research incorporated the following main objectives:

- To assess the availability of historical and recent satellite radar data
- To pre-process collected satellite data for the test sites;
- To perform regional forest mapping by integrated use of satellite radar and ground-based data sources
- To perform forest change monitoring using multi-temporal radar data.

In order to achieve these objectives, the present study has been divided into four main tasks:

Task 1. Selection of a fast-changing forest region in Russia
The objective of this task is to select a region in Russia where there has been significant temporal variability in the forest state. Such a test region should be chosen on the basis of an expert evaluation of the availability of field observations.

Task 2. Identification and collection of historical and recent radar data on the selected fast-changing region
The objective of this task is to investigate the availability of relevant SAR data for the selected region. Identification in existing JERS and ERS SAR catalogues historical and recent radar data on the selected region. The selected SAR data is then to be collected.

Task 3. Pre-processing of collected satellite data
The objective of this task is pre-processing of the collected SAR data for thematic mapping of the test region. This task includes evaluation of suitability of the available GVM pre-processing software.

Task 4. Pre-feasibility study for forest mapping using satellite radar data
This task addresses the assessment of benefits of ERS/JERS SAR data implementation for detecting different categories of forest areas and non-forest areas. The categorisation differentiates between such landscape elements as forest, wetland and others.

The main work under this Project has been completed under a three month research research visit to JRC/GVM, with additional preparations and reporting completed at NIERSC in St. Petersburg. The work at JRC-SAI was carried out in cooperation with Leif Eriksson under the contractual supervision of Director Dr. Alan Belward and Dr. Frederique Achard. During the Project period also one contractual progress meeting between JRC, NIERSC and NERSC was arranged in addition to several Project meetings for planning of the work and reporting at SAI. The Nansen Center (NIERSC and NERSC) had several meetings in the planning and preparations of the project work and reporting.

The Project activities under the four Tasks will be now described in detail in the following sections.

1. WEST SIBERIA AS A FAST-CHANGING FOREST REGION IN RUSSIA

1.1 General description

For the study, a region in the Ob' river basin, located at the central part of the West Siberian Plain, has been selected. The reasons that this area was chosen are follows: firstly, the natural environments in West Siberia are poorly studied. Studies of the chosen region landscape and natural process, such as inundation and swamping, are important from both the scientific and practical points of view. Secondly, Western Siberia has in general become a sort of testing ground to check the results of a heavy human impact on the environment. The huge forestland areas have been clear cut or affected by forest fires.

West Siberia is a vast region measuring 2.4 million km^2 (Figure 1). It accommodates the mountain systems of Altai, Kuznetskii, Alatau and Salair; steppe and forest-steppe massifs, a wide zone of the western-Siberian taiga, and the forest-tundra and tundra in the Yamal and Gydan peninsulas, as well as smaller Arctic islands (Belyi and others).

The territory of West Siberia is composed of the Tumenskaya, Tomskaya, Omskaya, Novosibirskaya, and Kemerovskaya oblasti (regions) as well as parts of the Kurganskaya, Cheliabinskaya and Sverdlovskaya oblasti and Altay and Krasnoyarsk kraya (territories). The principal city in West Siberia is Novosibirsk (1.5 million inhabitants) located on the Ob' riverbank.

The main natural axis of the region is the 3.680 km along the Ob' River, with its main tributary river Irtysh. In summer, the Ob' River becomes about three kilometers wide. The river drains an area of more than 2.590.000 sq km. An important water route for the region, the Ob' is used mostly to transport lumber and grain, although navigation is hindered/precluded by ice in winter. The river regime is characterized by a long high-water period in spring and summer. Spring waters, overflowing wide lowlands, form extensive flooded areas. In winter, the rivers freeze for a long period extending up to six months [Donchenko, 1997]. The combined Ob'-Irtysh system, which is longest river system of Eurasia, is about 5.410 km long and is the sixth largest catchment area in the world.

The valley of the Ob' River divides the territory into two parts: the left (west) side-bank and the right (east) side-bank. The characteristic feature of the left side is the ribbon-like rises in the relief, which stretch parallel to each other, their height being usually 3-10 meters. These "manes" (as Siberians call such rises) are former watersheds of ancient rivers formed after glaciers had melted a few thousand years ago.

West Siberia is often called "the lake land", as there is a great number of lakes here. In accordance with various assessments, there are from three to six thousand lakes [Kyrpotin et al.,1995]. But many of them are not larger than one square km. The lakes are mostly found in the Baraba lowland and are rather shallow. Their banks are marshy and covered with reeds. In the southwest there are many salt and bitter salt lakes. The largest lake of West Siberia is Chany, which is partly salty.

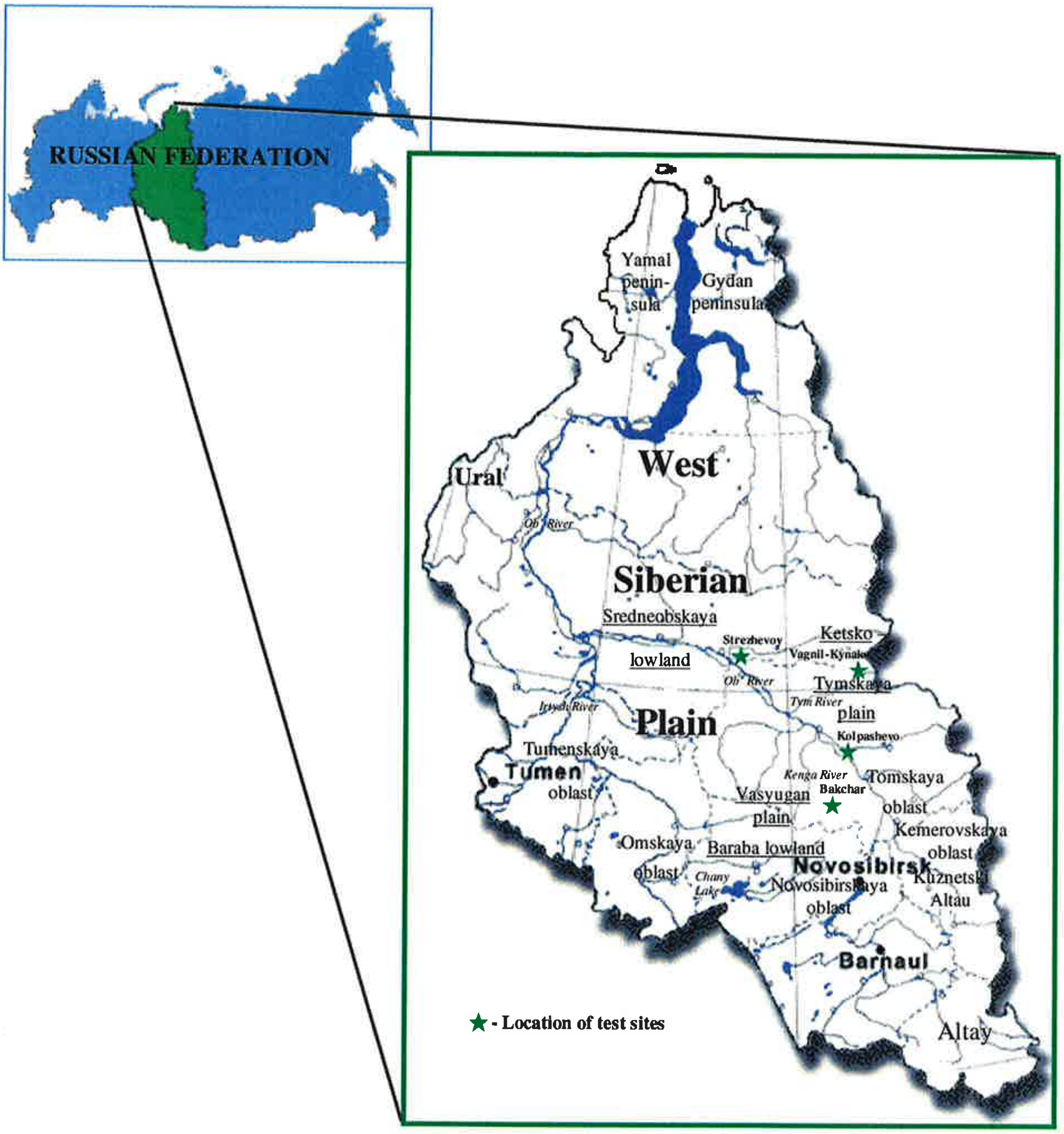

Figure 1. Map of West Siberia, including the location of the four test sites further studied in this report.

The areas is protected by the Ural mountain chain from the west remaining prone to cold Arctic winds. The flat type of the territory with lots of rivers, lakes and swamps determine specific climatic conditions.

The climate of the District is sharply continental. It is characterized by variable weather patterns especially during both interseasonal periods (transitions from autumn to winter and from spring to summer) and a day. The winter is long and severe with a steady snow cover, the summer is short and rather warm, transitive seasons (spring, autumn) are characterized by frosts in late spring and early autumn.

The average temperature in January varies from minus 18°C to minus 24°C. The absolute minimum was registered in 1973 : minus 59,3 °C. The coldest winters for the last 30 years occerred in 1968/69, 1986/87 and 1997/98. Unusually warm winters took place in 1931/32, 1947/48, 1981/82 and 1994/95.

The period with the air temperature below zero lasts for 7 months, from October till April. The period with a steady snow cover lasts 180-200 days: from the end of October till the beginning of May. Frosts often happen in the middle of June. The warmest month is July, the average temperature varies from +15,7 °C to +18,4 °C. The annual length of solar insolation is between 1600 to 1900 hours. The length of the vegetation period (growing season) does not exceed 115 days.

The northern direction of winds prevails in summer, whereas the southern direction of winds prevails in winter. The annual amount of precipitation is between 400 to 550 mm. The maximum precipitation in July is about 15% of its annual amount. The height of snow cover can be as high as 80 cm.

In wintertime, the atmospheric pressure is much lower than it is within the limits of the Asian anticyclone. The Atlantic Ocean-driven atmospheric circulation patterns provoke growth in temperature, snowfalls and thaws.

The West Siberian Plain occupies 80% of West Siberia. It represents the most extensive wetland plain [Kyrpotin et al.,1995]. Different types of wetlands (Figure 2) cover more than 50%, but mainly there are large flood-plain systems, including extensive raised bogs. The flood plain undergoes seasonal flooding during the snow melting period. The temporal and spatial dynamics of the inundation are however uncertain.

Figure 2. Wetland near Tomsk

The Western Siberian plain is the largest peat region of the world, with peat deposits covering more than 760.000 km^2. Over 0.7 m deep, these peat lands contain some 113 Gt of peat, which is 60% of the total peat resources in Russia. Around 2% of the peat lands have been drained, but a much larger proportion has been disturbed or otherwise affected by man's activities, including agricultural conversion, hunting, oil exploration and extraction, timber production and construction of new roads. Besides direct human impacts, there are also problems caused by chemical and radioactive pollution from industrial enterprises within such main industrial centers as Tomsk, Kemerovo and Novosibirsk.

1.2. Natural zones of the West Siberian forests

West Siberia includes five major natural zones*: tundra, forest-tundra, forest or taiga, forest-steppe and steppe* (Figure 3):

Tundra occupies the northern part of the Tumen region (Yamal and Gadinskiy peninsulas), within which only an area of 160.000 km^2 is not covered by forest.

Forest-tundra extends to the south from the tundra. It's a band of approximately 100-150 km width. As a transition zone between tundra and taiga, it is a combination of sparse forest, swamps and overgrows with shrubs. Wood with predominantly thin lurch species cover rivers valleys.

Forest or taiga zone ranges between 66°-56° N in an approximately 1.000 km wide band. It includes the northern parts of the Tumen, Tomsk, region, Omsk and Novosibirsk regions, and covers 62% of West Siberia. The forest zone of the West Siberian plain is divided into north, middle and south taiga sub-zones. Although the forest area is large, the forest cover represents only 30,5% of the land area. Low percentage of forested land resides in slow drainage of the territory which is conducive to intense swamp processes here. As a result of a cold continental climate, the forest has low biodiversity. The plant cover is heterogeneous with the dark coniferous forest type in the Taiga zone including spruce *(Picea obovata),* fir (*Abies sibirica*), and cedar *(Pinus sibirica).* The light coniferous forest type includes pine *(Pinus sylvestris)* and larch *(Larix sibirica).* The deciduous forest type includes birch (*Betula pubescens)*, poplar and aspen stands. Birch-aspen stands are uniformly distributed. Larch forests mostly grow on well-drained soils, often mixed with birch and pine and dark coniferous species like spruce and cedar. Pine forests have a most uniform distribution throughout the region and mostly coincide with alluvial soils. The pine forest accounts for ~35,6% of the total forested area. In the marshy forests of the area, there is a luxuriant growth of various kinds of moss and lichen. Ledum bushes, ferns and many important berries such as cranberries and cowberries are common here.

Forest-steppe side with broad leaves forest of taiga zone, and characterised by the presence of forest and forest-steppe vegetation communities, along with swamps, saline lands and meadows. The wood species present here are birch and aspen-birch. In contrast to dark coniferous stands, pine and larch forests spread to some extent into the forest-steppe zone.

Steppe zone covers the southern part of the Omsk and southwestern part of the Novosibirk regions, as well as the western part of the Altay Krai. Ribbon pine forests are occasionally encountered among the steppes.

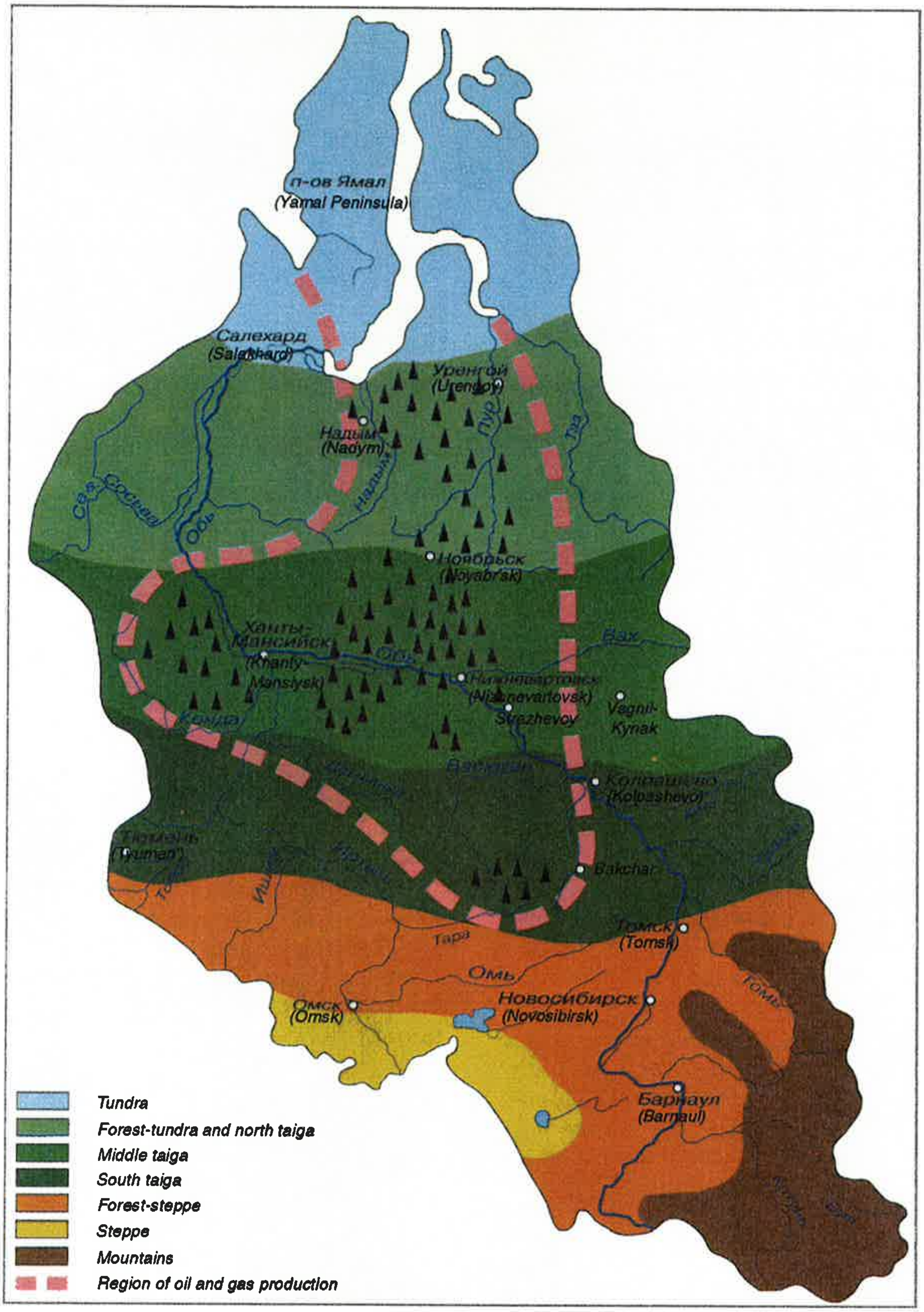

Figure 3. West Siberian natural zones included the region of major oil and gas production activities [adopted from Sedich, 1997]

1.3. Human impact

Western Siberia in general has become a sort of testing ground to evaluate the results of heavy human impacts on the environment and the efforts undertaken for environmental protection. Great changes took place in the northern districts, where in the 1960s, major oil and gas fields were discovered to provide energy not only for Russia but also for many countries of Europe. The area of oil and gas lands extends over 2 million km^2 (see Figure 3).

Railroads were constructed, transecting forests and swamps. Once backward villages turned into new cities, such as: Surgut, Nizhnevartovsk, Nadym, Urengoi and many others. This could not help affecting the nature of the territory, which presently is unable to sustain such an impact, even given the territory vastness.

The majority of the rivers of Western Siberia have been polluted by petroleum products as a result of fairly frequent accidents of various kinds in pipelines and exploration sites. The gas content in the air over industrial centres is impermissibly/appaulingly great.

The huge forestland areas have been clear cut or afflicted/destroyed by forest fires. The data provided by the State Committee on Statistics evidences that timber wood cutting output in 1996 in % to that of 1991 constitutes: Key-use cuttings - 25.8, Sanitary clearings 82.5% and other cuttings 21.4 % [Isaev et.al., 1995]

In the areas of taiga and tundra, the indigenous people used to be engaged in traditional subsistence (Khanty, Mansi, Nenets and others, engaged in hunting, fishing and reindeer herding). Only during the last years they did become entitled to laying claims to the lands belonging to them and to the traditional subsistence practices that they are used to. All that determined the development of a fairly active environmental protection movement during the last decades.

2. REVIEW OF ERS AND JERS DATA APPLICATION TO FORESTRY

2.1. Remote sensing tools for forestry application

In forestry and ecological studies, information is needed about the general growing conditions, forests resources and their temporal changes. Information on changes is needed to keep the resource data updated and in order to monitor the dynamics of the forest ecosystem. The change detection required information on ecosystem changes should include all the major parameters which constitute basic inventory.

Forest inventory provides the fundamental information for making forest management decisions. It includes management inventories. These maps give in detail: the forest species composition, forest density, height, age, and other features such as site quality, environment-sensitive wildlife habitat and potential operability. Forest inventory also includes regional inventories that consist of broad forest type mapping to give the location and extent of forest, its general composition, and sometimes a quantitative estimate of volume.

Further, the use of satellite Earth observation (EO) data with thematic classification can be applied to highlight certain features of interest, thus facilitating the mapping process. Most commonly used are the multi-spectral EO data. In this type of classification satellite EO radar data have shown much higher capability to map forest types in the temperate and northern forests than in tropical forests which is due to the fact that much more research has been devoted so far to temperate and northern forests. The high efficiency is also promoted by smaller species diversity, a tendency towards uni-species stands, and perhaps, by the species characteristics themselves [Anon., 1998].

Microwave radar data does not have the possibility to providing complete forest information as required by management level inventories. Radar data therefore generally fit into a forest management environment that requires (and has) reasonable information on species composition, density, height and age class. Radar data will hence not often be used in isolation, but along with other existing information. Indeed, most often it will be used to help update or confirm existing forest data or add specific information on the forest stand and condition.

Variations in the microwave dielectric constant of vegetative elements of the ground surface play a central role in determining the intensity and phase of the recorded and processed SAR-derived images. Factors affecting the dielectric constant of vegetated surfaces include the temperature of the scattering medium, relative moisture content in vegetation, soil, and snow cover, and the presence of water on the surface of vegetation elements (i.e., leaves, stems, etc).

A satellite EO radar system emits pulses of electromagnetic energy, which are reflected from an illuminated target area. Since the incident electromagnetic radiation interacts with the illuminated target, the process that returns energy to the sensor is referred to as scattering rather than the more familiar reflection obtained from optical sensors. Where the transmitting and receiving antennae are the same, as in imaging radar, it is usually referred to as backscattering since the energy is scattered back to the transmitting antenna.

Backscatter from terrain occurs as a result of volume scattering in inhomogeneous media, such as vegetation canopies. The degree of penetration in vegetation will depend on the radar wavelength, the geometry of the plants, the water content, the vegetation volume and many other parameters.

In general, longer radar wavelengths will penetrate deeper into the vegetation than for the shorter microwaves. The penetration will also be higher if the water content in the plants is low.

Over the forest, the backscatter has a small dynamic range and saturates before high biomass densities are reached. At low biomass densities, for example forest clear-cuts, recent regeneration, grassland and agricultural areas, the backscatter is determined as much by moisture content and surface roughness as by the biomass density.

Several spaceborne SAR systems deliver valuable information about the Earth surface. In this study we present the results related to the application of ERS and JERS images for forestry management. The ERS-1 and ERS-2 SARs operated in the C-band (5.6 cm) and JERS-1 SAR operates in the L-band (23.5 cm). Results from ERS and JERS have produced both encouraging and discouraging results for forestry monitoring applications.

The Siberia project study [Siberia, 1999] showed that the JERS intensity are highly sensitive parameters to interpret forest and other land use classes. Several features made JERS-1 SAR particularly suitable for forest monitoring, most notably the low L-band frequency SAR, which is sensitive to the above-surface biomass [Beaudoin, 1994]. The dynamic response of backscatter to stem volume (biomass) is higher in the JERS SAR l-band than in the ERS SAR C-band. In L-band observations, backscatter always increases with increasing stem volume, which is not the case when observations are conducted in the C-band [Pulliainen at al., 1999]. However, Kasischke et.al. [1994] demonstrated the sensitivity of ERS-1 SAR backscatter to changes in above-surface woody biomass in young pine forests with low biomass. The correlation decreases as biomass increases and the canopy closes. This demonstrates the potential for the C-band to monitor biomass at early vegetation stages.

Harell et.al. [1995] show that ERS-1 data to be more strongly related to forest density than to the height or biomass. The JERS-1 data are more strongly related to height and biomass than to density.

During discrimination of land types at C-band, open areas sometimes are misclassified as forests. For example, coniferous with characteristically low backscatter can often have backscatter similar to open areas. Sometimes there is a confusion in distinguishing between open areas and water bodies [Donchenko et al., 1999].

With the C-band there are difficulties in mapping broad forest types, e.g., coniferous from deciduous and open areas versus forest lands. The range of backscatter is, however, much less for different deciduous species and they are generally difficult to distinguish. Donchenko et al.[1999, 2000] have shown that the best results were achieved for coniferous and mixed forests. The classification accuracy is 52,2% for coniferous and 44,3% for mixed forests. For lowland coniferous and deciduous forests, the accuracy of classification was lower (respectively, 37,4% and 11,3%). According to L. Kurvonen

[1999] high accuracy was obtained for coniferous stands (74,1%), while deciduous and mixed forests in many cases were classified as coniferous, based on C-band SAR data.

The longer wavelengths (L-band) are generally less useful for distinguishing different forest types, particularly specific species composition, but better for discrimination the forest from non-forested areas. In most cases, the backscatter from the forest at these wavelengths is greater than from non-forested areas. Within the forest, L-band backscatter from coniferous is generally higher than from the deciduous forest. This proves the results [Donchenko et al., 2000] obtained for coniferous stands: the accuracy achieved in the case of JERS1 SAR images is 16,8% higher than obtained from ERS 1-2 SAR images.

Table 1 summarises the potential, demonstrates the capabilities of these system relative to applications for forest studies and provides some comparison with a system working in the visible and Infra Red (IR) regions of the electromagnetic spectrum.

Table 1. Summary of the remote sensing tools for forestry applications and indications of their general capabilities.

Applications	Microwave				Visible/IR	
	ERS SAR		JERS SAR			
	CAPABILITY					
	poor	good	poor	good	poor	good
INVENTORY MAPPING						
Forest composition	*		*			*
Density	*			*		*
Height	*			*	*	
Age		*		*	*	
CHANGE DETECTION & MONITORING						
Clearcuts		*		*		*
Burned areas		*		*		*
Bogging		*	*		*	
Inundation		*		*	*	
Forest regeneration	*		*			*

2.2. Examination of the most common radar processing techniques

In order to extract the desired information from satellite SAR images, it is necessary to develop special tools for processing and analysing them. Below we examine the most common radar processing techniques used for land applications. It should be noted that there exist numerous approaches to apply these techniques. Progress in understanding and application is still underway, and full utilization of the radar capabilities is yet to come.

Texture

Texture is one of the important characteristics used in identifying objects or regions of interests in a remotely sensed image, especially SAR images. Texture can be defined as a spatial distribution of local intensity variation. Unfortunately no rigorous definition of texture exists, it is used both as a statistical measure and pattern sctructure of pixel values in an image. Schistad Solberg [1995] defines the concept of texture to contain important information about the structural arrangement of surfaces and their relationship to model-based methods and signal processing methods.

For texture analysis of SAR images, the most common approach is to use features derived from the gray-level co-occurrence matrix (GLCM). GLCM describes how the gray levels in a spatial neighborhood of a pixel are related [Schistad Solberg, 1995].

Based on the results of numerous studies [Kurvonen et al., 1999 and 1999b; Donchenko et al., 1999 and 2000], the texture parameter quantification is of a higher information value for the land-cover and forest type classification. The use of textural parameters significantly improves the classification of land-cover and forest types. Texture has been used to help discriminate open areas from forests (the open areas generally have a smoother texture). Texture also helps distinguish between forest types, e.g., deciduous trees often have coarser texture than coniferous ones, and mixedwood stands have either intermediate or coarser texture. Texture can also be used to help identify and delineate forests units with similar species composition, age and density. Nonetheless, the land-cover types classification accuracy varies between 60 to 80% [Kurvonen et al., 1999]. In forest type classification, the classification accuracy was 60-70% [Kurvonen et al., 1999; Donchenko et al., 1999 and 2000].

Multi-temporal image analysis

Multi-temporal analysis can be carried out if more than two SAR images are acquired over the same geographical area. This kind of analysis is particularly interesting when investigating phenomena throughout a full growing/vegetation season, or over a period of several years. As with change detection, accurate geographic registration has to be done prior to the data analysis. The SAR backscatter within each image can then be evaluated for land use and forest type discrimination. A change detection analysis can also be done based on ratio images.

Multi-temporal analysis of SAR data may add a valuable new dimension to the classification of major land use classes and then forest in separating between different forest types based on seasonally different images. This is because surface classes may give different temporal backscatter profiles. When a single SAR image is used [Kurvonen et al., 1999], the textural and /or intensity information is inadequate for a satisfactory land-cover and forest type classification. However, the multi-temporal approach has proven to be beneficial, especially for the textural measurements.

EO sensor synergies

The variety of different EO sensors presently available or planned in the near future creates a number of opportunities for data combination and fusion to provide better capabilities to get more adequate information about the study object and to improve scene interpretation capability.

The integration of data from different sensors can be performed at various processing stages. Each sensor has its own characteristics and the image usually contains various artefacts, which should be corrected or removed. Combining various interpretations coming from sensors with different spatial and spectral resolutions and characteristics, poses several methodological problems: processing stages, namely the data classification, the geometric co-registration, and the thematic fusion of complementing interpretations [Mayaux et al., 2000]. Additionally, multi-sensor images are often not acquired at the same date and temporal changes must be taken into consideration.

Recent work [Wegmuller et al., 1995a and 1995b] shows that the combined use of radar backscatter intensity and image coherence has a strong potential for vegetation mapping and monitoring.

Coherence

The SAR coherence images are made by using both the amplitude and phase from the SAR image pairs: the coherence is an estimate of the phase stability of the image targets in the time between two different in time SAR acquisitions. In practice this means that if the surface is changing, the resulting coherence decreases. The coherence can also decrease if the signal has a significant volumetric component, as it often occurs in the case of forested areas and dense shrubs [Weydahl, 1998].

It could be further said that coherence is essentially a measure of geometric change, being depending on the scattering properties of the observed target, environmental effects, and the time difference between the master and slave image, and topography. Therefore the relationship between coherence and ground parameters can change from one tandem pair to the next. Also, the size of the pixel window, which is used to estimate the coherence, is important.

Coherence is an additional information channel to SAR backscatter intensity, but it is not very sensitive to effects caused by different moisture levels [Engdahl et al., 1998]. This is because changes in the moisture content of the soil do not change the scatter geometry resulting in coherent intensity change. The analysis of the ERS SAR data in the Siberia project [Siberia, 1999] has shown that the coherence is a most suitable ERS SAR parameter for forest classification. The analysis has shown that ERS tandem coherence information is more sensitive to forest volume classes than JERS backscatter information [Siberia, 1999].

The ERS-1/2 tandem mission Single Look Complex (SLC) data are widely used for SAR interferometry application. The complex degree of coherence is an estimate of the amount of change in the complex backscatter between two SLC data sets recorded from the same area on the ground. In the case of the ERS-1/2 tandem mission, where the time difference between the two satellite overpasses is only 24 hours, it is expected that a change in the complex backscatter would mainly be due to a change in the position of the scatters in the ground resolution cell, as this affects the phase of the received signal.

3. STUDY AREA AND GROUND TRUTH DATA

The study area is located within the Siberian taiga zone and partly in the forest-steppe zone and covers a territory with the outer 61,50° N -78.35° E, 61,50° N -84,40° E, 53,50° N -74,50° E, 53,50° N -82,40° E.

Four specific test sites have been chosen for the study implementation. They differ one from another by forest nature, degree of antropogenic and natural influence and other factors. Size of every test site is about 10,000 km^2, which is corresponding with the size of EAR/SAR images (100 x 100 km). List of the four chosen test sites is given in Table 2 and indicated on Figure 1 and 3 and more detailed present on Figure 4.

Table 2. List of selected test sites for this study and their geographical coordinates.

	Centre coord.	Corner coord.
	Lat. N Long. E	Lat. N Long. E
VANGIL – KUNAK	60^0 20′ 84^0 04′	60^0 55 83^0 05 60^0 42 84^0 51 59^0 48 84^0 21 60^0 01 82^0 38
STREZHEVOY	60^0 47′ 77^0 39′	60^0 54 75^0 54 60^0 41 77^0 40 59^0 49 77^0 11 60^0 02 75^0 28
KOLPASHEVO	58^0 17′ 82^0 17′	59^0 11 82^0 15 58^0 57 83^0 56 58^0 03 83^0 28 58^0 16 81^0 50
BAKCHAR	57^0 05′ 82^0 07′	57^0 25 81^0 27 57^0 12 83^0 03 56^0 18 82^0 37 56^0 30 81^0 03

3.1. The Vangil-kunak site

This test site is situated in the north-eastern part of the taiga region between the Tym and Paidugyna Rivers, in the Ketsko-Tymskaya plain. Its territory has stands of coniferous species mostly with a cedar plantation on the right side of the Tym River and some plantations of pine to the north off the Tym River and to the south off the Paidugyna River. A deciduous forest plantation with birch and aspen trees is located between both rivers. The forest here is most mature. The age of the plantations is more than 50 years, with only some young and middle-age cedar plantations located along the rivers. The average forest density of the test site plantations is 0,72. Plantations with high density (0,8-1) cover 32,4% and the ones with low density (0,3-0,5) account for 4,5% of the territory occupied

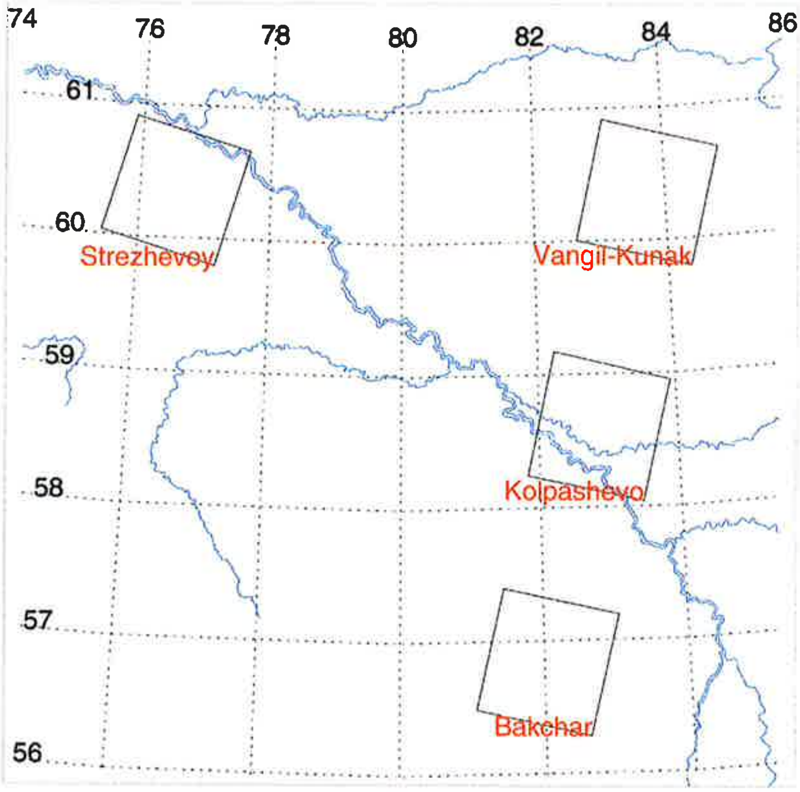

Figure 4. The SAR data coverage used in the studies of the four test site locations of this Report.

by forests. Respective of the data on forest husbandry in 1990-91, a number of changes caused by fires and forest cutting (clear cutting, sanitary cutting, advance thinning etc.) have taken place in forest. The main clear-cutting has been done among pine trees plantations on the right side of the Tym River. About 30% of the territory are covered by swamps, which are located to the north off the Tym River and to the south off the Paidugyna River. Swamps are covered by herbs and rarely pine trees, some small lakes are present here as well.

3.2. The Strezhevoy site

This test site is located in the north-western part of the taiga region on the Ob' River bank known as the Sredneobskaya lowland. A large percentage of the area is covered by swamp including a large quantity of small lakes. There is forest growing along the numerous rivers that are tributaries to the Ob' River. Pine plantations in mature stage are prevalent here, but young and middle age plantations can also be found here. There is cedar growing on both sides of the Ob' River, sometimes being mixed with pine and birch. As after-effects of fire and clear cutting, birch and aspen forests are widespread inside of pine and cedar stands.

3.3. The Kolpashevo site

This site is in the central-eastern part of the taiga region. The predominant types of forests are coniferous stands, which constitute the main proportion of forested area. The main coniferous species is cedar in mature and over-mature stage. The rest of the territory is covered by deciduous, birch and aspen stands. Forest stands here have middle and low density.

3.4. The Bakchar site

The area is located in the southeastern part of the taiga region in the Vasyugan plain. The forests grow mostly along the rivers. Swamps, with an extensive system of bogs (the Vasyugan bogs), cover the remaining area.

The broadleaf tree species such as birch, aspen and poplar are dominant here. The forest is mostly in the mature stage, episodically some stands in young and middle age can be found. The dark coniferous species spruce and fir are concentrated along the Kenga River. Here also can be found such trees as cedar and pine. A number of changes caused by forest fires took place in the test site area over the last years. There are numerous burned areas from recent and old fires.

3.5. Ground Truth Data

For the four test sites considered in this study, the following in situ data were collected:

- Topographic maps at scale 1:200.000
- Cartographic data of forest husbandry on 1992-1993 at scale 1:500.000

Topographic data were specially produced for each key site on scale 1:200.000. The data were processed using facilities of a Russian cartographic company, and are available in ARC/Info formats on a CD-ROM. Data are divided into four blocks corresponding to each key test site (Figures B5-B8).

Forest husbandry maps are sources of information about boundaries of homogeneous plantations (plots) and the limits of quarters. The forest husbandry data are based on the results of forest inventory. The attributive information contained at the regional level is based on the data of the Forest State Account of Russia of 1992-1993, aggregated over forestry. The inventory of forests is carried out every ten years over the whole forest stock of Russia and is based on data of forest husbandry, aerotaxation and other types of forest state inspections. An element of such inventory is forestry enterprise (leskhoz)*. The test region is related to the Tomsk forest enterprises. The forestry maps are in digital raster formats (see Figures A1-A4).

The topographic data include a thematic vector layer and its attribute information. The thematic vector layers contain the following information:

- relief
- geography
- hydrography
- settlements
- lines of communication
- electric power lines
- borders
- land cover
- vegetation cover

* The forestry enterprises (leskhoz) are administrative subdivisions of the Russian Federal Forest Service for which the country-wide forest inventory information is collected. The forestry enterprises are, among other roles, mainly responsible for the resource management.

The forest husbandry data contain quantitative as well as qualitative information about forest state, namely:

- The distribution of forests by land categories
- The distribution of forests by dominating species and age groups

The brief characteristics of the forest husbandry data are given in Table 3 and Figure 1-4 ANNEX B.

Table 3. The forest husbandry data available in digital raster format (see Annex B, Figures B1-B4)

ITEM	DESCRIPTION
Land category:	natural stand
	unclosed natural forest
	stand with culture under crown cover
	forest culture
	unclosed forest culture
	plantation
	burned forest
	dead forest
	clear-cut area
	glade
	arable land
	hayfield
	pasture
	river
	stream
	lake
	bogs
	quarry or gravel pit
Tree dominant specie:	pine
	spruce
	fir
	larch
	cedar
	beach
	aspen
	poplar
Age class	Young stand, 1 st class
	Young stand, 2 st class
	Middle-aged stand
	Immature stand
	Mature stand
	Overmature stand

Since the last forest husbandry on the territory of test site was conducted back in 1992-1993, it is necessary to update forest husbandry maps in order to take into account the changes in forest cover caused by forest fires and forest cutting. A digital map of such changes for the period of 1993-2000 is needed, unfortunately such information is not available at the moment in order to fully complete this study.

4. IDENTIFICATION OF EXISTING HISTORICAL AND RECENT SATELLITE RADAR DATA FOR THE SELECTED REGION IN JERS AND ERS SAR DATA ARCHIVES

4.1. ERS-1&2 SAR data

The ERS data from this region were acquired during the ERS tandem campaign in 1997/1998 by the DLR mobile ground station in Ulan Bator, Mongolia. Through an ESA ERS AO3 project, 80 ERS-1 and ERS-2 SAR scenes (40 tandem pairs) are available for this study. Data processing format: single look complex (SLC). Also for this study some ERS-1-2 SAR tandem data obtained by GVM from DLR are available.

The ERS tandem requested covers the major part of the Ob' River basin, corresponding to the outerlimit coordinates 61,50° N -78.35° E, 61,50° N -84,40° E, 53,50° N -74,50° E, 53,50° N -82,40° E. The majority of the scenes were taken between Sept. 21-Oct. 26, 1997, but we also have 8 scenes from July 1998. This is a unique dataset from an area that previously had no ERS SAR coverage. An overview over the selected ERS SAR scenes is given in Table 4 and Figure 5.

Table 4. List of available ERS 1&2 SAR data covering the four study areas.

Satellite	**ERS-1**	**ERS-1**	**ERS-1**	**ERS-1**
Acq. data	970930	971003	971006	971009
Orbit	32472	32515	32558	32601
Frame	2367 2385 2403 2421 2439 2457 2475 2493 2511	2367 2385 2403 2421 2439 2457 2475 2493 2511	2367 2385 2403 2421 2439 2457 2475 2493 2511	2367 2385 2403 2421 2439 2457 2475 2493 2511
Track	420	463	005	048
Satellite	**ERS-2**	**ERS-2**	**ERS-2**	**ERS-2**
Acq. data	971001	971004	971007	971010
Orbit	12799	12842	12885	12928
Frame	2369 2385 2403 2421 2439 2457 2475 2493 2511	2367 2385 2403 2421 2439 2457 2475 2493 2511	2367 2385 2403 2421 2439 2457 2475 2493 2511	2367 2385 2403 2421 2439 2457 2475 2493 2511
Track	420	463	005	048
Satellite	**ERS-1**	**ERS-2**		
Acq. data	980707	980708		
Orbit	36480	16807		
Frame	2439 2457 2475 2493	2439 2457 2475 2493		
Track	420	420		

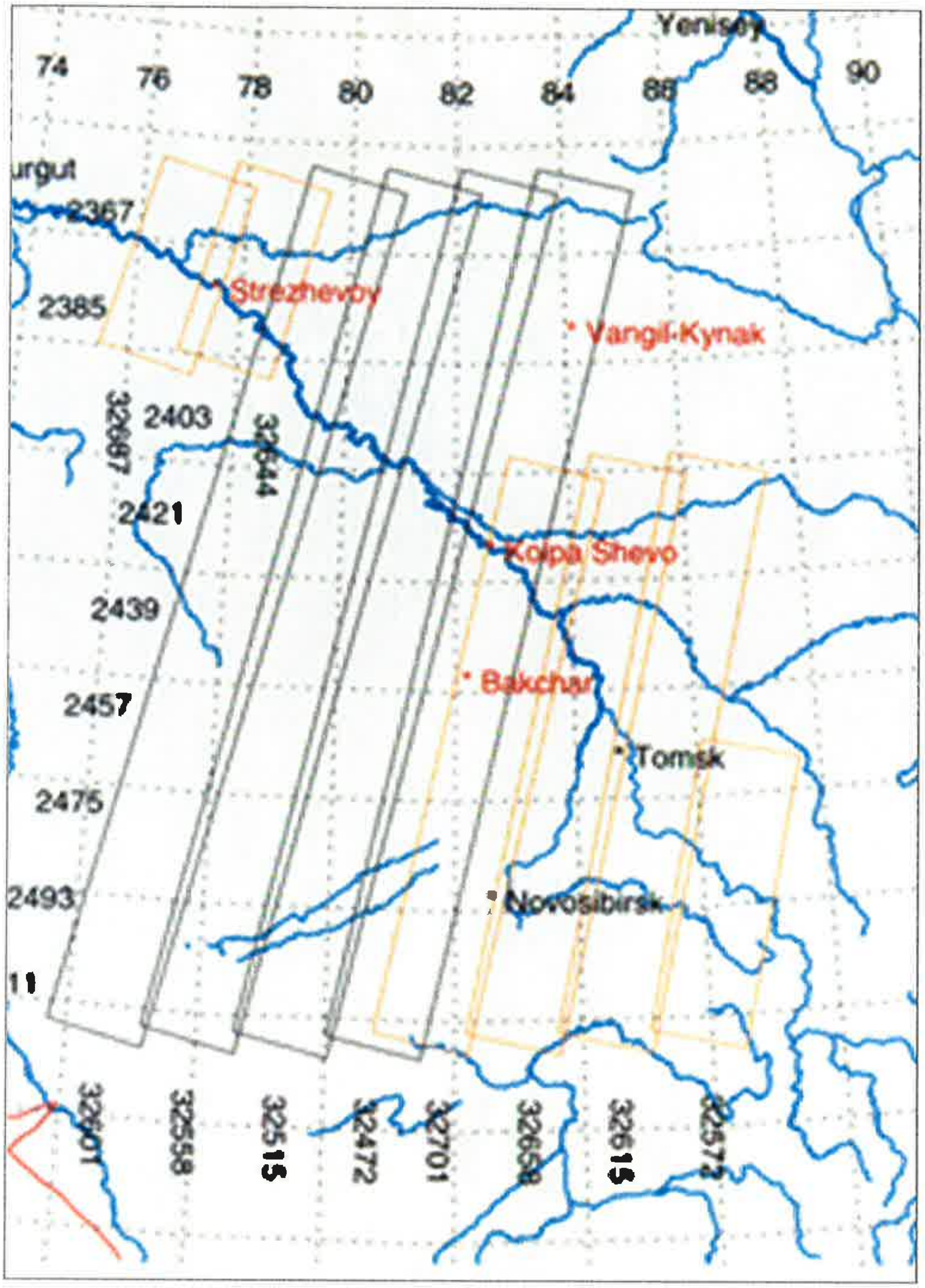

Figure 5. Scheme of ERS 1-2 SAR swath coverage over the four test regions (black –GVM data, orange-DLR data).

4.2 JERS –1 SAR data

JERS-1 data were obtained from the Japanese Space Organisation NASDA within the framework of the Global Boreal Forest Mapping (GBFM) project. The JERS-1 SAR data in turn, were acquired over the entire Eurasian subcontinent during the summer of 1997. For the current study, images most closely corresponding to ERS data by location and time have been chosen (Table 5).

Table 5 . List of available JERS-1 SAR data.

JERS-1/SAR		
Acq.date	**Orbit**	**Frame centre**
941015	0014635	N +60.39 E+083.97
960805	0024520	N +60.39 E+083.87
970426	0028474	N +60.39 E+083.75
961226	0026662	N +60.73 E +77.90
970209	0027336	N +60.74 E +77.32
970508	0028654	N +60.79 E +77.28
970621	0029313	N +60.74 E +77.51
960327	0022558	N +58.60 E+082.68
960510	0023217	N +58.60 E+082.61
960806	0024535	N +58.60 E+082.65
960919	0025194	N +58.60 E+082.58
960327	0022558	N +56.86 E+082.07
960510	0023217	N +56.86 E+082.00
960806	0024535	N +56.86 E+082.04
960919	0025194	N +56.86 E+081.98
961102	0025853	N +56.86 E+082.05

5. PRE-PROCESSING OF COLLECTED ERS AND JERS SATELLITE DATA

5.1 Description of data format and pre-processing status

Different software were applied and evaluated for co-registration, radiometric and geographic correction, and for processing of the interferometric coherence for the ERS tandem pairs of SAR images.

Software from the company SARMAP in Switzerland were evaluated as appropriate, and it was decided (with JRC) to use their software for most of the pre-processing tasks. However, it has not yet been evaluated if this software package also can be used for the Japanese JERS SAR data, and how well it would work on a large-scale operational basis for routine processing of large amounts of data.

For each test site, ERS SAR tandem pairs and JERS SAR images were processed and analysed. For each ERS tandem pair, we estimated the coherence and average SAR signal amplitude. For JERS data we analyze only SAR signal amplitude.

Twelve ERS 1&2 SAR Tandem image pairs have been processed to obtain 24-hour coherence images for each site. The Single-Look Complex (SLC) SAR data used in this study are presented in Table 6. Unfortunately, no ERS SAR multi-temporal data coverage are available at the moment, implying that it was not possible to perform multi-temporal change study analysis. For test sites Bakchar and Vangil-Kunak we have data for two seasons, but to make real multitemporal analysis as well as change detection analysis these data are not sufficient. Between these two dates there is little change in response due to changing state of the forest, for example frozen or thawed, leaves on or off, moisture state of canopy and etc. .

The JERS data (Table 7) received from NASDA are Level 2.1 products. A radiometric conversion has not been applied to JERS images. Some of the reason for this is mention in "User's guide to NASDA's SAR products" [Shimada, 1993] e.g. as if SAR products includes higher intensity targets, such as forested area, wetland area in the middle and far edge, the products should not be applied for the Normalized Radar Crosss Section (NRSC) conversion.

5.2. Co-registration of ERS and JERS images

The easiest way to co-register/superimpose a JERS image upon an ERS image is using Ground Control Point (GPS). This can be carried out using standard image processing software, e.g. ENVI and ERDAS (available at GVM) or ER Mapper and IDRISI (available at NIERSC).

At the moment, co-registration of the JERS scenes have been carried out image by image, using ENVI software. However this process of selecting control points for each individual image are very time consuming and takes too much time to be used if JERS scenes for the entire Ob' region are to be co-registered with the ERS SAR scenes.

Table 6. List of Single-Look Complex (SLC) ERS 1-2 SAR data used in the study.

Test site	Date	ERS-1			ERS-2		
		Orbit	Frame	Track	Orbit	Frame	Track
VANGIL – KUNAK 60°20' 84°04'	Oct. May	32472 35750	2385 2385	420 191	12799 16077	2385 2385	420 191
STREZHEVOY 60°47' 77°39'	Oct.	32687	2385	134	13014	2385	134
KOLPASHEVO 58°17' 82°17'	Oct.	32472	2421	420	12799	2421	420
BAKCHAR 57°05' 82°07'	Oct. July	32472 36480	2457 2457	420 420	12799 16807	2457 2457	420 420

Table 7. List of the JERS data used in the study.

Test site	Data	Orbit	Frame center
VAGNIL – KUNAK	941015 960805 970426	0014635 0024520 0028474	N 60.39 E 083.97 N 60.39 E 083.87 N 60.39 E 083.75
STREZHEVOY	961226 970209 970508 970621	26662 27336 28654 29313	N 60.73 E 077.90 N 60.74 E 077.32 N 60.79 E 077.28 N 60.74 E 077.51
KOLPASHEVO	960327 960510 960806 960919	0022558 0023217 0024535 0025194	N 58.60 E 082.68 N 58.60 E 082.61 N 58.60 E 082.65 N 58.60 E 082.58
BAKCHAR	960327 960510 960806 960919 961102	0022558 0023217 0024535 0025194 0025853	N 56.86 E 082.07 N 56.86 E 082.00 N 56.86 E 082.04 N 56.86 E 081.98 N 56.86 E 082.05

5.3. Digital Elevation Model (DEM)

Presently only the low resolution Digital Elevation Model (DEM) GTOPO30 from USGS [http://www.ermapper.com/gtopo30], approximately 1 km grid spacing, is available. A prerequisite for topography correction is the availability of DEM that will be produced in all areas where the coherence of ERS tandem pairs allows doing so. At the moment, a DEM based on SAR data has been produced by SARMAP only for Vangil-Kunak test site. For other test sites SARMAP has promised to process a DEM, however yet not delivered.

5.4. Coherence images

Test site Vangil -Kunak:

Available data ERS SAR Single Look Complex (SLC) images: one tandem pair from October 1997, one tandem pair from May 1998, and one single ERS-2 scene from July 1998.

Coherence images has been processed for October and May. October gives a very good result, but May only gives low quality, which SARMAP will try to correct. The backscatter and coherence images have been geocoded by SARMAP, but the result looked "flipped".

Test site Bakchar:

Available ERS SLC's data: One tandem pair from October 1997, and one tandem pair from July 1998. Coherence has been processed for October and July (Figures A1–A2). July gives low quality, which SARMAP will try to correct.

Test site Kolpashevo:

Available ERS SLC's data: one tandem pair from October 1997, one single ERS-2 scene from May 1998, and one single ERS-2 scene from July 1998. Coherence has been processed for October.

Test site Strezhevoy:

Available ERS SLC's data: one tandem pair from October 1997. Coherence has been processed for October.

It should be noted that the final image processing has been done at NIERSC in St. Petersburg, using the ER Mapper software.

Analyses of ERS SAR image intensity and coherence and JERS SAR data signal amplitude have been done only for Bakchar test site. The main reason to choose this site for interpretation analysis was that the area are more homogeneous then others.

6. RESULTS OF ERS AND JERS SAR DATA ANALYSIS

6.1. Assessment methods

The remote sensing data were analysed in order to assess their ability to detect and separate different but contiguous land cover classes.

We first assess how well different land types of interest can be distinguished from the existing satellite data and establish the separability between land types using both ERS and JERS sensors and their derived information products.

One of the important steps in classification, especially in supervised classification, is developing sufficient knowledge to define representative signatures for each class in the SAR images. In the cases where thresholds or limits are used, it is necessary to identify homogeneous areas for all classes in the image to be analysed.

Polygons of homogeneous areas were identified from the forestry map and superimposed over the SAR image data, which enabled the backscatter and the coherence generated from ERS Tandem pair and JERS single scenes to be analysed as functions of the different forestland cover classes. ERS 1& 2 (Figures A1-A4) and JERS SAR (Figures A5-A9) images for the Bakchar test site are presented in Annex A to this report.

In the forestry map of each test site, four main forestland cover classes are distinguishable, namely forested area, non-forested area, and wetland areas with herbaceous vegetation and wetland with rarely trees. The specification of each class is given in Table 8. For the purpose of comprehensive representation, 30 polygons were extracted for each class in the sets of ERS and JERS images. The number of pixels in the polygons is about 100.

Table 8. Specification of the studied forestland cover classes identified in the SAR images.

Forestland cover Class	**Class Specification**
Forest	High biomass areas with different types of wood species
Wetland-herb	Wetland with herbal and rarely wood vegetation
Wetland	Wetland with herbal vegetation
Non-forest	Low biomass area : clear-cuts, forest burned and agricultural fields

Based on the assumption that these polygons correspond to homogeneous areas in the SAR images, the pixel values (coherence and backscatter intensity) inside each sample polygon were averaged to give the local mean value and standard deviation of ERS 1&2 SAR coherence and intensity and JERS 1 SAR backscatter intensity.

6.2. Analysis of ERS SAR data to distinguish forests classes - the Bakchar test site

Radar backscatter analysis

The intensity of the radar backscatter is a response to moisture and roughness of the reflecting target/surface. In West Siberia, the range of vegetation moisture is minor compared to soil moisture, such that radar measures either soil moisture or roughness or both. Over the forest areas the radar backscatter has a small dynamic range. At non-forested areas such a forest clear-cuts, burned areas, agriculture areas, the backscatter is as much determined by moisture content and roughness as by the biomass density.

Difference between July and October were detectable. July is a middle of vegetation season (high biomass) as well as this time is characterised by low content of moisture in soil. As biomass increases, the surface backscatter decreases because of increased attenuation by the canopy and trunk layer [Kasischke, 1997]. In addition Dobson et al. [1995] has shown that at low biomass sites the backscatter intensity for ERS increase with decreasing soil moisture. As a results we should expect not to be able to discern forest, non-forest and wetland with herbal and low tress vegetation classes. However, since even in a dry season wetland still is the area with high volume of moisture, it is possible to discern this class from others using only image intensity, as shown in case of July (Figure 6), where the mean values and standard deviation is generally higher for the wetlands.

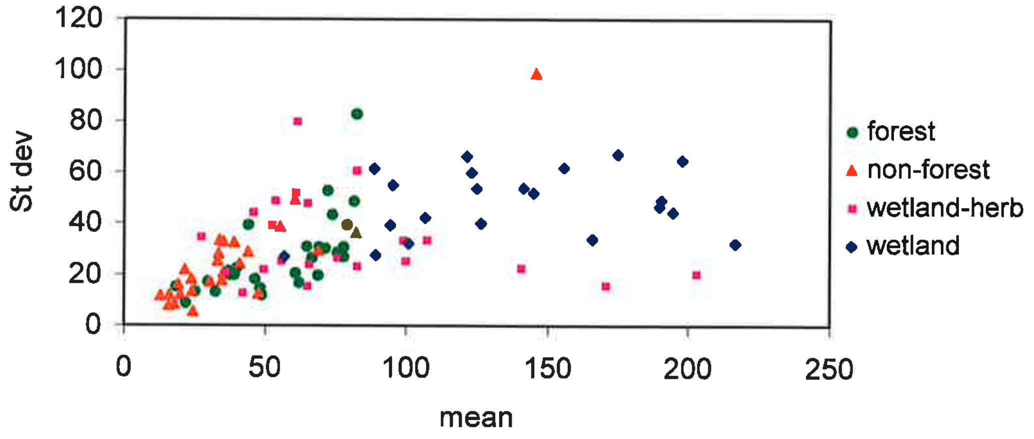

Figure 6. Mean value and standard deviation for ERS 1-2- SAR averaged radar backscatter intensity (Bakchar July'98).

October is the end of vegetation season (biomass decreased) and soil after rainy September is quite moist. Distinguishing of the classes is hence more distinct (Figure 7) than in case of the July data.

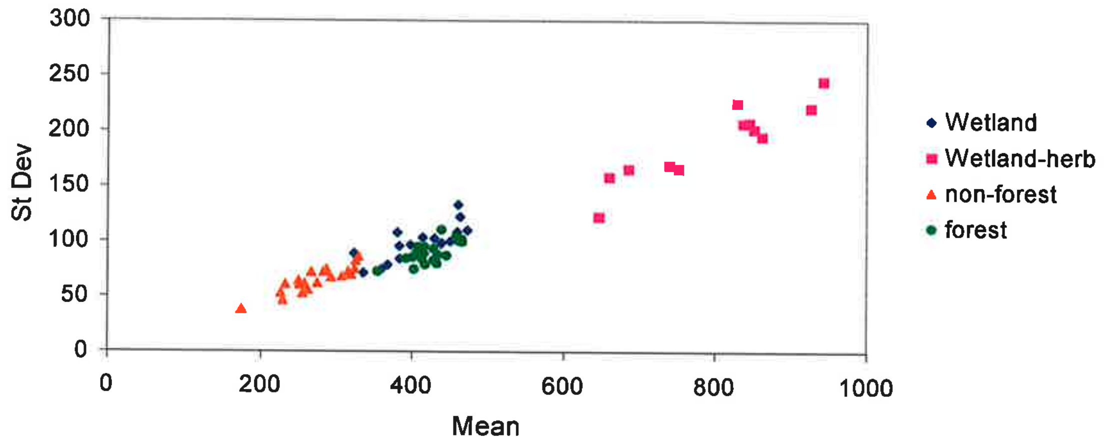

Figure 7. Mean value and standard deviation for ERS 1-2- SAR averaged radar backscatter intensity (Bakchar October'98).

Image coherence analysis

Using the ERS C-band SAR for studies of forest it turned out to be more useful information in the coherence between the ERS-1 and ERS-2 coverage obtained one day apart as is available from the tandem mission. At an areas dominated by medium to high coherence wetlands, low biomass and non-forested areas were identified. Low coherence was found in forest areas. As well as in a case with SAR backscatter intensity the coherence data shows seasonal variations as seen in the mean value and standard deviation for the forestland classes as presented for July (Figure 8) and for October (Figure 9).

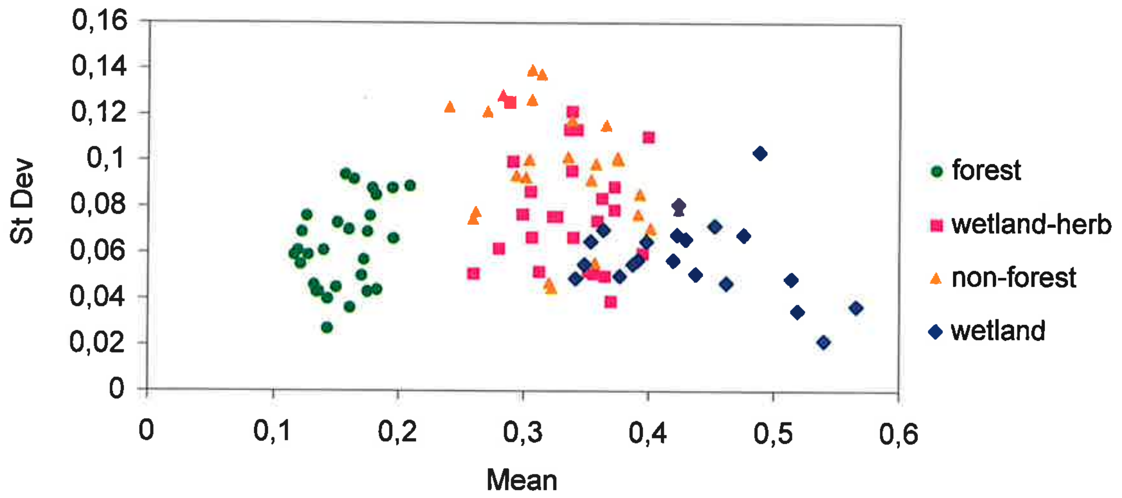

Figure 8. Mean value and standard deviation of ERS 1&2 SAR coherence image (Bakchar July '98).

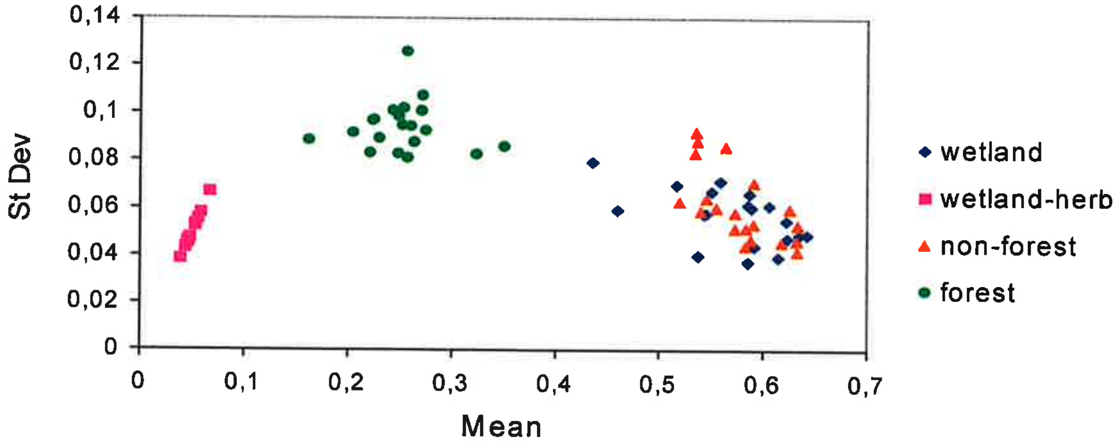

Figure 9. Mean value and standard deviation of ERS 1&2 SAR coherence image (Bakchar October '98).

Wetlands where vegetation is generally low and the surface is presumably smooth the coherence is high for both dates. To distinction a wetland in our case better using the data from July (Figure 8).

Wetlands-herb -wetland with not only herbal vegetation: the coherence is in the middle range for July and low for October. Such wetland very distinct on October data set (Figure 9).

Forest has low coherence and does not reveal any significant seasonal variation between the two data sets. Normally, grown forests (not burned, no clearcut) cannot have high coherence [Siberia, 1999]. Small variations between the two data sets could be explained by the fact that in October the deciduous forest is under leaf-off conditions. The forest areas are very good definable on both data sets from October and July (Figure 8 and 9).

Non-forested classes have variation from middle (July) to high (October) coherence. This class is not distinguishable for any of the data sets and mixes with both wetland and wetlands-herb classes.

For a given site, the dependency between coherence and different forestland classes is not fixed and depending on vegetation season, weather and sol moisture conditions. Also we can conclude that coherence is not only depending on scattering properties of the observation target, but also on observation geometry, environmental effects and phase of vegetation season, which makes its use for classification purposes limited.

Joint backscatter and coherence analysis

A combination of averaged backscatter intensity and image coherence is a method to get better classification results for both July (Figure 10) and October (Figure11). But still for July we have mixed non-forest and wetland-herb classes. For October every class forms non-overlapping clusters, which is one criteria for use in classification.

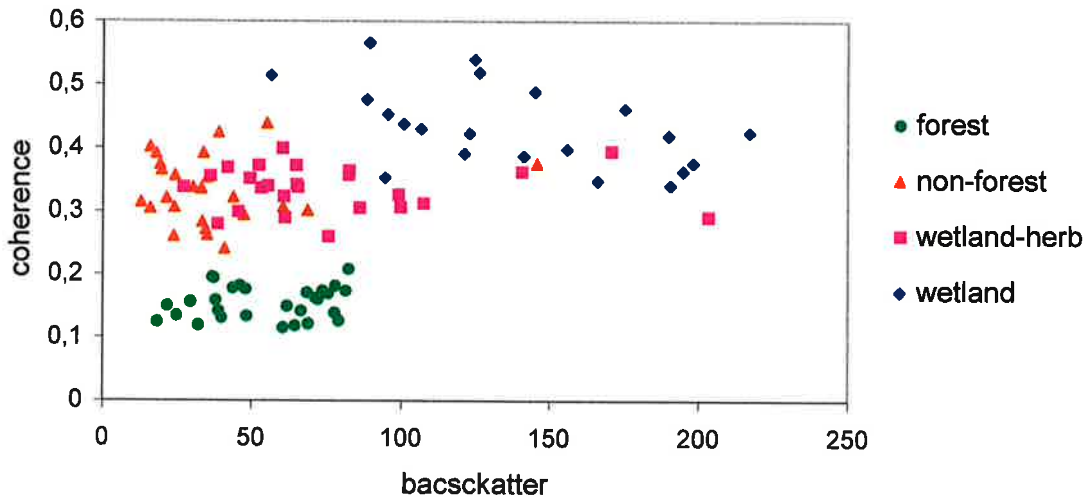

Figure 10. ERS 1&2 SAR coherence and backscatter amplitude mean value (Bakchar July '98).

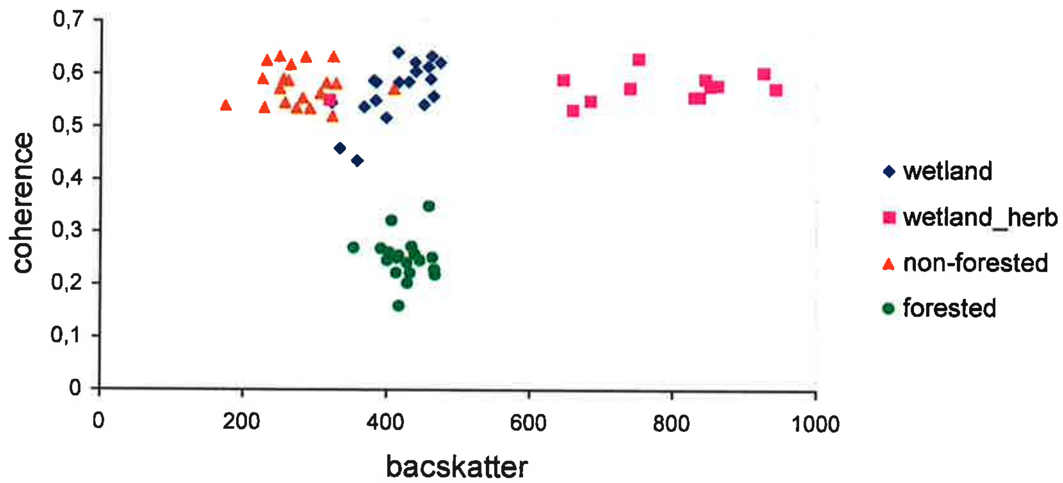

Figure 11. ERS 1&2 SAR coherence and backscatter amplitude mean value (Bakchar October '98).

6.3. Analysis of JERS SAR data to distinguish forests land-cover classes - the Bakchar test site

Since no coherence was produced for the JERS image as well as no radiometric correction have been done on the data, we analyse only the JERS SAR signal amplitude.

For the Bakchar test site a multi-temporal set of images is available (see Table 7). It gives us a possibility to perform multi-temporal analysis and to endeavour establishing a temporal variation of the studied forest classes.

No image from JERS data set was capable of accurately distinguishing between all the studied forestland classes using the radar backscatter signal. In particular overlapping between forest and wetland –herb classes and non-forest and wetland classes are predominant (Figure 12).

The best separability was found for forest and non-forest classes mostly for high vegetation period such as May (b), August (c) and September (d).

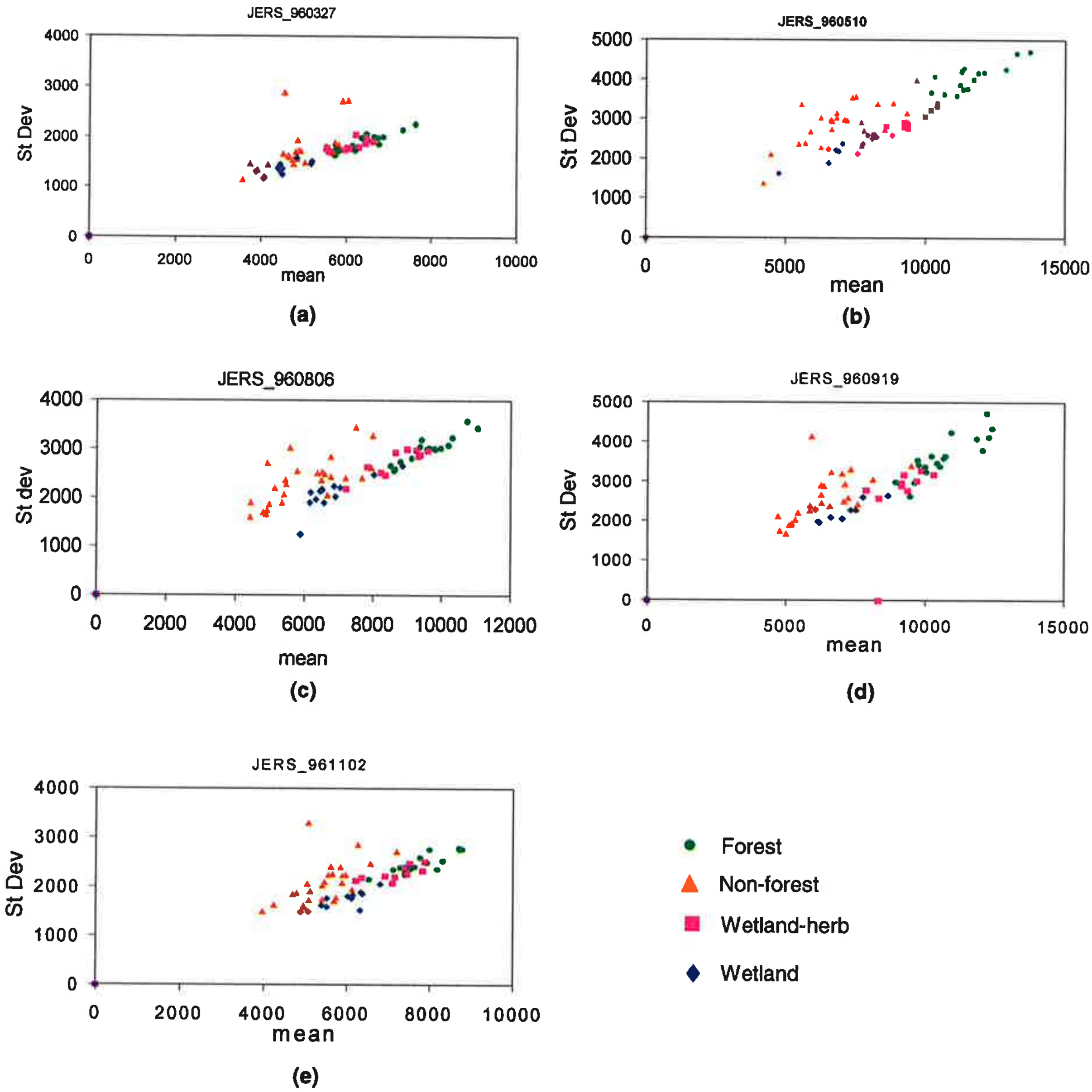

Figure 12. JERS SAR signal amplitude means value and standard deviation for the various images (JERS_yr/mo/date) from the Bakchar site.

Temporal variability of the JERS backscatter amplitude

The temporal variability of the signal amplitude was defined as the ratio of the standard deviation to the mean value.

Based on the analysis of the time series of the signal amplitude, we can conclude that the JERS radar backscatter signal has a pronounced seasonal dependence. The temporal signal amplitude over forest (Figure 13) and wetland with herbal and woody vegetation confirms the JERS sensitivity to biomass (Figure 14), throughout the growth season.

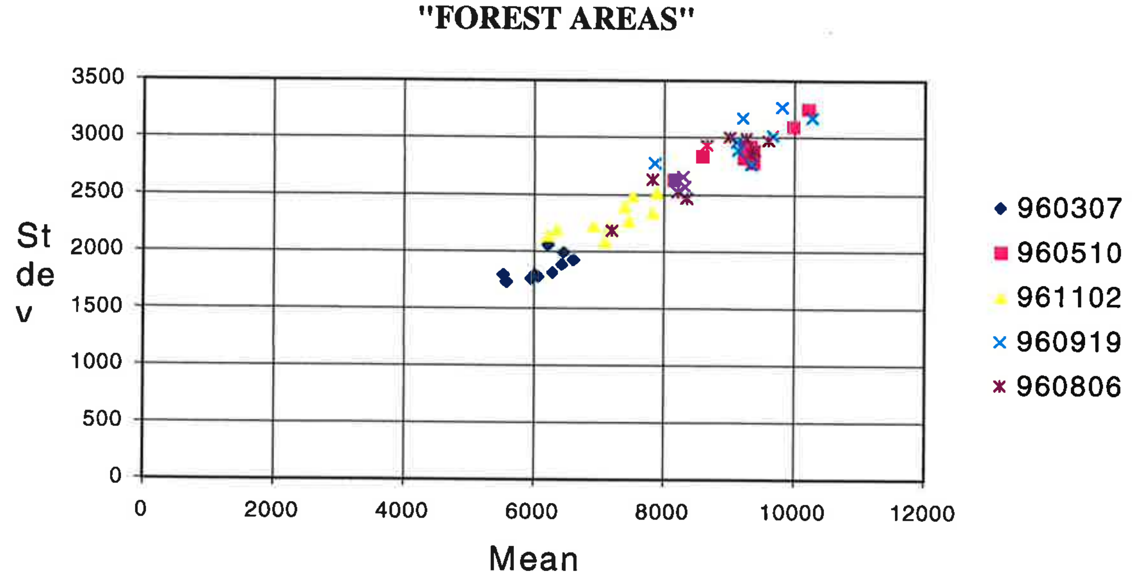

Figure 13. Mean and standard deviation of the signal amplitude for the forest classified area, plotted for the five seasonal different JERS images.

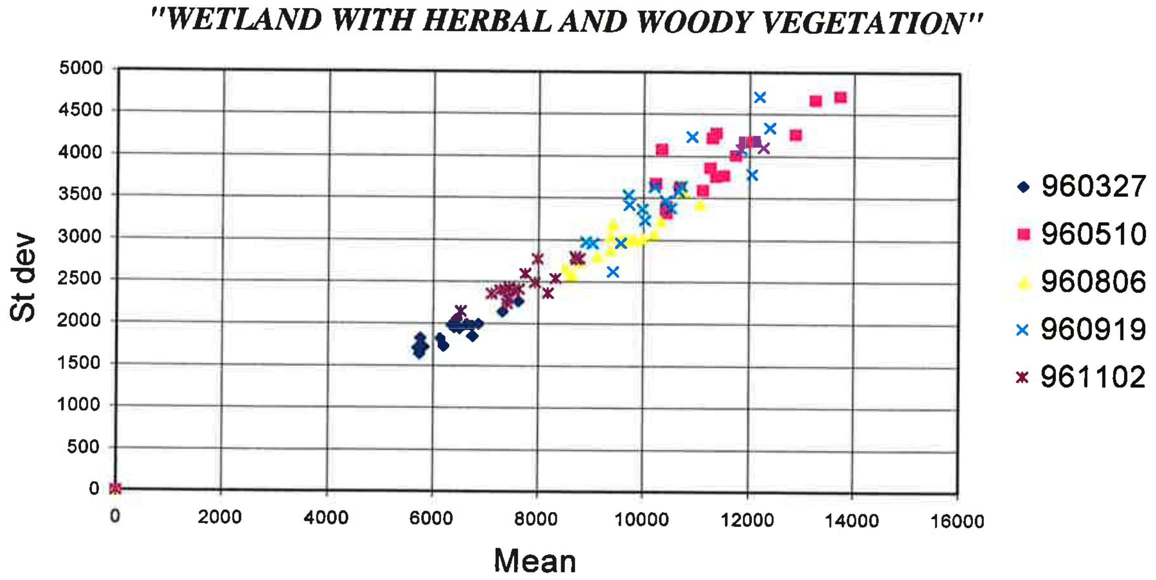

Figure 14. Mean and standard deviation of the signal amplitude for the wetland with herbal and woody vegetation classified area, plotted for the five seasonal different JERS images.

The JERS-1 observations of the radar backscatter show a strong increase with the increasing volume of biomass (growth season). The highest signals are registered for May and September with lower values in March and November. In May and September, especially for the study region, both the vegetation and ground are wet due to respectively the snow melting and heavy rainfall. The L-band observation for northern Finland discussed in [Pulliainen et al., 1999] has shown similar results.

6.4. Summary of ERS and JERS SAR analysis

Based on the analysis of ERS1 & 2 SAR and JERS SAR images for the Banchar test site the following conclusions can be drawn:

For the C-band studies of forest more useful information resides in the coherence between the ERS-1 and ERS-2 coverage one day apart during the Tandem mission. At an areas dominated by medium to high coherence wetlands, low biomass and non-forested areas were identified and distinguishable. Low coherence was found for the forestland classes, however, the coherence has strong seasonal dependence, which is also the case for the SAR backscatter signal.

For a given site, the dependency between coherence and different forestland classes is not firm and depending on vegetation season, weather and soil moisture. Also we can conclude that the coherence signal is not only depending on the scattering properties of the observation target, but also on the observation geometry, environmental effects and phase of vegetation season.

The combined analysis of averaged backscatter intensity and image coherence signal shows a possibility to get better results, with respect to identify and distinguish the various classes.

No image from the JERS data set was capable of accurately distinguishing between the studied forestland classes, in all the temporal data overlap between the various classes were observed.

Based on the time series of the signal amplitude we can conclude that the JERS signal has a pronounced seasonal dependence, which makes standardised classification routines doubtful.

The JERS-1 backscatter signal shows a strong increase with the increasing volume of biomass and surface soil moisture. The highest signal are registered for May, August and September.

7. SUMMARY AND CONCLUSION

The spatial distribution and characteristics of Russian boreal forests are poorly mapped. This goal can be reached only by integrated use of Earth observation (EO) techniques, and through application of remote sensing methods for the study of such large and non-uniform areas as the Siberian boreal forests. Realisation of this aim presents a strong technical challenge, both in acquiring appropriate satellite EO data and development of robust processing and analysis methods.

Satellites with optical sensors have played a leading role in monitoring forest ecology dynamics. However, the optical sensors have serious limitations such as dependence on weather (cloud cover) and sun illumination conditions (day light). In contrast, satellite radar remote sensing provides daytime independent all-weather information. Spaceborne radar remote sensing has become an increasingly important tool for observations of forest ecosystems [Anon., 1998].

For the study, the region located in the central part of West Siberian Plain, the Ob' River basin has been selected (see Figure1). The reasons that this area was chosen are follows: Firstly, West Siberia is weakly studied. Studies of the landscape and natural process, such as inundation and swamping, have a significant scientific as well as practical importance. Secondly, Western Siberia in general has become testing ground to study the results of a heavy human impact on the environment, since huge forestland areas in this region have been clear cut or affected by large forest fire.

Within this region four test sites that have been chosen for the implementation of this study. They differ from one another by forest nature, degree of antropogenic and natural influence and other factors.

Topographic data were specially produced for each key test sites on scale 1:200.000. The data were processed using facilities of a Russian cartographic company, and are available in ARC/Info formats on a CD-ROM (Figures B5-B8).

The forest husbandry data are based on the results of forest inventory (mapped in 1992-93). Maps in digital format are available for the main part of the territory included the four selected test sites (Figure B1-B4).

The focus of this study has been to evaluate the benefit of using satellite Synthetic Aperture Radar (SAR) in classification of major forest land cover classes. For this purpose SAR data from both the European ERS-1 and -2 and the Japanese JERS have been acquired.

During the overlap period between the ERS 1 and 2 missions - the so called tandem mission - repeated SAR data coverage was obtained at 24 hours interval. In this period the German (DLR) mobile ground station in Ulan Bator, Mongolia acquired SAR coverage for major parts of the Ob' River basin. The ERS data were acquired by. Through an ESA ERS AO3 project, the Nansen Centers have 80 ERS-1 and ERS-2 SAR scenes (40 tandem pairs) available. Also for this study some ERS1-2/SAR tandem data were obtained by JRC/GVM from DLR. The majority of the scenes analysed were taken between Sept. 21-Oct. 26, 1997, but we also have 8 scenes from July 1998. This is a unique dataset for an area that previously had no ERS SAR coverage.

JERS-1 data were obtained from the Japanese Space Agency (NASDA) within the framework of the Global Boreal Forest Mapping (GBFM) project conducted by SAI/JRC. For the current study, images most closely corresponding to ERS data by location and time have been chosen. Total 18 JERS scenes were available to this study.

Different software were evaluated for co-registration, radiometric and geographic correction, and for processing of the interferometric coherence for the ERS tandem pairs of SAR data.

Software from the company SARMAP in Switzerland were evaluated as appropriate, and it was decided (with JRC) to use their software for most of the pre-processing tasks. However, it has not yet been evaluated if this software package also can be used for the Japanese JERS scenes, and how well it would work on a large-scale operational basis.

For each other four test sites ERS SAR tandem pairs and JERS SAR images were processed and analysed. For each ERS tandem pair, the coherence and SAR signal average amplitude have been estimated. For JERS data we analyse only the SAR signal amplitude, due to the lack of data available for coherence studies.

The remote sensing data were analysed in order to assess their ability to detect and separate different but contiguous forestland cover classes, i.e. forests, non-forested, wetlands and wetlands with herbal and rarely wood vegetation (see section 6.1).

The study concludes that more useful information on the land cover classes resides in the coherence between the ERS-1 and ERS-2 coverage, one day apart. A combination of radar backscatter amplitude and image coherence can provide good facility to distinguish forestland classes especially during the low vegetation season.

For a given site, the dependency between coherence and different forestland classes is not unambiguous and depends on vegetation season, weather and soil moisture. Also we can conclude that coherence does not only depend on the scattering properties of the observation target, but also on the observation geometry, environmental effects and phase of vegetation season. This conclusion implies that further research is needed in order to develop robust classification methods.

The JERS backscatter data do neither show sufficient capability to accurately distinguish between the studied forestland classes. However, a strong seasonal dependence of the JERS signal and its sensitivity to the biomass volume allow utilisation of these data for forest composition mapping purposes.

The conclusion of this study with respect to the capabilities of imaging satellite radars to investigate forest cover in the West Siberian summarises as follows:

- Use of imaging radar (ERS1&2 SAR and JERS SAR) has a capability to map and monitor forested –wetland terrestrial areas;
- Multi-channel ERS SAR data (i.e. from analysis of backscatter and coherence) provide a means to distinguish different forest land-cover patterns;
- JERS SAR data are sensitive to variations in vegetation structure as well as vegetation and ground-layer moisture, resolved through seasonal variation;

- The ERS SAR data are currently most appropriate for detection of wetland with herbal vegetation as well as with herbal and woody vegetation.

These analyses have confirmed the high information content of ERS SAR products with respect to low biomass classes and hence the capability to map wetland and identify and map burned and logged forest areas. But it is still questionable whether ERS SAR data can be applied for estimation of forest volume and species composition. From scientific perspective this is a challenging question, but the current methods do not satisfy the expectations for forestry mapping.

Still ERS SAR data provide unique opportunity to study dynamic wetland processes related to biogenic trace gas emissions, with relevance to studies of the role of the boreal forests in relation to global change.

Today, one of the greatest uncertainties concerning the global carbon budget arises from a lack of information on forest biomass. JERS SAR have demonstrated some capability to retrieve and monitor variations in forest biomass. Both ERS and JERS SAR have hence a considerable potential for mapping and monitoring forests on a regional scale and in particular the Siberian boreal forests.

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Appendix

Assessment of radar techniques for regional forest cover mapping over Siberian forests

by
Victoria V. Donchenko, NIERSC
and
Lasse H. Pettersson, NERSC

Bergen, 19. September 2000

ANNEX A

SATELLITE SAR IMAGES FOR BAKCHAR TEST SITE USED IN THE STUDY

Figure A1. Coherence image generated from two ERS-1&2 SAR images on 7 July 1997 and 8 July 1997.

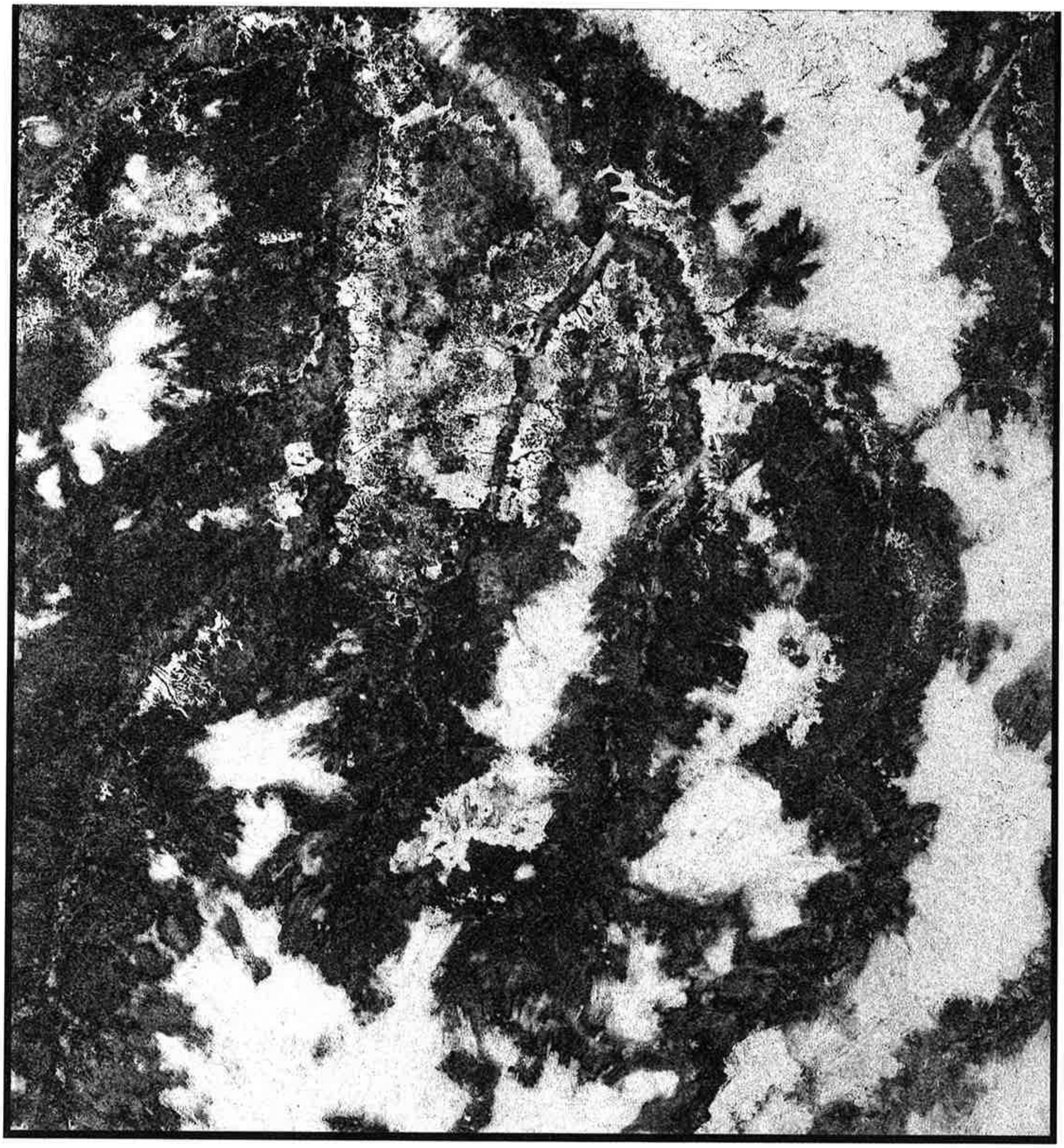


Figure A2. Coherence image generated from two ERS-1&2 SAR images on 30 September 1997 and 1 October 1997.

Figure A3. The average of two ERS-1&2 SAR images on 7 July 1997 and 8 July 1997.

Figure A4. The average of two ERS-1&2 SAR images on 30 September 1997 and 1 October 1997.

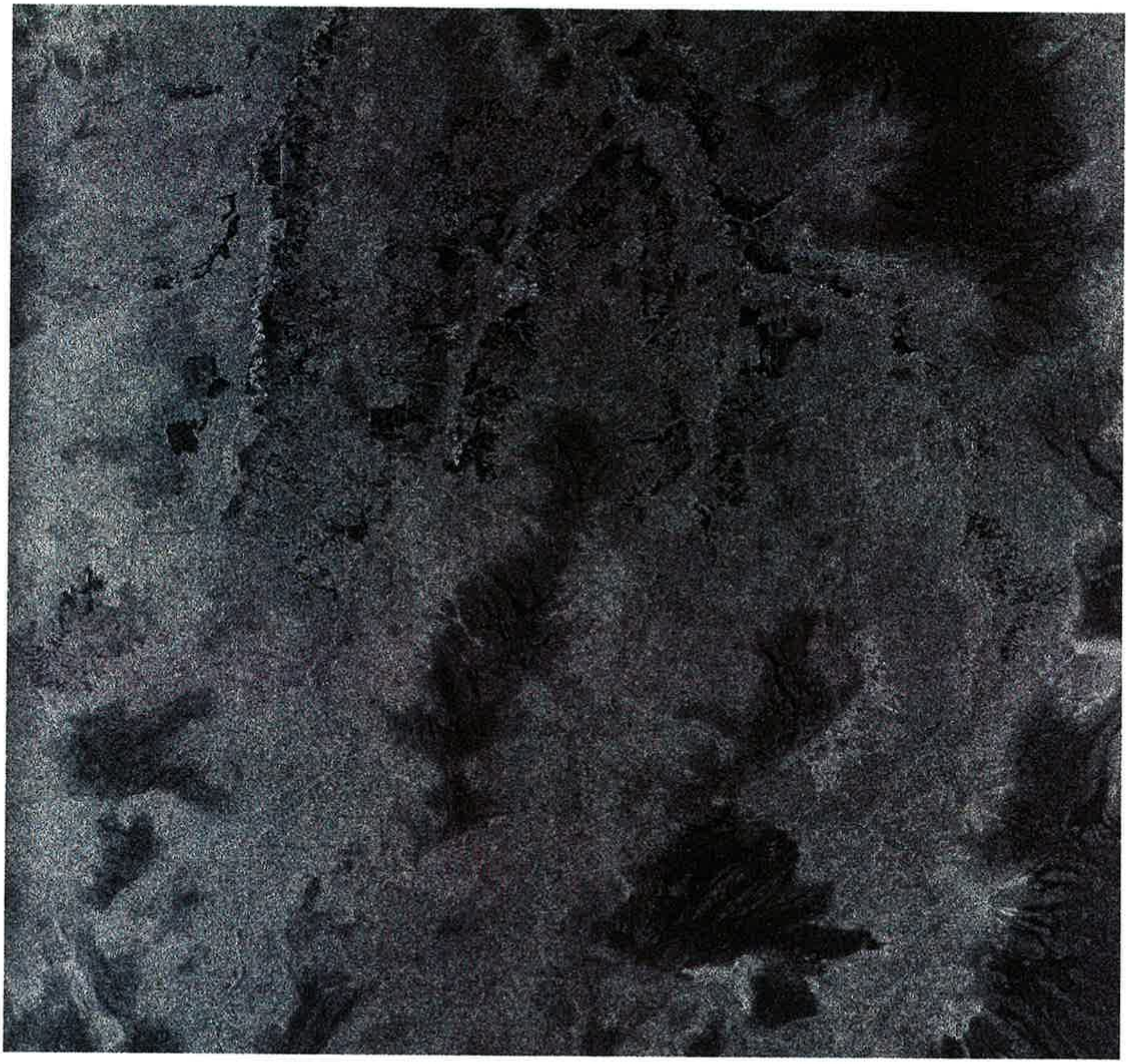


Figure A5. JERS-1 SAR image on 27 March 1996.

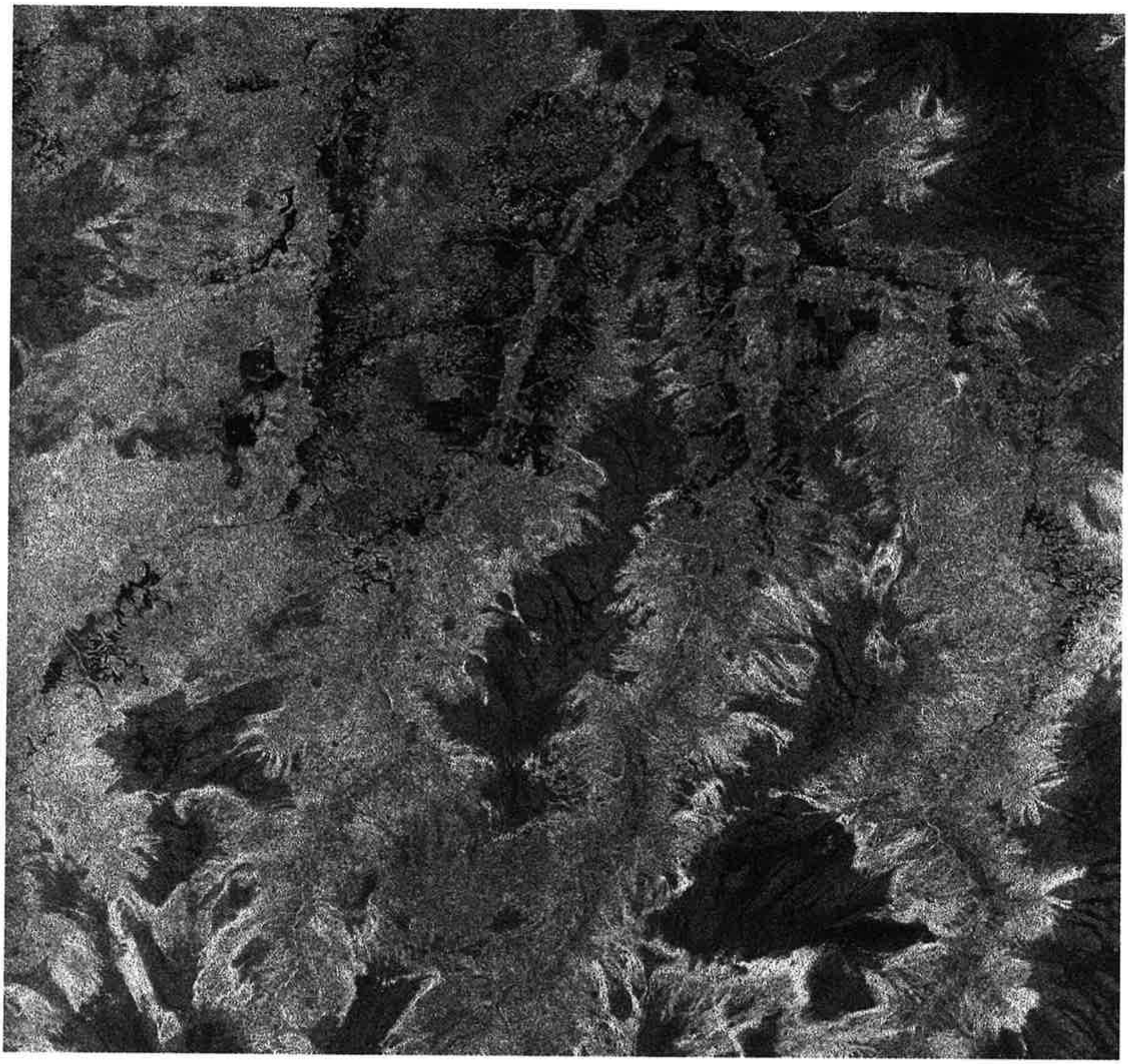


Figure A6. JERS-1 SAR image on 10 May 1996.

Figure A7. JERS-1 SAR image on 6 August 1996.

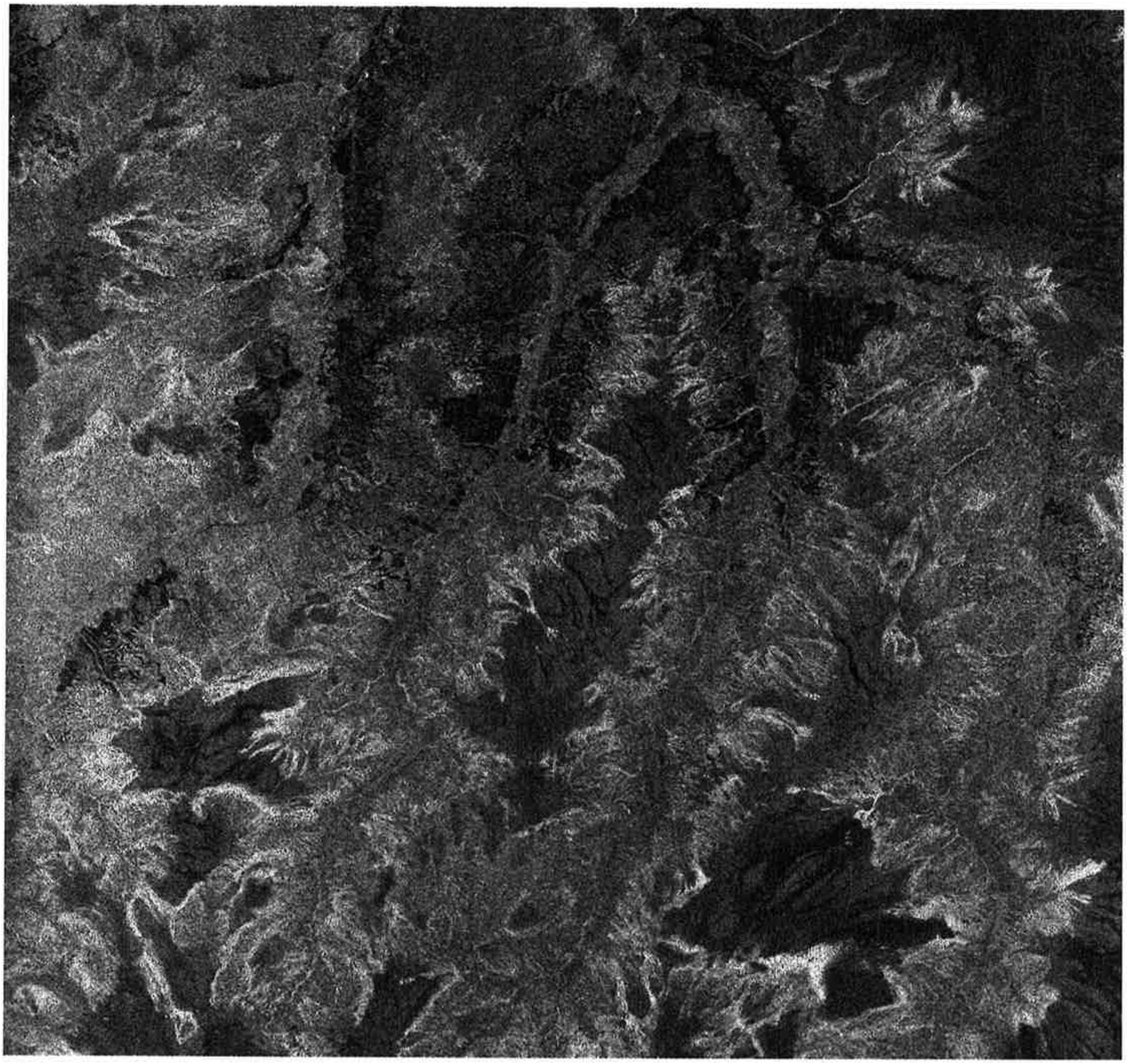


Figure A8. JERS-1 SAR image on 19 September 1996.

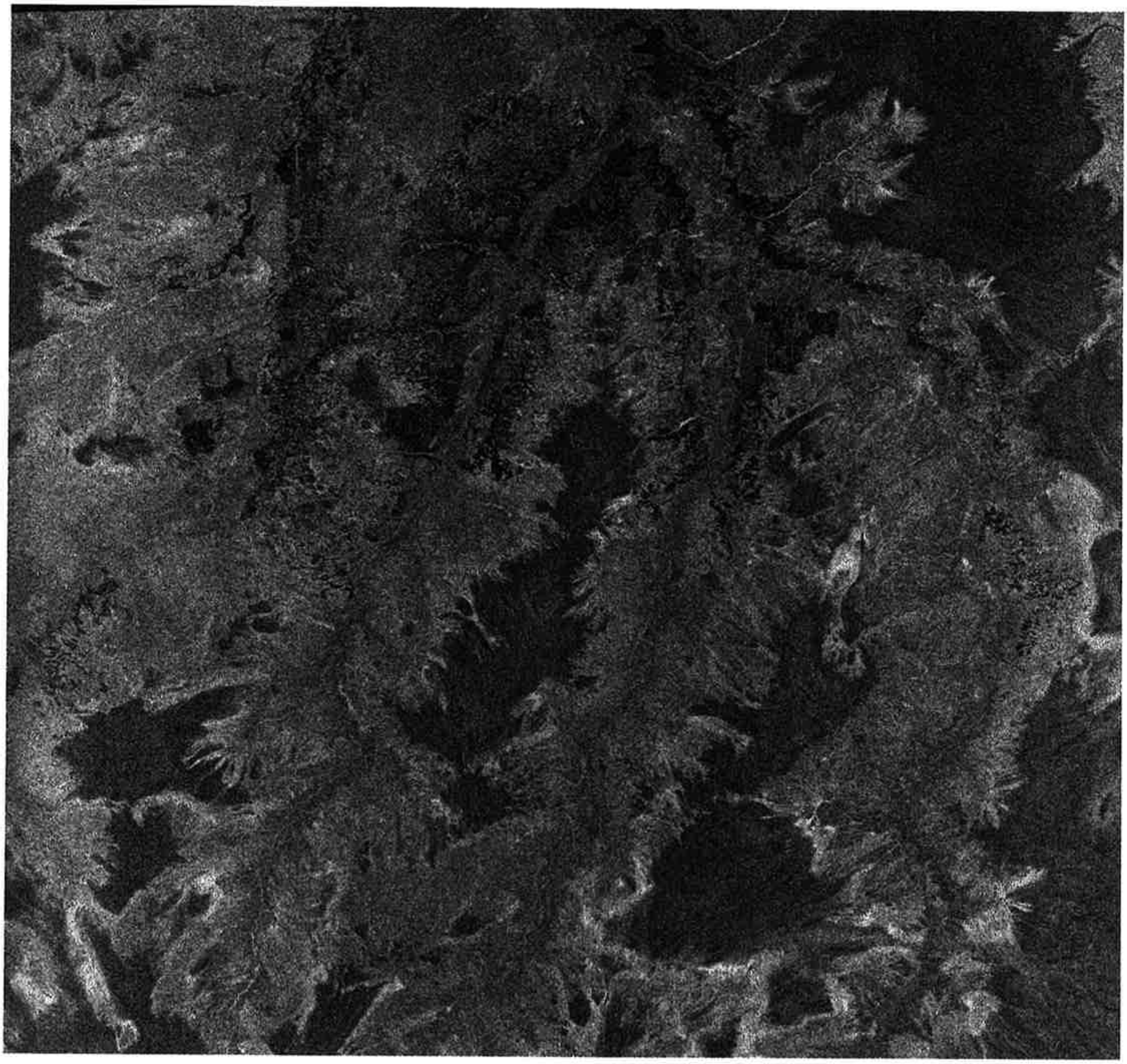


Figure A9. JERS-1 SAR image on 2 November 1996.

ANNEX B

GROUND TRUTH DATA

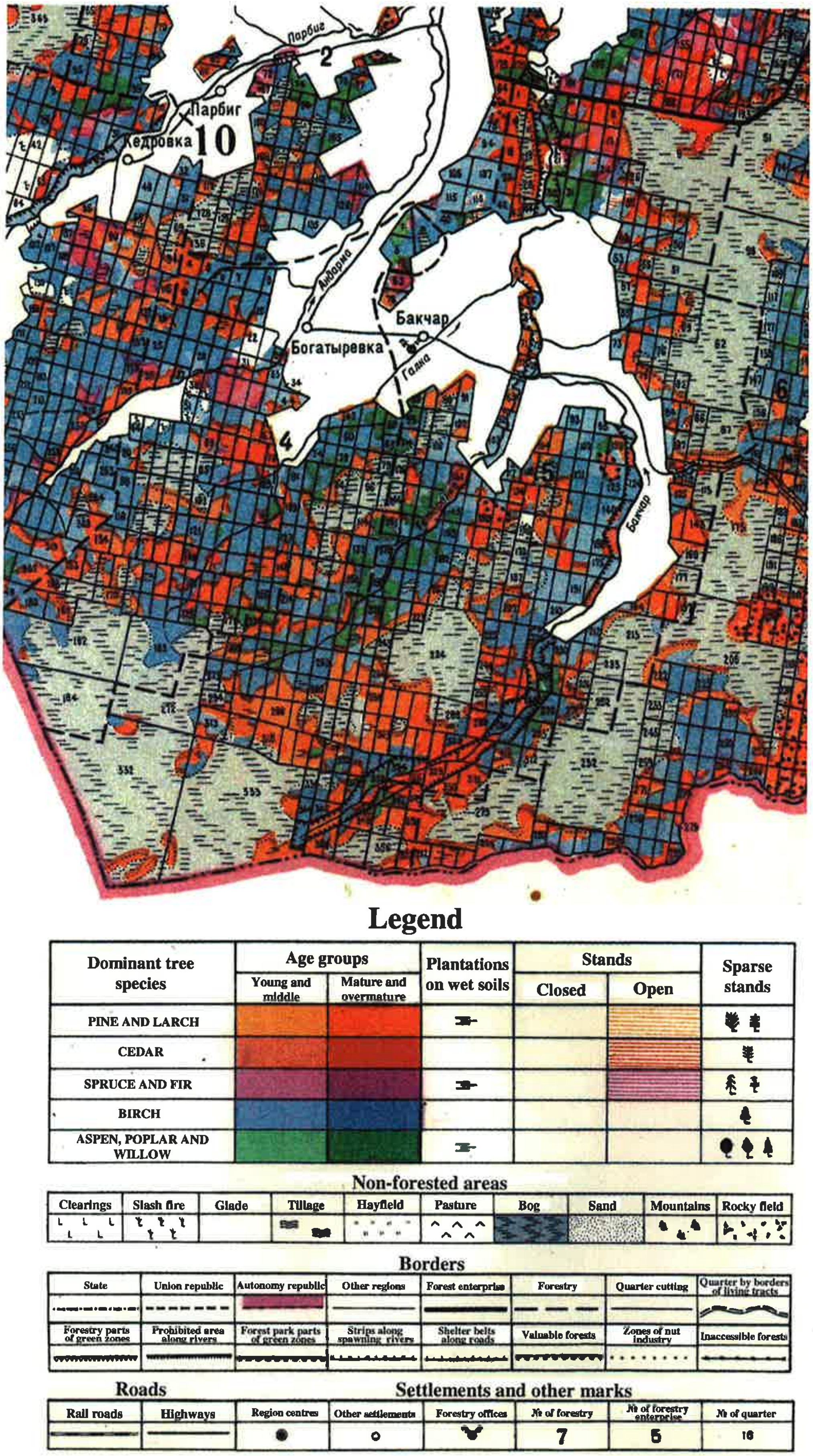


Figure B1. Forest husbandry data for Bakchar test site, 1:500 000.

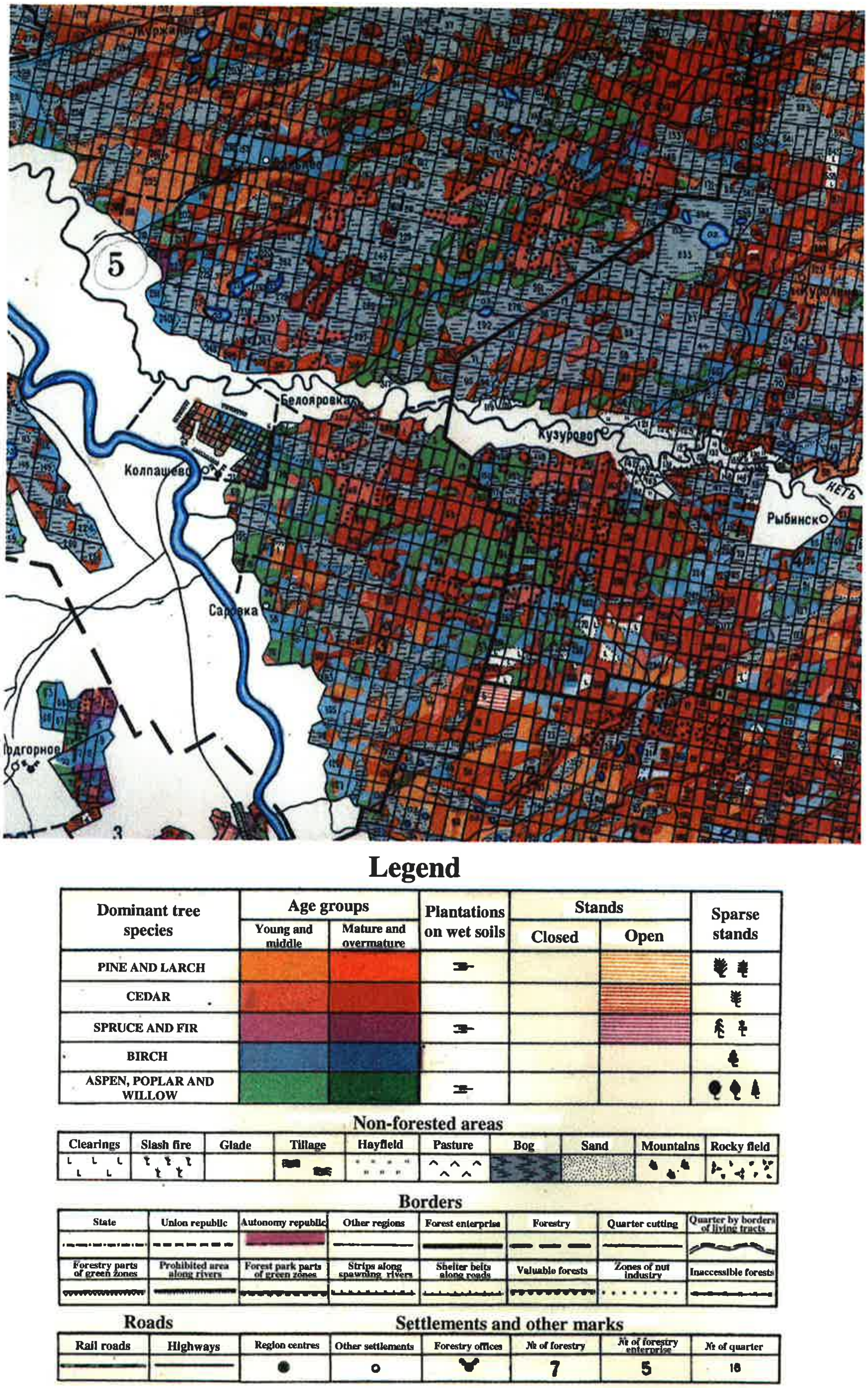
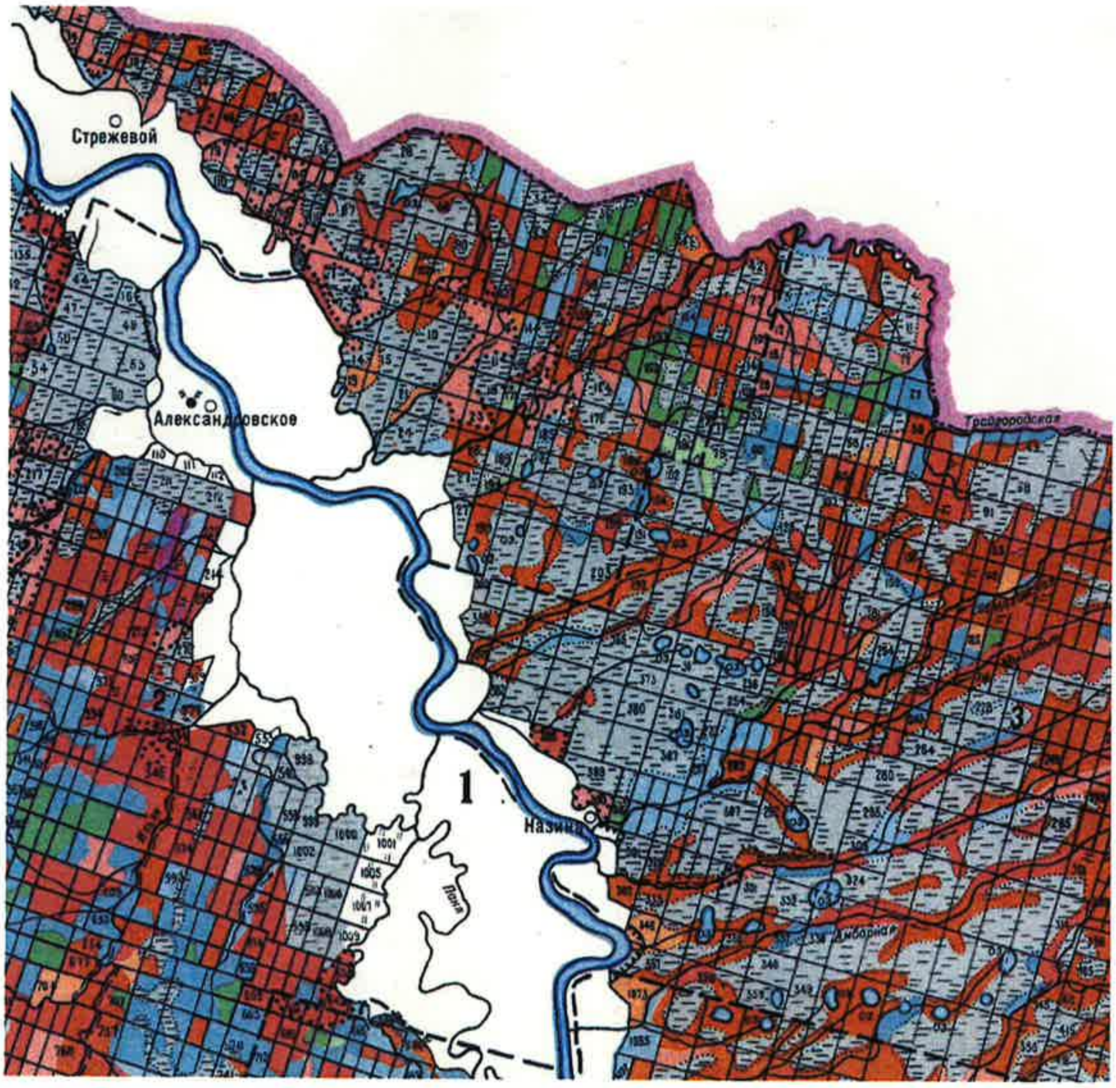


Figure B2. Forest husbandry data for KOLPASHEVO test site, 1:500 000.



Legend

Dominant tree species	Age groups: Young and middle	Age groups: Mature and overmature	Plantations on wet soils	Stands: Closed	Stands: Open	Sparse stands
PINE AND LARCH						
CEDAR						
SPRUCE AND FIR						
BIRCH						
ASPEN, POPLAR AND WILLOW						

Non-forested areas

Clearings	Slash fire	Glade	Tillage	Hayfield	Pasture	Bog	Sand	Mountains	Rocky field

Borders

State	Union republic	Autonomy republic	Other regions	Forest enterprise	Forestry	Quarter cutting	Quarter by borders of living tracts
Forestry parts of green zones	Prohibited area along rivers	Forest park parts of green zones	Strips along spawning rivers	Shelter belts along roads	Valuable forests	Zones of nut industry	Inaccessible forests

Roads / Settlements and other marks

Rail roads	Highways	Region centres	Other settlements	Forestry offices	№ of forestry	№ of forestry enterprise	№ of quarter
					7	5	16

Figure B3. Forest husbandry data for Strezhevoy test site, 1:500 000.

Legend

Dominant tree species	Age groups		Plantations on wet soils	Stands		Sparse stands
	Young and middle	Mature and overmature		Closed	Open	
PINE AND LARCH						
CEDAR						
SPRUCE AND FIR						
BIRCH						
ASPEN, POPLAR AND WILLOW						

Non-forested areas

Clearings	Slash fire	Glade	Tillage	Hayfield	Pasture	Bog	Sand	Mountains	Rocky field

Borders

State	Union republic	Autonomy republic	Other regions	Forest enterprise	Forestry	Quarter cutting	Quarter by borders of living tracts
Forestry parts of green zones	Prohibited area along rivers	Forest park parts of green zones	Strips along spawning rivers	Shelter belts along roads	Valuable forests	Zones of nut industry	Inaccessible forests

Roads / Settlements and other marks

Rail roads	Highways	Region centres	Other settlements	Forestry offices	№ of forestry	№ of forestry enterprise	№ of quarter
					7	5	18

Figure B4. Forest husbandry data for Vangil-Kynak test site, 1:500 000.

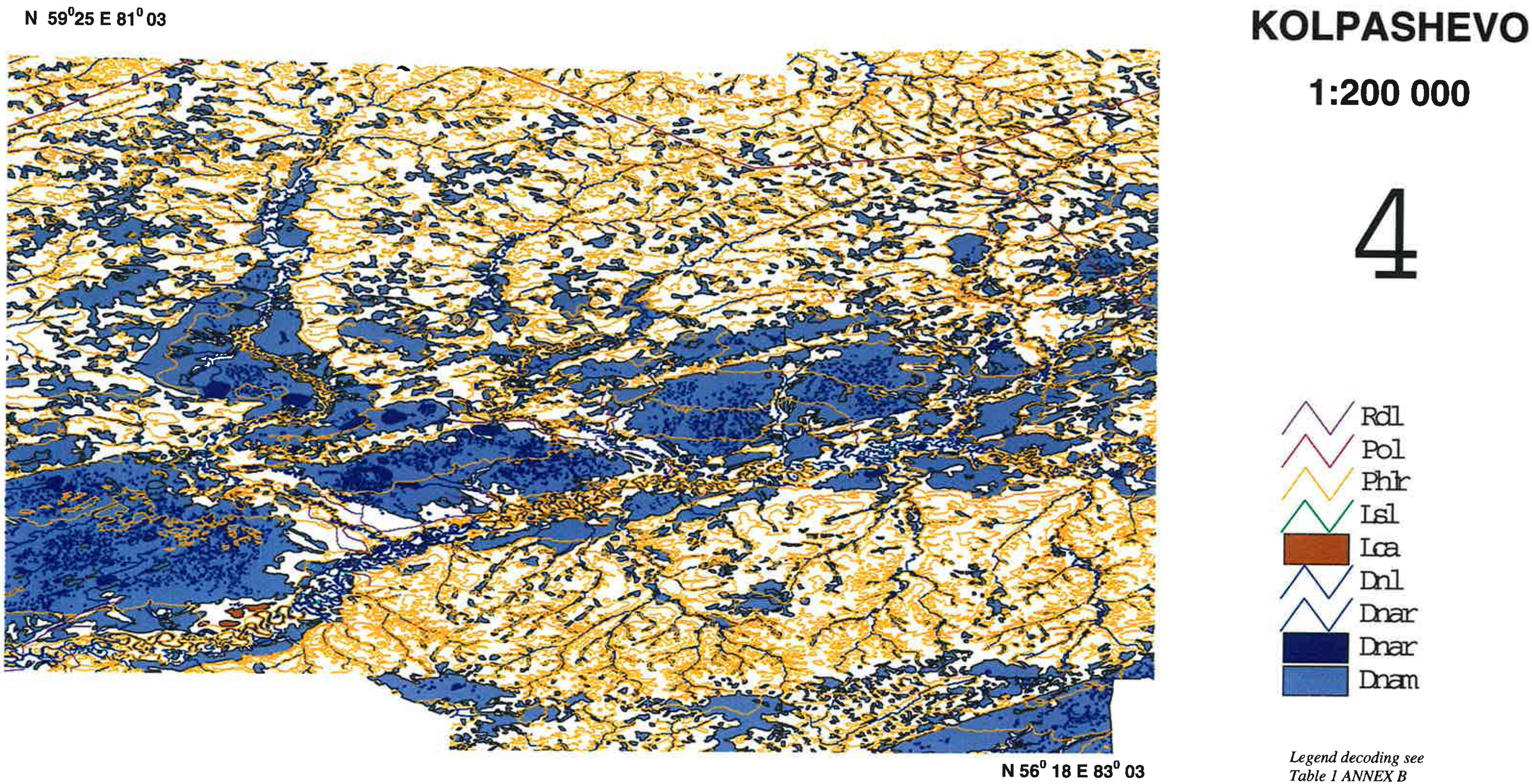


Figure B5. Topographic data on Kolpashevo test site

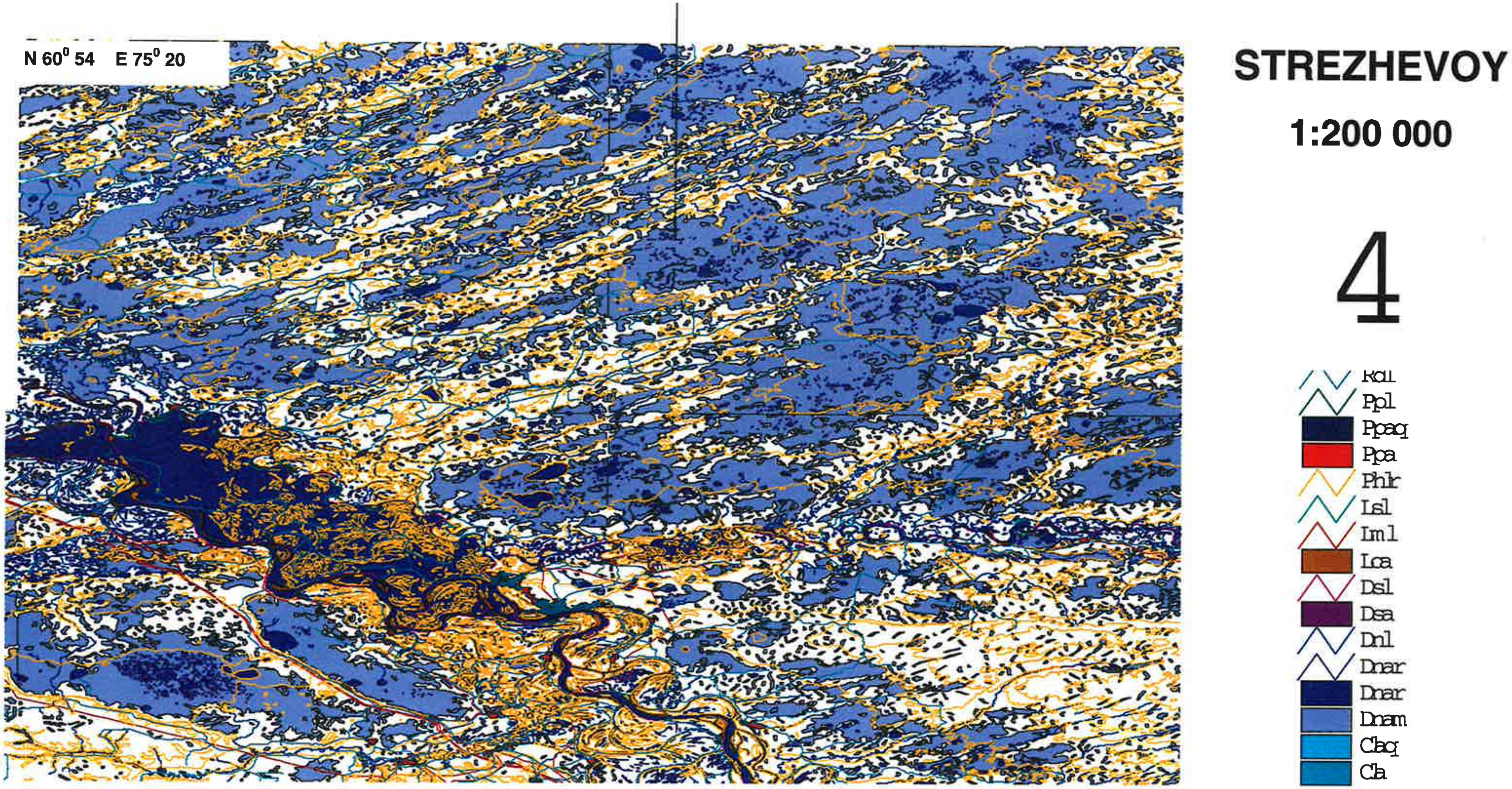


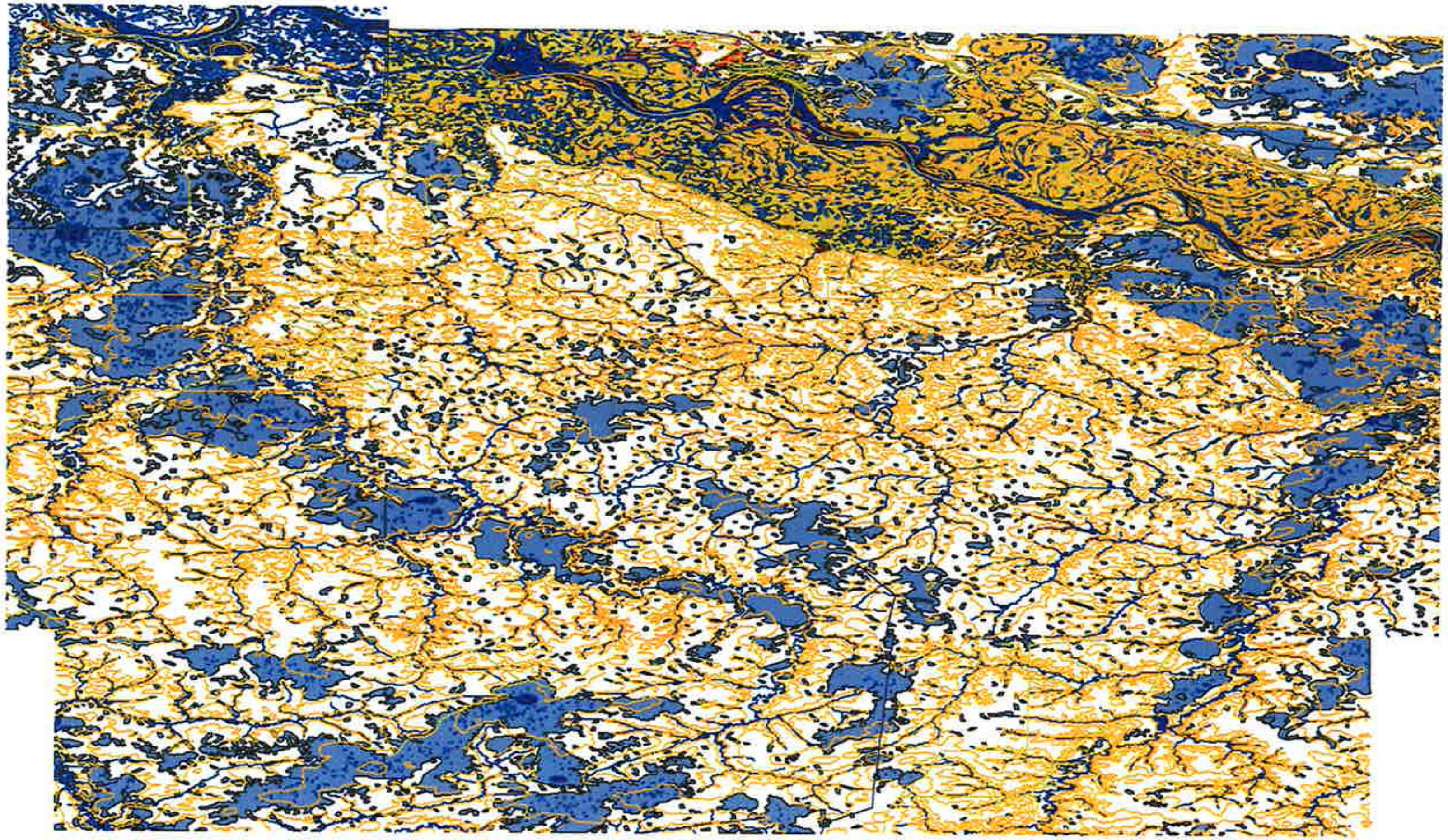
Figure B6. Topographic data on Strezhevoy test site

Legend decoding see Table 1 ANNEX B

VANGIL-KUNAK

1:200 000

N 60^0 55 E 82^0 38



N 59^0 48 E 84^0 51

4

Rdl
Ppaq
Ppa
Pol
Phlr
Isl
Lsa
Iml
Lca
Dsl
Dnl
Dnar
Dnar
Dnam
Dnaf
Cll
Cla

Figure B7. Topographic data on Vangil-Kunak test site

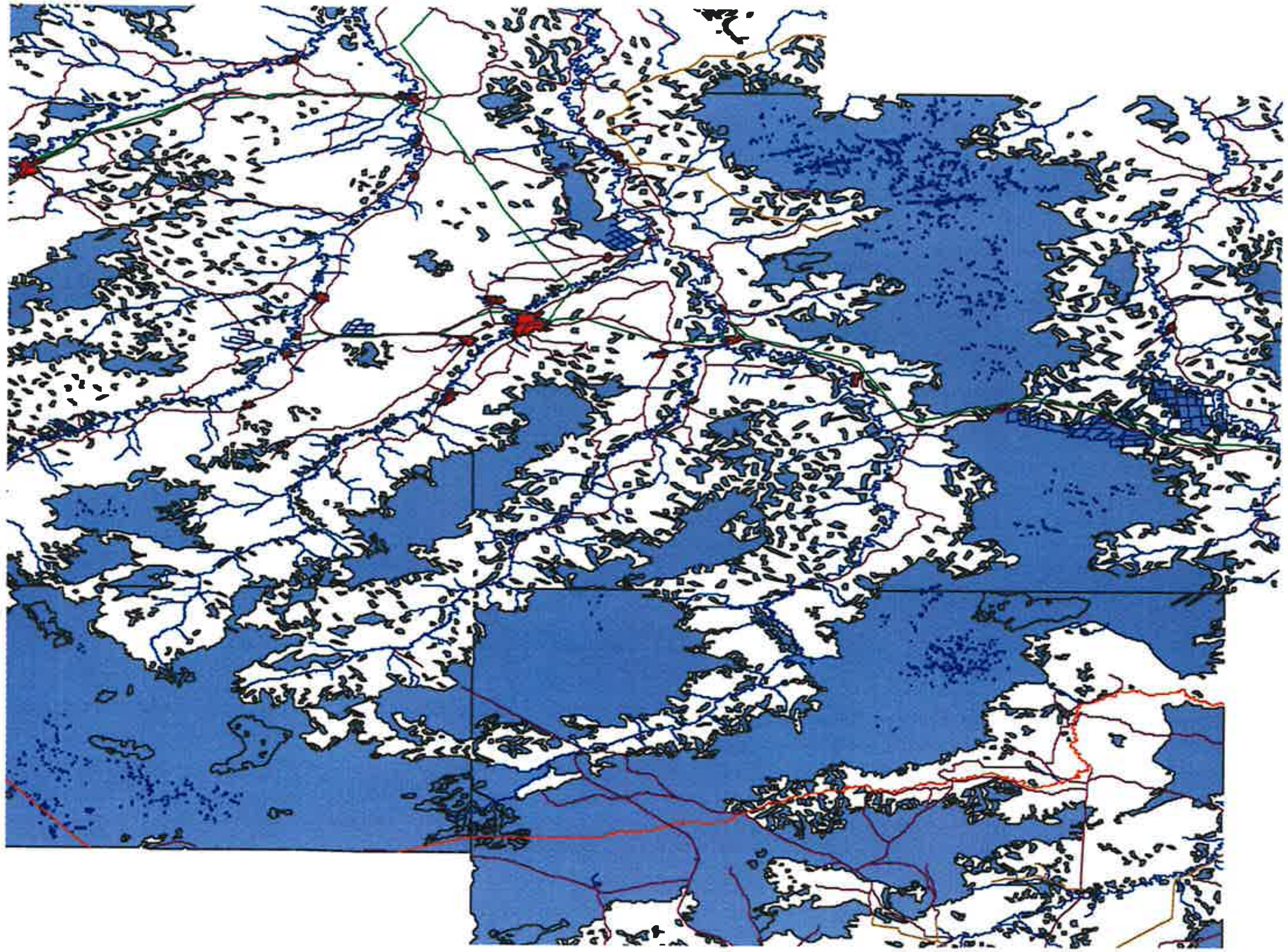
Legend decoding see Table 1 ANNEX B

N 57^{0} 25 E 81^{0} 27

Bakchar

1:200 000

4



Rrl
Rdl
Ppa
Pol
Isl
Iml
Dsl
Dnl
Dnar
Dnar
Dnam
Cla

Legend decoding see Table 1 ANNEX B

N 56^{0} 30 E 83^{0} 03

Figure B8. Topographic data on Bakchar test site

Table B1. Legend decoding for topographical maps, 1 : 200 000

Name of layer	Decoding
PHLR	Contour line
DNAR	Lakes, rivers, water reservoirs, canals
DNL	Lakes, rivers, water reservoirs, canals, drains
DNAM	Swamps, saline land
DNAF	Squares and areas of floods
DSL	Waterfalls, rapids, water pipe
PPA	Towns, villages
PPAq	Towns, villages
LML	Transmission facilities, lines of communication, pipelines
RRL	Railways, monorails, tramway roads
RDL	Highways, roads, winter road, ways, paths, descents
POL	Borders, walls, fences, meridians, parallels
CLA	Industrial and agricultural objects
CLL	Industrial and agricultural objects
LCA	Soils, sands (areal)
LSA	Glaciers,frazils,avalanches,pits,ravins,hillocks ,morain, taluses.
LSL	Moraines, scoures, billows, precipices, landslides, glacial fissure