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Changes of Boreal Vegetation in Permafrost Areas of Central Yakutia

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Changes of Boreal Vegetation in Permafrost Areas of Central Yakutia

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Abstract (English)

Mankind influences the vegetation in the northern permafrost areas of Eurasia by its activities, such as mining, forest clearing and pollution. However man is not the only factor inducing changes in Siberian boreal conifer forests, forest fires and other natural processes, e.g. climate change, also have impacts on the vegetation.

In an area besides the Russian river Viluy in Central Yakutia those changes are eminently evident. The combination the local vegetation and the expansion of the cropped area are the mainly influencing factors. For this area, which is mainly covered by larch forests and geomorphological and hydrological very dynamic thermokarst depressions (alases) that are often filled with water, some approaches to quantify these processes are sampled in this work to extract tendencies for the whole circumpolar boreal forest belt. Therefore it has been worked with Landsat-remote-sensing-data and with climate data that were recorded at a weather station in the study area, which have been analysed thoroughly. The presented results show the exploration of the extent and possible reasons for the change of the forest cover.

Abstract (German)

Der Mensch beeinflusst die Vegetation in den nördlichen Permafrostgebieten Eurasiens durch Folgen seiner Wirtschaftstätigkeit, wie Bergbau, Rodungen und Umweltverschmutzung. Allerdings ist der Mensch auch nicht der einzige Faktor, der Veränderungen in den borealen Nadelwäldern Sibiriens bewirkt, Waldbrände und andere natürliche Prozesse wie zum Beispiel der Klimawandel beeinflussen diese ebenfalls.

In einer Region am russischen Fluss Wiljui im zentralen Jakutien sind solche Veränderungen besonders offensichtlich. Für dieses Gebiet, das vorwiegend mit Lärchenwäldern und geomophologisch sowie hydrologisch sehr dynamischen Thermokarst-Senken (Alase), die oftmals mit Schmelzwasser gefüllt sind, bedeckt ist, werden in dieser Arbeit erste Ansätze zur Quantifizierung dieser Vorgänge erprobt, um daraus Tendenen für die gesamte boreale Zone der Erde abzuleiten. Dabei wurde vorwiegend mit Landsat-Fernerkundungsdaten sowie mit Klimadaten einer im Untersuchungsgebiet befindlichen Wetterstation gearbeitet, die jeweils detaillierten Analysen unterzogen wurden. Als Ergebnis stehen die Erforschung des Ausmaßes und mögliche Ursachen der Waldveränderungen.

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List of used abbreviations:

AWI: Alfred-Wegener-Institute for Polar and Marine Research

NASA: North American Space Association

USGS: United States Geological Service

MSS: Multi-Spectral Sensor

TM: Thematic Mapper

ETM: Enhanced Thematic Mapper

NIR: Near Infrared

MIR: Middle Infrared

NDVI: Normalized Differenced Vegetation Index

FAO: Food and Agriculture Organisation of the UN

Note: Because there are several approaches to transcribe Russian and Yakut names into Latin letters, the in corresponding literature most common transcription has been used, although it is not the official method. Sometimes it is different from the rules that have been officially defined for transcription into English by the *GOST 16876-71* rule**.**

Therefore the names of towns, rivers, and other landscape elements are additionally written in their original way in Cyrillic letters.

List of images

1 Introduction

Permafrost and its supposed decline as a consequence of climate change became a highly discussed topic during the last decade. Nevertheless, the public focus is mainly on the reaction of ecosystems in the tundra belt and the rigidity of the ground, e.g. for construction of facilities to exploit and transport natural resources. A lack of information still exists about processes happening within the vegetation in boreal forests on permafrost.
Central Siberia is an ideal region for researching such topics, because the there changes there very visible, because both climate change and human activity influence the ecological circumstances more intensive than in comparable regions.

During researches on changing extent and number of lakes in permafrost areas, it has been noticed that also vegetation has changed. Not only meadows drowned and swamps developed, also the combinations of forest and shrub communities have altered.

The aim of this work is to quantify these changes of vegetation in context to their origin, using remote sensing methods and climate data. Landsat-Data will be used for land cover classifications. The different classifications then will be compared and later related to changes of the climate in the study area. A special focus is put on the influence of forest fires and human activity.
Finally the results will be compared to previous work, to evaluate, whether they turn out to be typical for boreal climates or weather they are a special phenomenon of the study area and its environment.

2 Principals

2.1 Environmental Circumstances in Permafrost Areas

Permafrost is a phenomenon that can be observed mainly in polar and sub-polar latitudes, as well as in some mountain ranges. In sum, around 24% of the continents on the northern hemisphere are permafrost (Brown & Haggerty 1998). The permafrost distribution on the northern hemisphere is visualised in fig.1. On the southern hemisphere permafrost does only occur in highest altitudes, like in the Andes. Relics of permafrost can be found also on the peaks of Kilimanjaro, Mount-Kenya-Range and Rwendzori-Mountains, New Zealand (Allen et al. 1997) and in the rare ice-free parts of Antarctica (Bockheim et al. 2007). As a hangover from times where the sea level was below its present height, submarine permafrost occurs in the shelves of the Arctic Ocean.

Fig. 1: Permafrost distribution on the northern hemisphere
(Source: OceanLink 2010)

Permafrost is defined of frozen ground for at least two winters and the intermediary summer (Brown et al. 2002). Additionally the climate should be relatively dry, otherwise an ice shield, a glacier or a thick snow cover isolates the soil against further cooling. According to Zepp (2004, p. 205), the annual precipitation sum has to be below 1000mm. The same isolating effect can be caused by vegetation coverage with a high density. Only in mountain permafrost and in some protected sites, like cirques, snow cover can have a cooling effect.

Those requirements are given in Alaska, Canada, the polar islands (e.g. Svålbard, Greenland), and Russia, northern Scandinavia (Norway and Sweden) and in several high moun-

tain ranges worldwide (Fig.1).
Although the deeper soil is frozen during the whole year, the top layer partly thaws during the summer months. This thawed soil is called *active layer* and is mostly between 5 and 15cm deep, but could reach at some sites (like in the study area) depths of 70 to 200 cm. The ground below this seasonal unfrozen layer remains ice and is called *ground ice.* In central and eastern Siberia, in areas that have not been covered by continental ice sheets or glaciers, permafrost can reach depths down of 1500m below surface. The thawed ground ice in the active layer supplies the vegetation with water in the growing period.
The literature (e.g. ZEPP 2008, p. 212; KOLSTRUP p. 78 in KOSTER 2005) and FRENSH & SLAYMAKER, p.22) defines 3 types of permafrost, depending on the percentage of the frozen ground in an area. The *continuous permafrost* is defined for regions covered by more than 90% frozen ground. The bottom sediments of lakes or rivers remain unfrozen and are called *taliki.* If more than half of the region has frozen ground, the definition is *discontinuous permafrost*, and if less than 50% of the ground is permafrost, it is called *sporadic permafrost*.

2.2 Latest state of the Art

The knowledge of changes occurring in boreal forests on permafrost areas is very rare. Most of the literature attends to change processes occurring in the tundra. Information about processes occurring in boreal forests in permafrost areas are more rare. The most common fact according the reaction of boreal ecosystems on climate change is, that the timberline is shifting northwards, following the 10°C-July-isotherm, that is the approximated boundary value for forest growth.
During the last years, several researches have been done by, mainly Canadian and Russian scientists, about permafrost areas southerly of the tundra. The influence of changed soil moisture regimes was increasingly researched, e.g. for the right banks of the Lena River by FEDOROV& KONSTANTINOV (2007). But the knowledge that was extracted by these researches is too less to allow principal statements on global developments of moisture in context with climate change.
Relative well established is the active role that boreal forests play in the global climate system (Chapin et al. 2010). Due to the enormous capacities to store carbondioxide, they damp the consequence of climate change significantly. But about the passive role, how react forestal ecosystems on changed climate circumstances, a lack of information exists. One aim of this work is to reduce this deficit.

3 Study area

3.1 Spatial Location and Topography

The study area is situated on Russian territory in eastern Siberia, Yakutia *(respublika Sakha)*. The extension is from 64.4° to 63.6° northern latitude and 118.5° to 121.5° eastern longitude (Fig. 2).

Its acreage is about 18317.7 square kilometres. The largest settlement is the town of Viluysk (Вилюйск), main town and economic centre of the homonymous borough (Russ.: *rayon*). Its population is a bit less than 10000 inhabitants. The second biggest settlement is Verkhneviluysk (Верхневилюйск), also the capital of a homonymous *rayon*. The elevation is between 90m a.s.l. up to nearly 200m a.s.l.

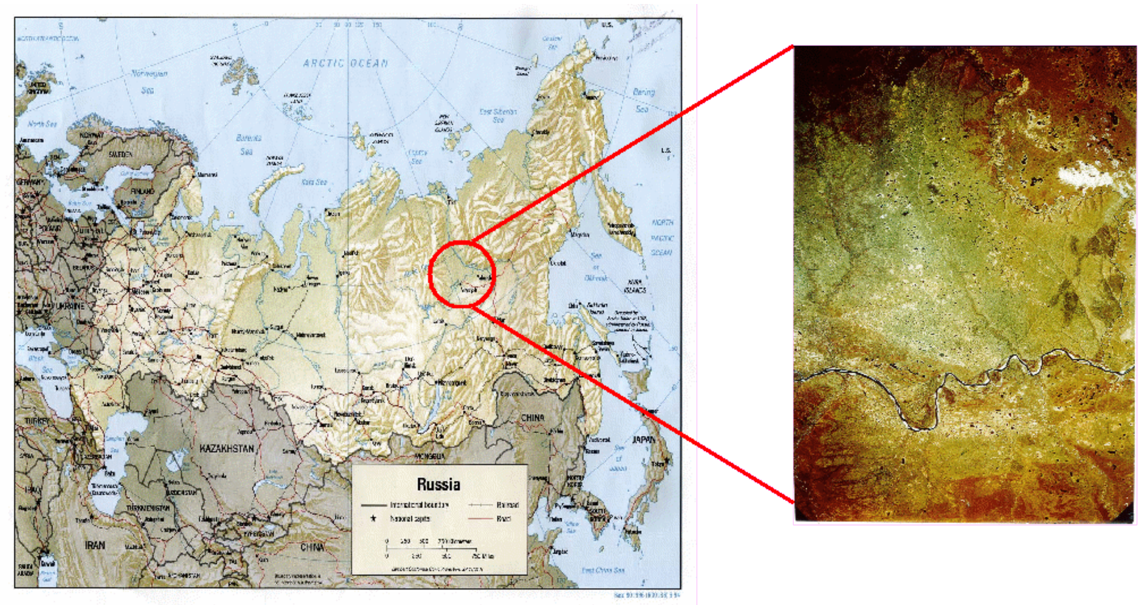

Fig.2: The Study Area and its Location in the Russian Federation (own scheme, map taken from Listen to Russian, Photography: Sagdayev et al. 1982)

3.2 Relief and Geomorphology

The area is situated in the Central Yakutian Basin, and is surrounded by the Middle Siberian and East-Siberian Plateaus in the West and the East, and the Aldan Upland in the South. There are no greater peaks or mountain ranges inside. It is a landscape dominated by hills and small valleys.

One typical shape of permafrost landscapes is the thermokarst relief, which is existent in

approximately 75% of the study area. The name is the transliteration of the Yakutian *Алас.* The genesis starts by a local thawing inside an area with frozen ground and with a high percentage of ice. In some parts of Siberia the ground consists of about 70% of ice (Boike & Kutzbach 2010 after Russian Geocryological Map).
Possible reasons for thawing are disturbances in vegetation coverage, e.g. by fires or cleaning of forests. As a consequence, the radiation balance on ground is more positive, because the protecting trees surface is lost. More radiation can be transformed into warmth, so the frozen soil thaws. The ground subsides, because the density of frozen water is smaller than of liquid. The liquid water flows into the depression and a lake develops. After a period of time that differs from place to place, those lakes unify with others to build alas-valleys and later dry out, being replaced by vegetation. On the basin floor of these dried depressions typical meadows or shrub communities, partly with tendencies of increasing moisture or swamping, are the predominant vegetation. If the alas lakes are filled up by sedimentation or vegetation, heat fluxes change. The former thawed area becomes permafrost again. Now that there is more water in the ground than before thawing, ice lenses develop and form several high hills with vegetation coverage, that are betoken with the Canadian word *Pingo (Fig. 3)*. If they collapse after several years of growth, they form alas depressions again.
The resulting relief is called *thermokarst*, because the oval or rounded lake shapes are evocative of dolinas, which are a typical shape in karst regions. The two landscapes look similar, but their genesis is totally different. Alases develop as a consequence of physical characteristics of water, whereas dolinas are formed by the chemical process of limestone solution.
Another permafrost-typical landscape element that can be observed in the study area are polygonal structures, formed by ice-wedges. Those wedges develop due to thermal contraction and cracking of the ground, followed by infiltration of snow-melt water that freezes within the cracks.
The most impressive elements in the study area are the sand-bodies that are surrounded by the river Tyung (Тюнг). This complex is called "Tyungovskian structure" and consists of countless small sand dunes with heights up to six metres with very sparse vegetation coverage, so-called *tukulan (Тукулан)* in Yakut language. They are a unique phenomenon of the Lena-Viluy-area (Troeva et al.. 2010, p. 204). The significant difference to desert sand dunes is their localisation in areas with a high density of lakes and other water bodies. The tukulans are relics of times characterised by more arid climate than it is now.
This geological structure also is the element with the highest elevation in the area, but still

does not reach levels of more than 200m above sea level. Therefore no change in vegetation due to altitude changes is noticeable of this vegetation pattern (“vertical zonality”).
The river valleys form wide systems of terraces with various widths.

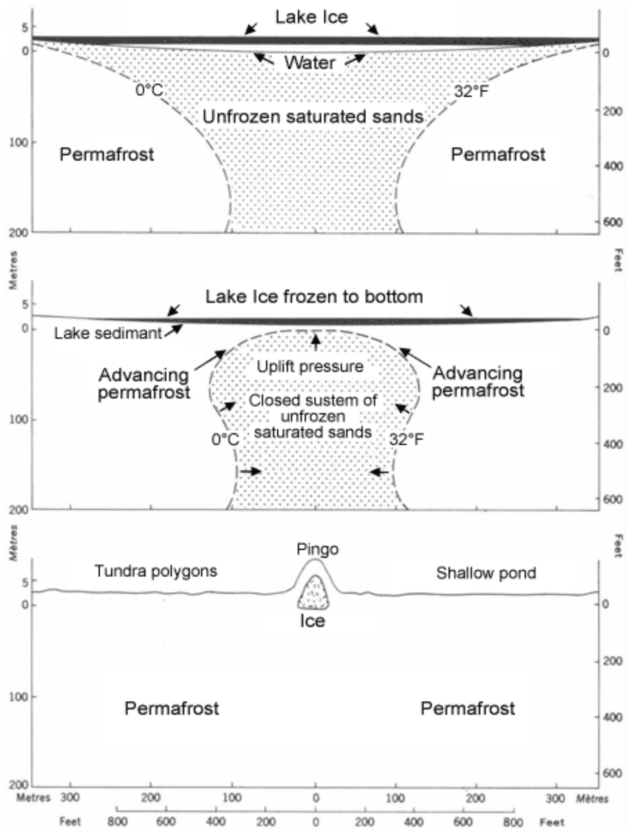

Fig. 3: Development of ice lenses (Pingo). (Source: CITS 2010)

3.3 Climate

The area shows an extremely continental climate with long and cold winters and moderate summers. As a consequence, more than 90% of the ground is permafrost. Exceptions are the valleys of the rivers Viluy (Вилюй), Tyung (Тюнг), Tyukyan (Тюкян), Tonguo (Тонгуо), Tchybyda (Чывыда) and Tchylly (Чыллы). Those climatic characteristics could be observed in wide parts of Yakutia, where the coldest place of the planet could be located in Oymyakon (Оймякон) at the right side of river Lena.
Annual mean temperature is about -9.5°C, with maxima up to 27°C in July and minima with temperatures down to -57°C in February. The range of more than 80K per year is typically for extremely continental climate. The long year average of annual precipitation is about circa 228mm. The seasons are dominated by a long and strong winter. As a con-

sequence the area is snow-covered from late September or early October until the end of April or May (Figure 4). During winter weather is dominated by Aleutian cyclones.

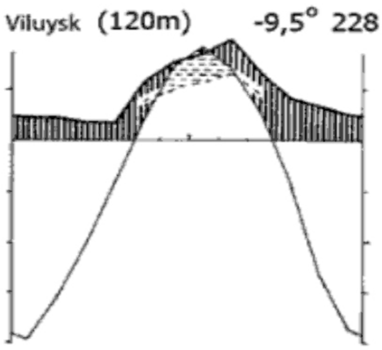

Fig. 4: Climate diagram (Walter/Lieth method) of Viluysk
(Source: Troeva et al. 2010, p.6)

Typical for boreal forests is a higher precipitation in summer than in winter, but the climate is humid or semi-arid during the whole year.
Micro-climate differs with different stand density of the trees. In dense forests, the temperature rises not up to the temperatures in open land or wide-standing near-tundra-forest (Schultz 2008, p.186)

3.4 Surface-Near Geological Ground

The permafrost in the study area reaches depths between 500 and 600m (fig. 5) below surface (Weise 1983)

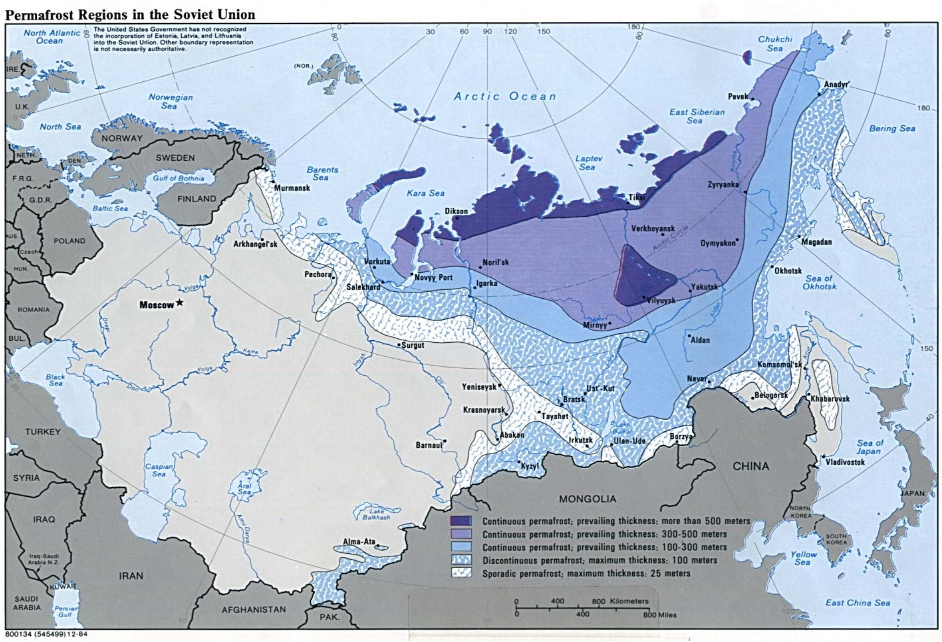

Fig. 5: Permafrost distribution in north-eastern Eurasia. (Source: Maps Primorye 2010)

The surface-near ground is mostly dominated by quaternary sediments like loess and sands. In the valleys of the river Viluy and streams of higher order, quaternary and recent fluvial and lacustrine sediments are predominant. In the north-eastern part of the study area chalkstone occurs, covered by quaternary and recent sandy alluvial (washed up) and deluvial sediments, completed by peat.
The beds of alas-lakes and valleys are commonly covered by lacustrine sediments, when they are dried as well as when they are filled with water.

3.5 Vegetation

3.5.1 General Properties of Flora

The vegetation in boreal forests of Yakutia is well discribed in Troeva et al. (2010). The following information on vegetation patterns have been taken mainly from these works, if no other author is especially cited.
Central Siberia is the only region worldwide, with large areas of forest growing on continuous permafrost. In more maritime stamped permafrost regions, the tree border is nearly the same as the permafrost border (Abaimov & Sofronov in Goldammer & Furyaev 1996, p. 372). Also bogs occur around the alas-dominated parts of the study area.
The area is situated in the holarctic ecozone and the floristic boreal zone.
The vegetation of this area can be described as typical boreal conifer forest of the continental climates, as described as *middle taiga* (Troeva et al. 2010) or *eastern Siberia light-coniferous taiga* (Osawa et al. 2010; p. 5). In Russian classification, the area belongs to the "light coniferous dry continental taiga" (Isaev et al.). Along the riversides and on areas that have burned lately, also birch trees *(betula nana, b. pendula, and b. ermanii),* willows *(salix caesia)* and poplars *(populus tremula suaveolens)* are also present. The space between the trees is filled by tundra-typical lichens, mosses and shrubs like marsh labrador tea *(ledum palustre*), cowberries (*vaccinium vitis-idaea*), blueberries (*v. mytrillus*) and bog bilberries (*v. uliginosum*).
The conifer forest is dominated by larches *(larix gmelinii, l. sibirica, l. cajanderi)*, completed with pine trees *(pinus sibirica, p. sylvestris)* and, more rarely, spruces *(picea obovata, p. ajanaensis)*. Firs *(abies spp.)* were not detected in the study area. Canopy closure is moderate, with values from 40% up to 80% coverage.
Frequently returning fires as they are typical for boreal forests are the initial point for returning forest juvenescence. They destroy the existing forest and induce a replacement by

pioneer species like birches. In the course of time this pioneer vegetation becomes more and more equal to the surrounding area.
Unwooded areas contain communities of meadows and different shrub species. In some alas-valleys some populations of dwarf-shrubs can be found, which are called “Yernik” if they are species of *betula*-genus.
Areas used for agriculture are rare, due to the usage of grazing areas of natural origin. Barren ground could be found in the so-called “Tyungovskian structure” in the north-eastern part of the Soyuz-image (→ chapter 3.1, appendix A), where large complexes of sand dominate. Other areas that are clear of any vegetation are blank rock-complexes in the south of the area, probably used by the mining industries, as well the populated areas of the towns Viluysk and Verchneviluysk with airports.

3.5.2 Tree Species and Vegetation Communities

Spruces (Picea spp.)

Contrary to European boreal vegetation patterns, in eastern and central Yakutia spruces appear not widespread, only near to rivers or lakes. If they appear, *picea obovata* and *p. ajanaensis* are dominant. Their scarce occurrence is due to the high water needs that cannot be guaranteed under extremely continental climate circumstances. The winter, where no liquid water is available, is too long and cold. The second reason is that spruces only develop shallow roots, with maximum depth of 20cm below the surface (WALTER & BRECKLE 1999). Therefore only areas with high groundwater level or frequently occurring flood events are adequate for spruces. In addition to the river valleys, spruces often form belts around alas lakes (ISAEV ET AL. in TROEVA ET AL. 2010 after SHERBAKOV 1992)

Pine trees (pinus spp.)

Pines (*pinus sylvestris, p. sibirica*) do not form zonal vegetation. They only fill gaps in the typical zone of Larches, or, in Europe, spruce forests. Pines can grow on stands with low habitat quality, which larches and spruces can avoid, especially on very dry stands. After fire events, pines follow the prime birches, and cannot be displaced by larches for a long time, until 200 years (WALTER & BRECKLE 1999). Trees of both mentioned species have very low habitat preferences, so they can be observed on dry sands and gravels, in river meadows and bogs. On the *tukulans,* Siberian dwarf pines (*p. pumila)* often replace *p. sylvestris*.

Larches (larix spp.)

In eastern and central Siberia *larix gmelinii* (or *l. dahurica*), *l. cajanderi* and *l. sibirica* are the dominant species, forming the so-called "light taiga". They are the northernmost occurring trees, forming the border to the forest-free tundra, because they are extremely resistant against temperatures down to -70°C.

Larix sibirica has also low habitat preferences. It can grow on very dry stands, no matter whether on carbon or siliceous rock. They form wide-stand mixed forests with pines, due they both having a high demand of light. Due to its relatively rapid growth, it is often a secondary pioneer species on cleared areas.

Birches (betula spp.)

Birches are the genus of deciduous trees, with the highest resistance against the extremely climatic conditions in the ecological zone of boreal forests. In maritime toned boreal forests, they are the northernmost growing trees, of both deciduous and conifers.

In Yakutia *betula ermanii, b. pendula* and the dwarf-shrubs *b.humilis* (=*b. fruticosa*) and *b. nana* (Russian: *Yernik*) are the most found species. Birches are pioneer species on recently cleared areas, e.g. after forest fires or storm events, but can remain for a long time part of the post-incident plant community.

All birch species have relatively low habitat requirements. They can grow in extreme wet bogs as well as on very dry stands and sandy grounds. Water and sunlight demand is relatively high. *Betula nana* prefers very wet stands like bogs, swamps and peat.

Poplars (populus spp.)

Those deciduous trees are the most typical species of river floodplains, on the banks of regularly floods. Most frequently occurring species are trembling poplar or aspen tree (*populus tremula)* and, more rarely, the Siberian balsam poplar (*p. suaveolens).* Poplars never form homogeneous populations in the study area. They grow always in mixed societies with the other tree species, especially with birches and willows, but also with conifers and shrubs. Poplars do not tolerate draught, they need very wet habitats and avoid silty grounds.

Willows (salix spp.)

This tree species is the other one to form forests on the banks of the greater rivers in the study area. The only occurring species is the blue willow (*salix caesia*). This is due to the fact that they, equally to poplars, also need very wet stands to grow. They built communities with birches, poplars and conifer trees.

The plant communities in alas-depressions

In thermokarst depressions without a drainage outlet in younger stages of their development, the vegetation composition depends on the moisture and salinity of soil. In wet meadows, creeping foxtail grasses *(alopecurus arundinaceus)* and common river grasses (*scolochloa festucacae*) are the most frequent species. On highly saline or alkali soils, alkali grasses (*puccinellia tenuiflora*) occur, while very dry stands are indicated by sedges (*carex duriuscula*).

3.6 Hydrological Situation

The hydrological situation is dominated by the river Viluy, the largest tributary of the river Lena besides the Aldan River. The Viluy River originates in the Central Russian Upland in the region Krasnoyarsk and flows in eastern direction, meandering very strong. The river density is very high. There are a lot of bigger and smaller streams that mound in the Viluy River. Thus, the river network can be classified as poorly developed (CHEVYCHELOV & BOSIKOV, in TROEVA ET AL. 2010, p.4).

All rivers are extremely meandering, and therefore developing lots of backwater-filled or almost dried meanders.

Annual run-off has a peak in times of snow melting in later April and May, resulting in periodical flood events. After PARDÉ the run-off-regime could be classified as a snow-regime of plains. Melting of snow is the main factor influencing the run-off. The drainage in winter is relatively low, because the rivers are frozen for 180 to 200 days per year (CHEVYCHELOV & BOSIKOV in TROEVA ET AL. 2010, p.5)

Annual precipitation is distributed relatively equal on all twelve months, but the retention is very high in winter. As a consequence, flood events occur in spring every year, most of them between mid-May and early June when the snow is melting. The rivers and streams are, like it is expected in humid climates, permanently water-bearing, alas-valleys periodically in spring and after strong rain events. In the Landsat-1-scene (→ chapter 5.1) the river Tyung has overflowed its riversides massively and also the Vilyui River has noticeable high-tide.

3.7 Soil

The question for the dominating soil types could not be answered definitely. The classification of the FAO differs from the declarations of several authors, e.g. Abaimov & Sofronov (in Goldammer & Furyaev 1996, p. 374).
In general, soils of the boreal forests have a high acidity, with pH values significantly below 5.5. As the main reason the conifer needles can be accounted for, as they need a long time for disintegration while they continuously release their needle acids into the soil. Husk gets disintegrated only very slowly, because of the low temperatures and high moisture of the soils. As a consequence, a thick organic layer (O-horizon) develops above of the humous topsoil (Ah-horizon).
No further complex soil types can develop, because of the very high dynamics of the relief. Annual flood events as well as the annual thawing and freezing processes linked with soil erosion and denudation are reshaping the landscape frequently and do not allow constant conditions for long-term pedogenesis.
Regarding to the FAO-classification the dominant soil types include histosols, gelic,dystric or eutric cambisols, podzols and podzol-luvisols. Often the soils have tend to gleying. Contrary to that, Abaimov and Sofronov published in Goldammer & Furyaev (1996, p. 347), that no real podzolic soils exist in central Yakutia. Regarding to the Yakutian National Atlas (1989), the parts on the left banks of the Vilyuy River are non-podzolic. In the alases tchernozemic soils exist. Not far south from the right bank of the river, more podzolic soils are dominant (Map: Sagdayev et al. 1982, p. 29).
Chevychelov & Bosikov (in Troeva et al. 2010, p. 18) postulated that in the open lands of Central Yakutia frozen solonchaks and solonetzes are the dominant soil formations. In the wooded parts of the Middle-Yakutian Basin, they declare frozen pale and frozen grey soils as typical. On the upper parts of Yakutia, below pine stands, e.g. the southernmost part of the study area, frozen soddy-carbonate podzolized soils develops as well.

4 Reasons for Changes of Vegetation

4.1 Regeneration and the Role of Fire Events

In boreal forests, fires are a frequent event. About 45 percent of the study region in 1975 were covered by forests that stand on areas where forest fires occurred recently or some time ago (classes 9, 10, 11, 14 and 23 in the map of forest stand, → Appendix A). As KOROVIN (in GOLDAMMER/FURYAEV 1996, pp .112) detected, the distribution of the number of fire events in Eurasia and the size of the burned area, are both highly fluctuating (fig. 6). An obvious maximum of the number of fires occurred between 1970 and 1975 has been detected and could correspond to the high part of fire-influenced areas in the study area. SOFRONOV (in: GOLDAMMER & FURYAEV 1996; p.230) developed a map where he separates the Russian territory into five categories he called "fire incidence levels". Central Yakutia is part of the fifth category that contains areas with an "extreme fire incidence".

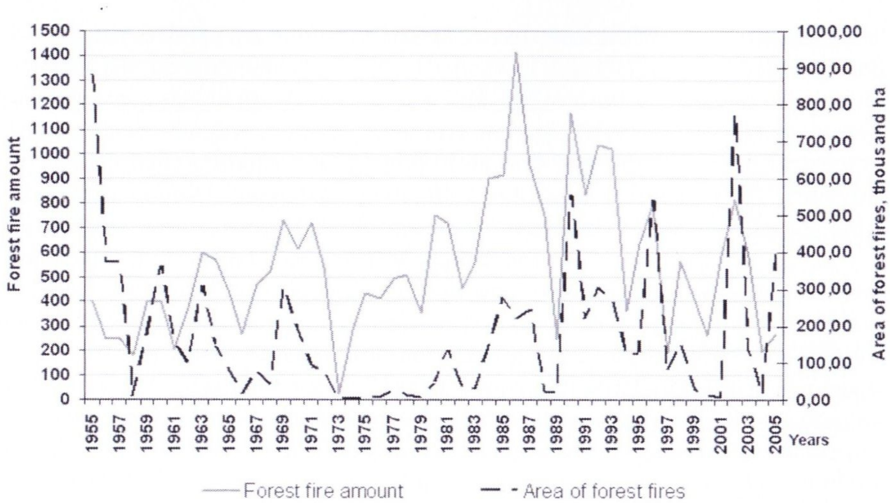

Fig. 6: Frequency and effect of forest fires in Yakutia between 1955 and 2006 (Source: TROEVA ET AL. 2010, p. 266)

Due to a high readiness to burn and the possibility to spread widely, fires are affecting the vegetation coverage that cannot be neglected. The biomass is high flammable, because the space between trees is overgrown by some flammable mosses and other tundra vegetation. Some tree species are more likely to burn than others. Relevant for the study area is the fact, that pine and large forests burn considerably more frequently than fur or spruce stands. The missing furs and the very rare spruce stands in the Viluysk-area, linked with the dominating pine and larch forests are a factor that significantly abets the readiness to burn.

In wide areas the paludification level is relatively low. Paludification is defined as "the process of bog expansion resulting from rising water tables as a consequence of peat growth" (Crawford et al. 2003). The resulting draught boosts liability to burn.

The most severe fires occur in summer, when anticyclones dominate the meteorological situation, because they are normally linked to times of extreme draught.

In 50-80% of the cases, the reasons starting fires in near-tundra forests of Central Siberia were lightning (Abaimov & Sofronov in Goldammer & Furyaev 1996, p.375). Man caused fires are a rare event, because of the very low population density. Where the next populated point is not far away from the fire, the part of man-caused fires increases significantly. Lightning only becomes a main reason for starting fires between June and August (Goldammer & Furyaev 1996; p 127). Schultz (2008,) stated after Wein & MacLean (1983) that in Ontario/USA and Quebec/Canada the small part of lightning-caused fires destroy 90%, respectively 43% of the area that is destroyed by forest fires during a normal year.

After the pre-fire vegetation has been destroyed, In most cases succession starts with birches and shrubs, followed by a replacement by larches. Birches do have low preferences to their habitat except of light, so they could settle fast in vegetation-free areas. Another factor is temporary increase of acidity of the soils, caused by the release of the plant acids into the soil (Bayley et al. 1992). Replacement takes place because the competition magnitude of birches is low, compared to larches. While competing for light, larches replace the weaker birches. The larches could grow because of some seeds that were not destroyed by the fires in small protected areas. If the fire event is not severe enough to kill the whole tree stand, some individuals survive and can produce new seeds, which make the regeneration of the pre-fire vegetation faster.

The re-growth of the pioneer species takes time spans of about ten years, but 80 to 100 years could pass, until the larch-dominated vegetation reaches the pre-fire level. If sources for conifer-seeds are far enough from the post-fire birch stand, those stands can last for a long time until they are replaced.

Probably the very high density of alas-shapes in the central parts of the Soyuz-scene was developed as a consequence of the last bigger fire event, that destroyed a high percentage of the forests in the photography (→Appendix A).

Forest fires are not the only reason for drastic forest decline, juvenescence and regeneration. Storms can also destroy wide afforested areas, but they occur very rarely in central Yakutia.

Another possible process for reorganisation of forest communities, the Shimagare-phenomenon, has been observed in Japan first (Walter & Breckle 1999). If in an existing forest is a pure stand of one species and all individuals are at the same age, wide bands of natural forest decline followed by synchronic re-growth of the same tree species have been observed. Those bands are shifting against the normally prevailing wind direction. Walter & Breckle (1999) do not link this process onto a special tree species, but according to Nakamura & Krestov (2005) it only occurs in fir-forests in far-eastern Eurasia. If this is correct, the Shimagare- or "dead tree stripes"- phenomenon cannot be the reason for forest juvenescence in the study area, because here no firs are to be found.

4.2 Anthropogenic Influence on the Vegetation

Tribal population of Yakutia have been breeders of cattle and fur-bearing animals, using the wide-standing larch stands for rearing polar foxes and other fur-animals, as well as for forest-grazing-areas for their reindeers,.

Grazing is also practised in the dry alas-depression, because the speciose meadows of tundra plants are suitable for cattle. Adequate areas for these grazing economy became rarer during the last 40 years, because of the observed lake bed re-filling. This kind of extensive agriculture does not influence the natural vegetation seriously.

Industrialization and especially the exploitation of natural resources like oil, gas, diamonds and uranium increased the anthropogenic influence on the sensitive boreal environment. Agriculture was also intensified. Before these efforts, the landscape was nearly unaffected by human activity. The structural change attended by forest cleaning and long-time influences on forest ecosystems by pollution and emission of hazardous substances.

Troeva et al. (2010, p. 262) call the Viluy region Yakutias´ part with the most "negative ecological situation". The evidence for this description is numerous: As a consequence of the diamond mining thallium, strontium, arsenic and mercury were released into the ecosystem. A new power station in Viluysk is accountable for a phenol concentration in the Viluy River that is three times higher than permitted. The oil concentration is even five times higher than allowed. Fertilizers pollute the ecosystem additionally. Furthermore the literature stated 12 nuclear explosions below the surface in Yakutia. In the southernmost part of the study area, mining influences the landscapes, destroying the vegetation coverage in this area.

Beside the global climate change in the Middle Yakutian Basin a local anthropogenic change is noticeable in precipitation sums, since some dams in upper Viluy were built.

5 Data Material

The research is based on two kinds of remote sensing data, as well as detailed and long-term climate data.
The time series contains image data from July 1973, September 1976, August 2002 and August 2009 and daily climate data since 1961. The image data from the years 1973, 2002 and 2009 are Landsat-scenes, the data from 1976 is a Soyuz-multi-spectral-image and hence the secondary maps of several analysis, have been taken from Sagdayev et al. (1982).

5.1 Remote Sensing Data

The most important data-sources for this work are the multi-spectral satellite data of the Landsat programme. This programme is an earth-observation project of the NASA. Data is free and publicly available. The United States Geological Server (USGS) - Landsat Mission comprises a sequence of seven satellites that were launched into orbit to take multi spectral recordings of the earth's surface until today. The programme was started in the 1970s and acquires constantly remote sensing data.
Suitable for this work were all in all 3 Landsat scenes, which are very different to each other because of different generation of the NASA- Landsat-Program-Satellites. The oldest scene is taken in 1972 by the first Landsat-satellite (Landsat-1), and its MSS-sensor contains only 4 spectral channels(green (0,5-0,6 µm), red (0,6-0,7 µm) and two of near-infrared (0,7- 0,8 µm and 0,8 and 1,1 µm) radiation).
The 2002-scene has been taken by Landsat-7 with an ETM-sensor and contains about 6 spectral channels, three visible-channels (0.45 - 0.52 µm, 0.52 - 0.60 µm, 0.63 - 0.69 µm), added by 1 NIR (0.76 - 0.90 µm) -, 2 MIR- and one thermal IR channel. The image taken in 2009 was recorded by a TM sensor with Landsat-5, whose bands are sensible in the same wavelengths as the TM-sensor.

Detailed information is collected in Table A.1 (→ Appendix A.a)

5.2 Climate Data

The climate data is logged at Viluysk meteorological station by the Russian Federal Meteorological Service and its Soviet predecessor. As a reference to clear the data errors, recordings registered in Nyurba and Yakutsk have been used.

The climate data contains average temperatures and precipitation sums per day.

Continuous recordings have been realized in Viluysk since 1939, but with several missing data in the first 30 years of recording. Since 1961 the data is largely completely available.

(Further details: → Appendix A.c)

5.3 The multi-spectral photography and resulting maps

A Soyuz space photograph of the study site was taken on September 18, 1976 from the Soyuz mission (Appendix A.b). (SAGDAYEV ET AL.1982). It is an image that was combined out of three spectral ranges of all in all nine sensors, with each sensor detecting one spectral range. The date when it was taken is September 18th, 1976 (→Appendix A.b).

From different combinations of the spectral ranges, a collective of authors has analysed the study area and created several maps for different topics for the "Atlas of aeroscopic multi-spectral photography" (SAGDAYEV ET AL. 1982).

The camera, that was used to take the photo from the Soyuz-22 spacecraft, is called MFK-6. The photography is a composite of 9 different loggers; each logger senses another spectral range.

In different combination of the 9 grey scale values, several remote sensing operations have been done for the "atlas for interpretation..." in the early 1980s. Maps for topics like the distribution of polygon ice wedge relief, thawing processes and others exist beside the used maps for forest stand and near-surface ground for the study area. Those maps are all at a scale of 1:400000

All maps for the study area that have been created by Sagdayev et al. (1982) are listed below:

1 Surface near geological ground
2 Map of forest stand
3 Permafrost distribution and spatial differences
4 Seasonal processes of thawing and freezing
5 Polygon ice wedge structures
6 Thermokarst relief

6 Methodical Approach

6.1 Digital thematic maps

To get useful ground information for the later classification, the map “Vegetation stand” (SAGDAYEV ET AL. 1982, p. 32) that is based on the Soyuz-photography has been digitized manually with ESRI ArcGIS Editor-toolbar, on a scale of 1:30000. No automated line detection has been used. Result of the digitizing was an ArcGIS feature class layer.

Errors occurred by enormous stretching and shrinking of the analogue map, which exists only in a printed format for about 27 years. Those deformation processes are not inevitable and could not be cleared with simple methods of georeferencing with using polynomials of higher orders. So some borders of different vegetation types and especially the exact location of water types were assumed when they were digitized.
For researches according to the link between surface-near ground and vegetation, the map “combination and structure of permafrost ground” (SAGDAYEV ET AL. 1982) has been digitized. The intention to do this was not on improving the classification of remote sensing data, but for final interpretation of the results after comparing the classification results. The second map was digitized on a scale of 1:75000.

6.2 Landsat Satellite data

6.2.1 Preprocessing

First step was to search with USGS EarthExplorer (USGS 2010) for recently published data of the study area for the time between the 1970s and year 2002. For change detection tasks it is necessary that the different scenes have the same projection type, for the study area it is UTM zone 50N. Therefore the Landsat scenes from 1973 had to be georeferenced, because they were not congruent to the other scenes. Georeferencing was done with the ESRI software ArcGIS, 24 ground control points have been placed.

The next step was to decrease the data amount of the Landsat-images. Since the study area is covered by two Landsat rows (path 128 and rows 015-016), the two image sets

taken in 2002 and 2009 have been merged with ENVI *Mosaicking* tool. Because the two scenes of each year are taken at the same date, the possible error of the classification induced by different radiometrical properties is relatively small. The same procedure was done with two scenes taken by Landsat-1.
The study site covers the area of the Soyuz-photography and was defined as region of interest before applying the ENVI *subset* tool.

6.2.2 Higher Level Processing: NDVI

The Normalised Differenced Vegetation Index is an index that uses the red and the Near Infrared NIR information in the spectral signatures of vegetation. The higher reflectance of NIR for vital vegetation is due to intensive internal multiple scattering. Water absorbs the NIR and reflects the RED spectral ranges. Vital plants have more stable cell structures. That supports the multiple scattering, while in less vital vegetation the scattering is inhibited due to less stable cell compartiments. This fact is expressed in following term that is modified after ALBERTZ (2001, p. 219):

$$NDVI = (r_{NIR} - r_{RED}) / (r_{NIR} + r_{RED})$$

In this term, r represents the reflectance of the spectral ranges. The normalisation is used to express the results in values between -1 and 1. Positive values near 1 mean, that the vegetation in this pixel has a high percentage of water, an indicator for a high vitality and photosynthetic activity as it is normally to detect in young vegetation. Values near 0 or below 0 mean that there is no or only sparse old vegetation with low vitality and photosynthetic activity. Leaf trees have higher values than conifers.

6.2.3 Higher Level Processing: Supervised Classification

The ITT software ENVI 4.7 was used for the supervised classification. All in all 15 land cover classes have been created by defining several training sites for each class.
The definition of the training sites as regions of interest was based on the forest-stand map. The Maximum-Likelihood-algorithm (each pixel is classified to the class, to which it

is most probable that it belongs to, according to its spectral signature) was used as classification method after comparing to a test-classification with using the same training sites with using the Minimum-Distance-method, which resulted a more improbable appearing land cover. It would go beyond the scope of this work to define each of the 26 vegetation classes of the map, so the number of classes was reduced to 15. The separation of the classes “meadows in dry alases” and “Yernik/dwarf shrubs” was the most difficult one in the Landsat-1 scene, because their spectral signature is nearly equal in the MSS spectral information. To detect units of different tree ages as an indicator for past fire events, the NDVI has been used. Higher values of this index indicate younger, more vital vegetation, especially on riversides in high-tide water range or on sites with latest fire events.
The table in Appendix B lists the classes that were defined and their appearance in band combination “Landsat visible”, NDVI and the combination 4-2-1.

For the definition of the training sites, two band combinations were used, 3-2-1 (Landsat visible) and, for a more detailed separation of different forest combinations and forestal evaluation combination B4-B3-B2. All spectral bands were included in the classification algorithm.

After classification in ENVI the file was exported to ArcMap and clipped with the *clip (analysis)* tool into the shape of the Soyuz-image.
In the Landsat TM and ETM+ scenes, the definition of the regions of interest proved to be more difficult. Indeed the base vegetation map be used again, but it had to be decided, in which parts of the scene vegetation most probable did not change. Spruce stands did not change significantly, but forests on the riversides had changed their combination because of numerous floods, forest clearings and other influences. Meadows in dry alases were also easy to detect. More challenging was the separation of the different land cover unions with partly birch, willow and poplar stands that are mixed with conifers. A good indicator to solve that problem was again the NDVI. Higher values indicate a higher percentage of deciduous forests and lower values give hint to higher percentage of conifers. At first sight, those areas that were completely free of vegetation because of recent fire events in 1973 become visible on the Landsat TM and ETM+ scenes with band combination 4-3-2. These areas have higher NDVI-values than the surrounding larch-dominated and pure larch forests. Automated classification turned out to be imprecise in these areas, because the spectral signature of succession communities is very similar to the conifer-free forests on the riversides.

A correction of the classification results has been applied on the 2002- and 2009-Landsat-scenes. Because of the class border between the spruce and the swamped regions on the banks of alas-lakes, a pure water layer was classified. For both scenes the classes "water" and "shallow water" were created with ENVI. For correct water detection only the Infrared spectral band 5 was used, and a mask band excluded all regions apart from water bodies

6.2.4 Second Level Processing: Optimizing classes and GIS Vector datasets

After finishing the land cover classifications, the results still can be optimized. This was realised by applying the ArcGIS *majority filter* - tool with a 4-pixel environment. The algorithm of this tool replaces a pixel value if three or four of the neighbouring pixels have a unique value that differs from the pixel's value in the centre of the 3x3-matrix.
The file was clipped with the ArcGIS *clip (analysis)* tool into the shape of the Soyuz image. The filtered raster datasets had been converted into vector format, building an ArcGIS feature class. After this conversion process, lots of very small features had been created, with a negligible extent, caused either by atmospheric influences or the classification algorithm. This made a second simplification process necessary, so many small polygons were annexed to a neighbouring one, using the *eliminate (management)* tool. All features with an area below $7400m^2$ (three Landsat-1-pixels) were merged to their neighbour which it has the longest shared border, if the longest border was explicit. If a polygon has two longest borders that are shared with two different polygons, it was not eliminated. By applying this tool the amount of data had been reduced approximately to one third of the prime dataset.
. The resulting water layers also were converted into a shapefile with ArcGIS *raster to polygon*- tool. Afterwards, the complete land cover classification and the water-shapefile were merged with the *merge (analyses)* -tool to reclassify all features, which were wrongly classified not to be water or shallow water.
Optimized land cover classifications are pictured in Appendix C.

6.3 Thematic Spatial Analysis

Finally, several spatial analysis and overlays had been done in ArcGIS. By splitting the datasets into small subsets, several areas of special focus were created. That way it was possible to come to clear conclusions about the questions, how vegetation reacts on fire events, human activity (e.g. mining and forest clearing), changed climatic conditions and increasing lake number and extent.

The whole process of preparing and analysing the different types of remote sensing data with ENVI and ArcGIS is shown in the following chart:

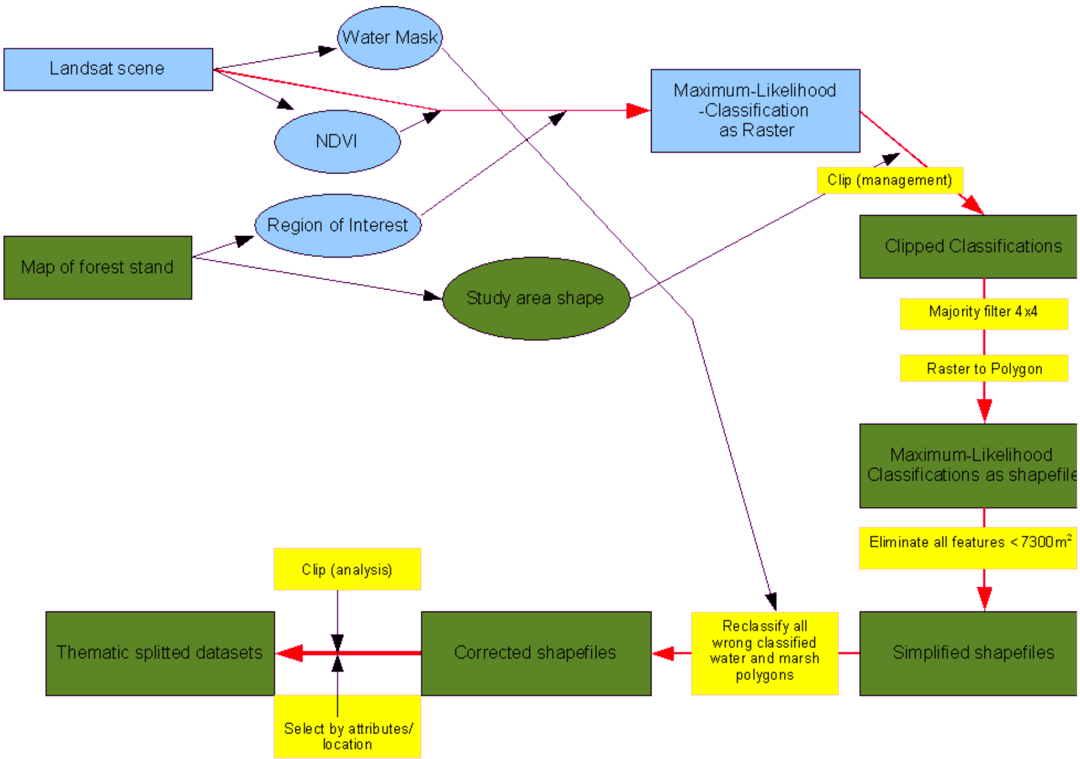

Fig. 7: Flow chart of working process. (Source: own scheme) Blue: Datasets created in ENVI 4.7, Green= Datasets created with ArcGIS 9.3, Yellow: operations in ArcGIS.

6.4 Analysis of Climate Data

The climate data had to be cleared of missing values by replacing with data of neighbouring weather stations and extreme outliers.

The season lengths were calculated by exporting those datasets, which contain values for air temperature that is below 0.3°C. The margin has been chosen a little above the physically correct freezing point for water, to accommodate the fact that snow does not only fall on days of frost in two metres height above surface. To calculate the seasonal distribution of rain or snow, only those days were selected on which a precipitation event occurred. If on a precipitation day the temperature was below 0.3°C, the data has been declared to be frozen, and on days with temperatures higher than the defined boundary value to rain events.

7 Results

7.1 Climate Trends

Analyses of climate data showed that the average temperature in Viluysk is increasing constantly over the whole time-scale (Fig. 8). The difference between annual temperatures in 1960s and 2005 is about 4.1K, from -10.6°C up to values around -6.5°C. The rise of the average temperature was about 0,41K per decade during the last century. This is more than 0.1K higher than the 0.3K that has been stated by Chapin et al. (2000) for a region in North America.

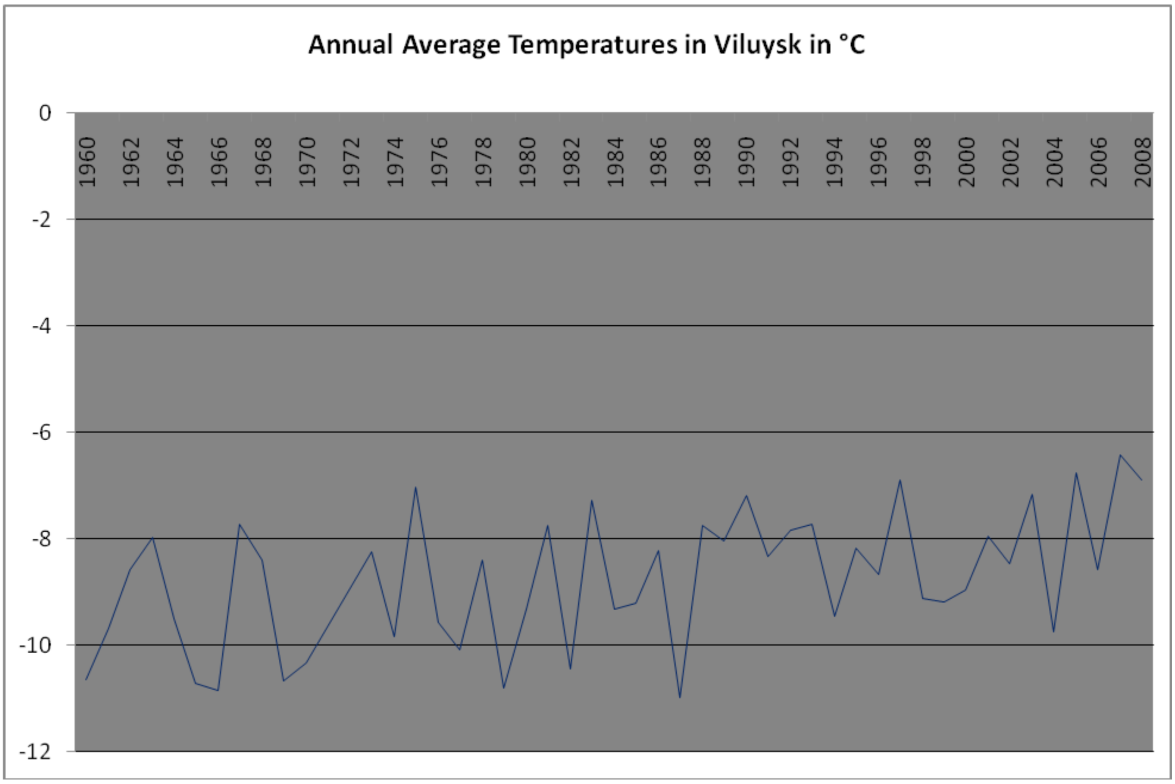

Fig. 8: Air temperature development in Viluysk between 1960 and 2008 (source: own scheme). The Y-axis represents the temperature in °C.

This is congruent to the aspect of the theory of global warming that says that the most rapid change occurs in central and eastern Siberia and the polar regions (IPCC 1997).

The trend of higher annual average temperature is linked to increasing amounts of precipitation per year. The calculated annual average (1960-2008) is about 304mm, a little less than a half of the amounts that are commonly recorded in eastern Germany, but significantly higher than in the climate diagram (fig.2).

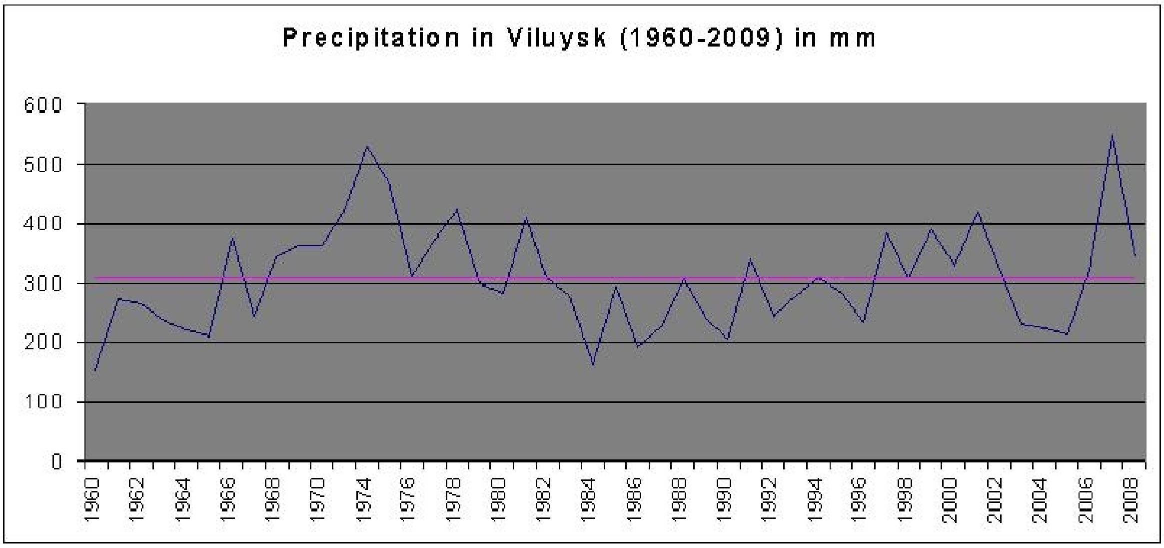

Fig.9: Development of annual precipitation in Viluysk (source: own scheme). Annual sum is represented as a blue line, the calculated average in purple

The development of the annual sums is pictured in Fig. 9. The amounts of regular years rose from values around 200mm up to amounts of 350 mm per year. This trend can be explained by the exponential increase of the saturation vapour pressure with rising air temperatures, so that more water can evaporate and precipitate. The number of extreme rain events also increased during this time. Especially in 2007 the amount was 176 percent (546mm) above the annual average, followed by the extremely moist year 1974, when annual precipitation value was 170 percent (527mm) more than the long-term-average. Between these two peaks the precipitation was relative constant around the average amount.

The distribution between summer and winter precipitation has also changed (Fig. 10). In the first years of the analysed climate data time series it was nearly equally distributed on each season. In the latest years, a movement of the peak to summer months that means to liquid precipitation is in evidence. This trend is not congruent to observations in North America, where a movement to higher precipitation sums in winter has been recorded (CHAPIN ET AL. 2000).

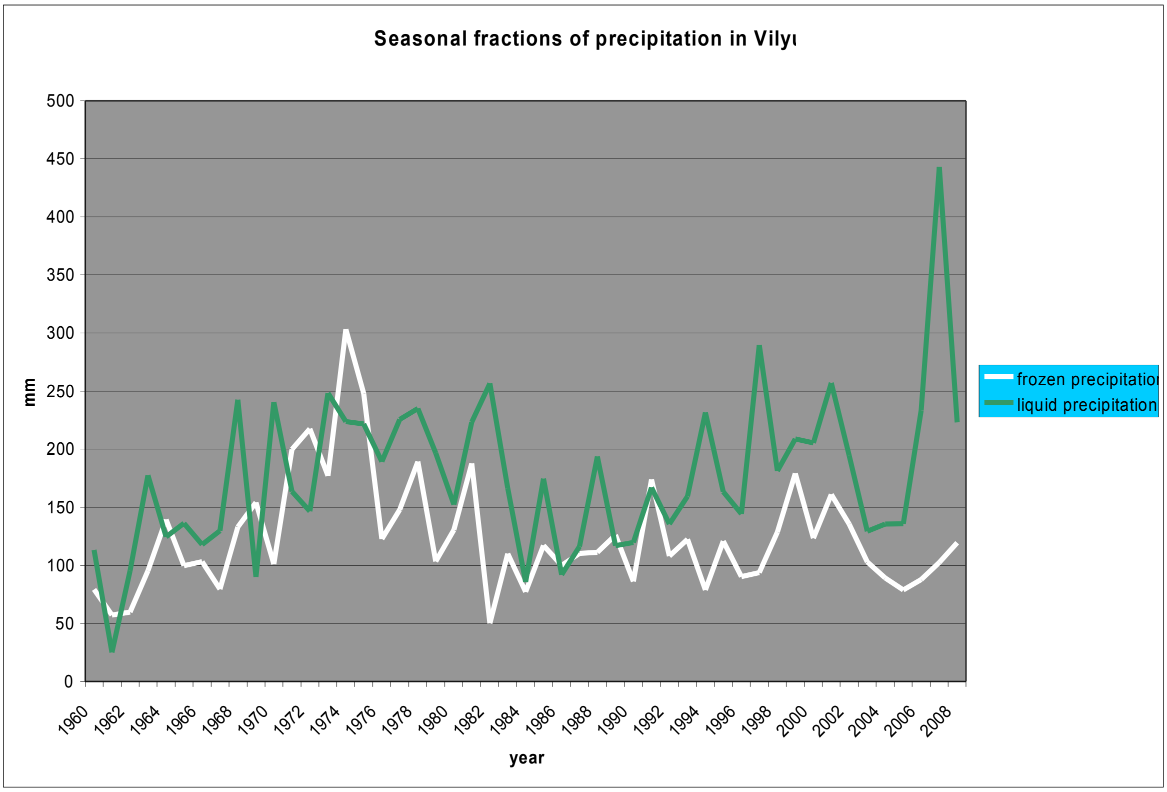

Fig. 10: Seasonal Distribution of precipitation (source: own scheme)

Also in the length of winter a change could be detected. The number of days per year, where temperature do not reach the freezing point is relatively unsteady (Fig.11).

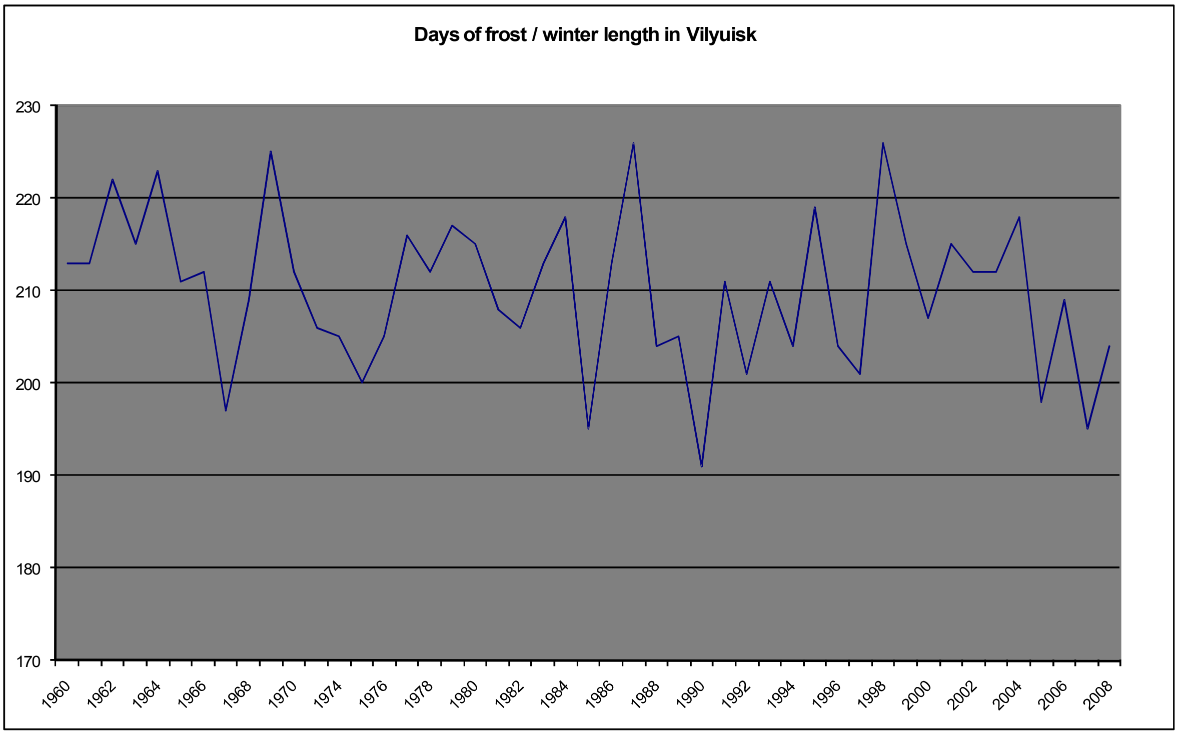

Fig. 11: Days of frost in Viluysk (source: own scheme)

The mean is 210 winter days, but alternating between 225 days in 1998 and 191 days in 1990. From 1960 to 1998 no clear trend is evident, winter length was not constant. But since 1998 it decreased constantly down to 204 days per year.

As a consequence of these two trends - more precipitation and shorter winters - it can be stated that the soil moisture in the area increased, thus inducing the refilling of the dry lake beds. The rising air temperatures and the decreasing number of days with an average temperature below 0°C both affect a deeper thawing of the permafrost in summer. A clear sign to verify this thesis is the dramatic increase of the lake count, that is visible by comparing the land cover classification of 2009 with the Soyuz-image. Several studies about the connection between the type of permafrost and the change of lake numbers have been published in the last years. The evident difference of the processes that take place if annual temperatures rise, is, that number of lakes on continuous permafrost increases, while it decreases on discontinuous and sporadic permafrost (Hinzmann et al. 2005, p. 265; Riordan et al. 2006, p. 1-11).

A soil with more moisture can also be seen as the most important reason for vegetation change, besides the fire events.

Besides the global climate change a significant change in the local climate of the Central Lena Basin had occurred, which is caused by building an embankment dam in the upper Viluy River. It permits the assumption of a more constant availability of liquid water that induces higher evaporation and thus more precipitation.

7.2 Land Cover Changes

7.2.1 Total change

The comparison of three multi-temporal land cover classifications showed a visible change of the vegetation, visualized in figure 12, the land cover in 2009 is pictured as an example in fig. 12b. (Land cover 2002 and 1973 → Appendix C)

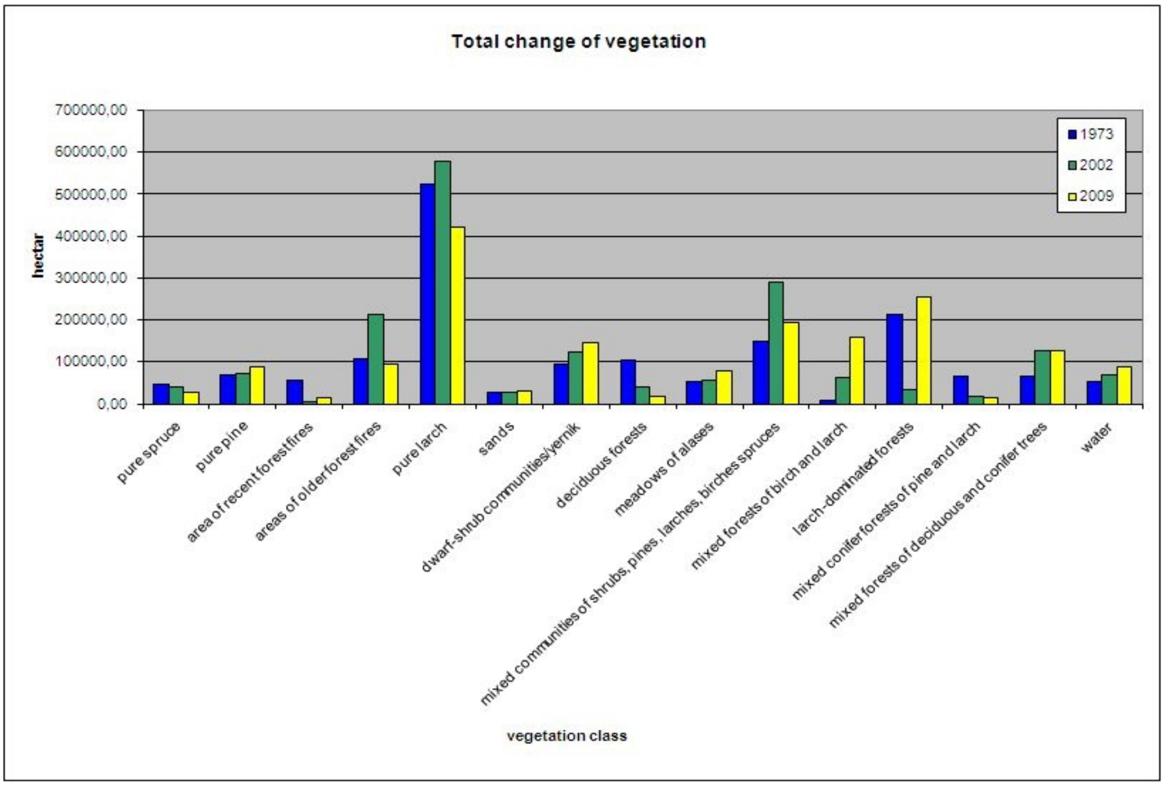

Fig. 12a: Vegetation units and covered area in the whole study area (source: own scheme)

In all of the scanned years pure larch forests are the dominating vegetation type, but with a decline of one fifth of their size, shrinking from 51000ha down to 41000ha between 1973 and 2009. The area wooded by spruces decreases a little. This might be due to clearing in the river depressions of the river Viluy that have become necessary as a consequence of population growth in the settlements beside the river. The pine forest amount has grown a little, but this may be caused of inaccuracies in the classification because of disturbances by atmospheric particles. It is to expect that the real change of this class is insignificant. For vegetation class III (areas recently affected by forest fires) the result is as it was expected, because on the big area that was affected by a recent fire event in 1973 regeneration of the vegetation occurred. No large fire events happened in the last ten years.

The result of class III might be wrong for the year 2002. If no bigger areas had been destroyed fires, no post-fire successions in narrower sense can develop. The area of vegetation-free sands increased a bit, mainly in the south of the study area, where areas were cleared to allow exploitation of natural resources.

The increase of the shrub-covered area is linked with the decrease of areas recently affected by fires, where shrub communities often form the pioneer vegetation. The growth of areas covered by meadows is probably a consequence of forest cleaning to establish new grazing areas for cattle. Draught of thermokarst lakes could not be the reason, because of the rising amount and size of lakes. Larches mixed up in pure forests that consist of deciduous trees to built mixed forests what causes decrease and increase of the adequate classes.

For this work, the NDVI was a good indicator to separate younger vegetation on burned areas from older vegetation, that not have been influenced by fires for a long time, as well as deciduous-tree or mixed stands from conifer-dominated forests

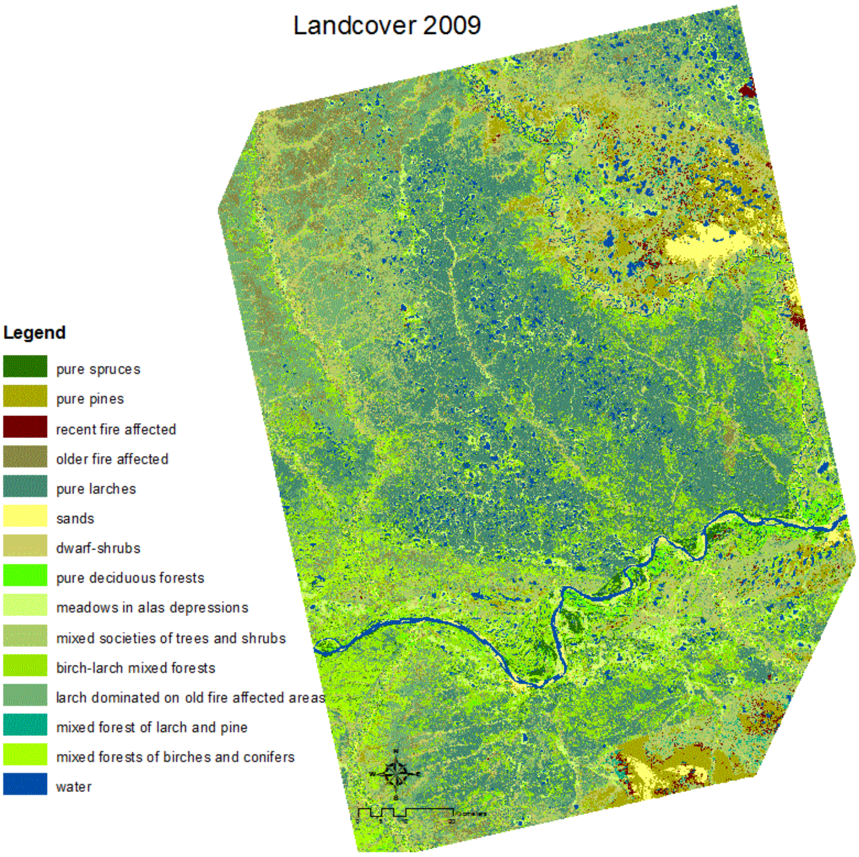

Fig. 12b: Land Cover Classification of the Viluysk area 2009. (source: own scheme)

7.2.2 Regeneration after fire events

The best part of the study area to visualise the vegetation regeneration on areas that have been burned by forest fires recently, is the noticeable black area on the right edge of the Soyuz-photography (→ appendix A). The fire destroyed an area of 1.142.082 square metres of forest, briefly before the first Landsat-Image was taken.

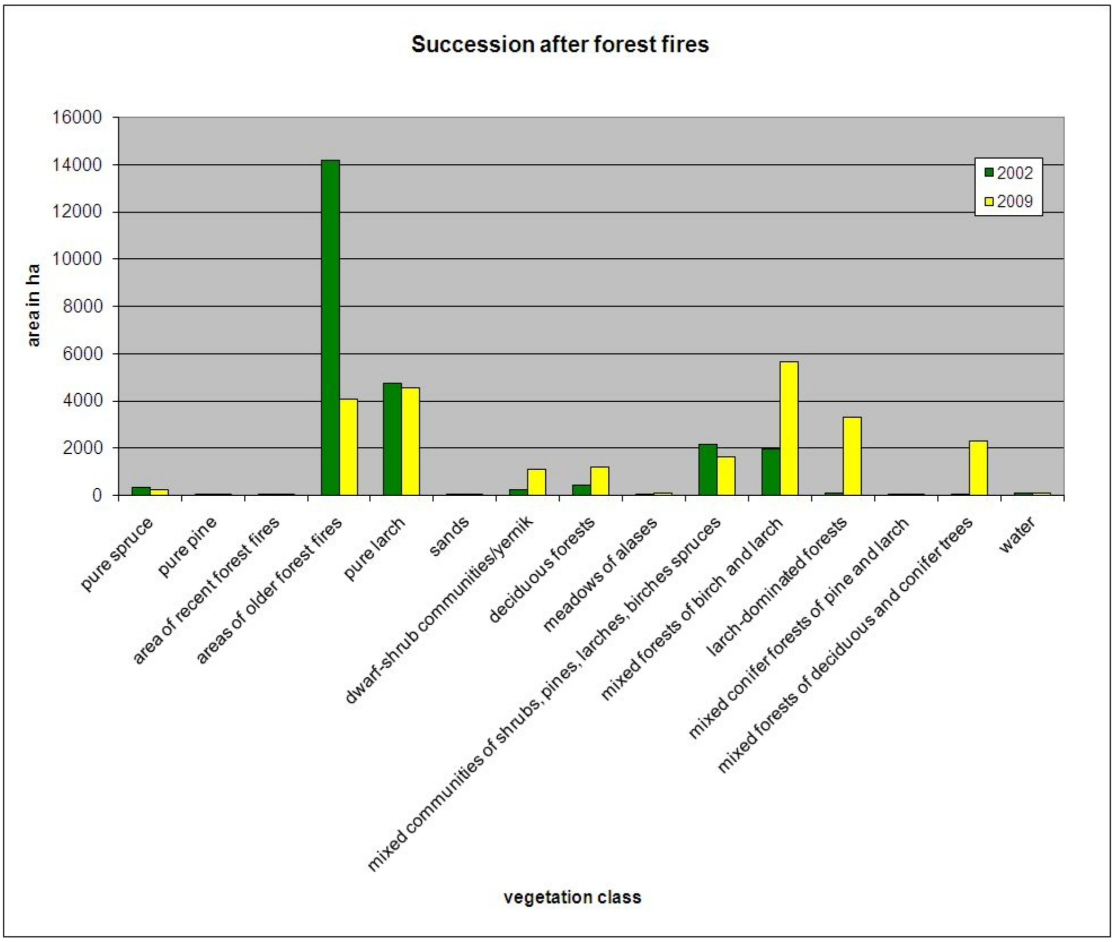

Fig. 13: post-fire vegetation in 2002 and 2009 on 1973s burned area

Using the approach of Cherosov (in Troeva et al. 2010, p.268), the regeneration is expected to be on the border of the "birch stage" and the last stage of birch-larch and larch young forests. The evidence for this is the heavy decrease of areas covered with succession communities after older forest fires and the simultaneous increase of mixed forests of birches and larches as well as larch-dominated forests between 2002 and 2009 (fig. 13). The observed succession stage seems to take place a little faster than stated in the theory of Cherosov (in Troeva et al. 2010, p. 268). The change between the two stages is normally at a time between 40 and 45years after the fire event, however the study period is only 36 years long.

Succession on burned areas

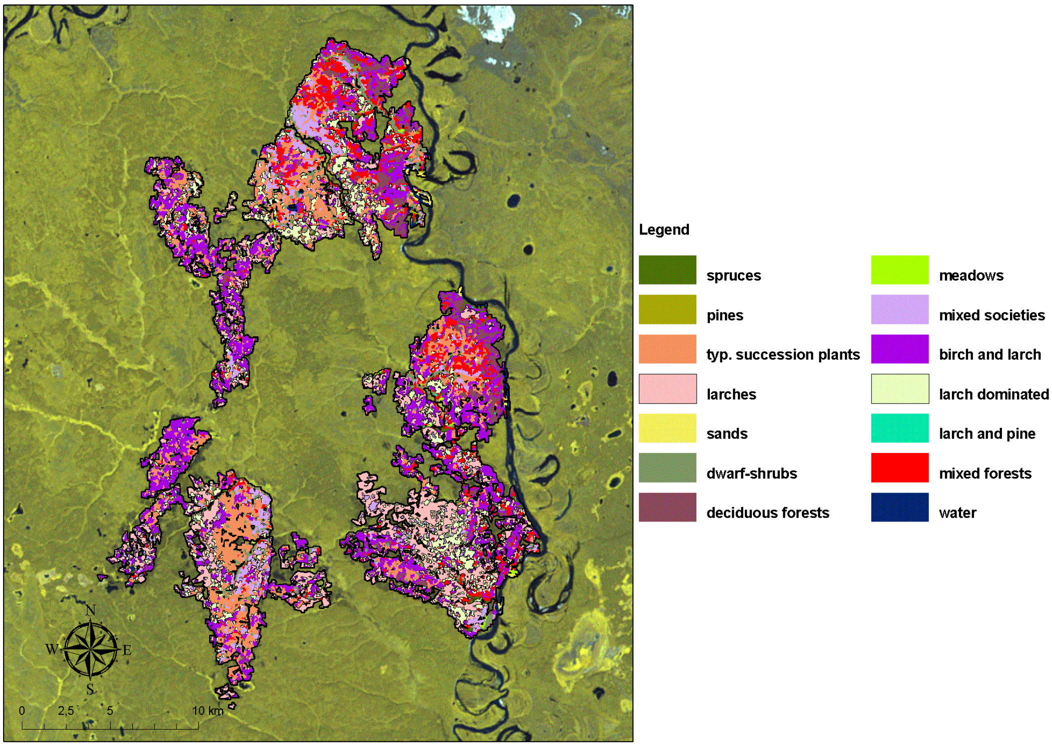

Fig. 14: Post-fire communities and their distribution in the burned arean (source: own scheme with the Land-sat-1-scene as base and the land cover classification of 2009 in the fire affected areas)

A surprising result is that in contrast to the well-established theory (SCHULTZ 1998, p. 188) that declares fires to be a reason for development that neither the meadows nor the lake cover larger areas of the fire grain. Some areas were classified as meadows, but they are all located near the river Tyung, where the ground is possibly moister than in the rest of the area and the lakes had probably existed before the fire event. Thus the meadows might be situated on older *taliki* and not on recently thawed permafrost. Figure 14 shows the recent coverage of the area.

7.2.3 Mining

At the southern border of the study area open cast mining visible, because of a direct link to prevailing tree species. In the 1970s, the area was covered nearly completely with pure pine forest. In the recent Landsat-scenes, the consequences of mining are clearly visible.

Wide and continuous vegetation-free areas are dominating instead of pines and some wide-spread sand bodies in 1973. Also several fires destroyed the vegetation on the western and southern edges of the area, possibly started by fire clearing.

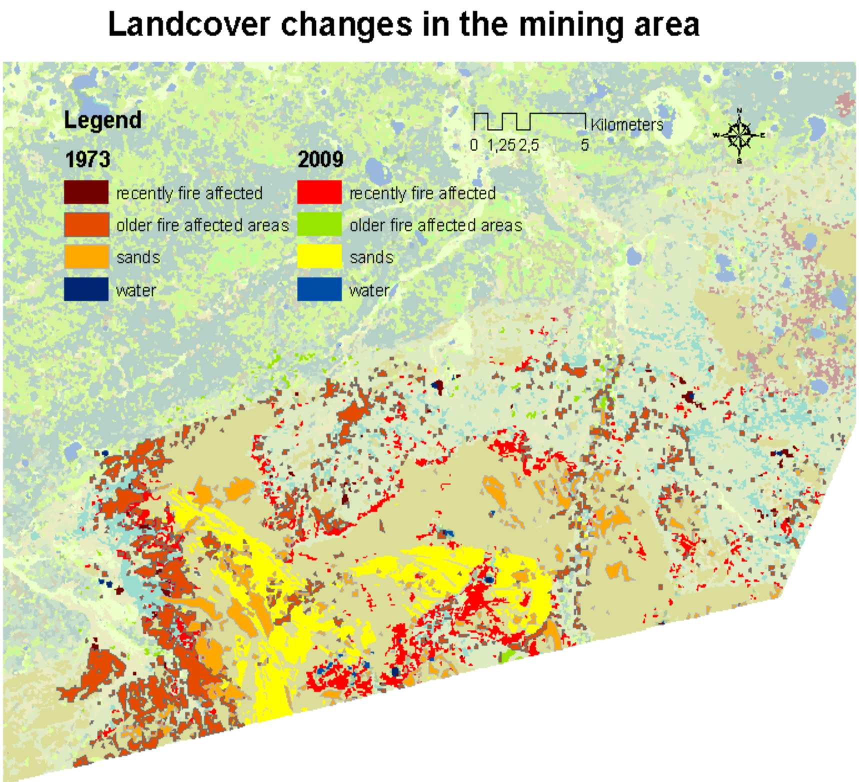

Fig. 15a: Map of land cover changes in the mining area. (source: own scheme, land cover classifications of 1973 and 2009)

The map subset 15a and the diagram 15b show, that all stages of the vegetation changing process exist simultaneously. The natural pine forest amount decreases, linked with an increase of sands and mixed societies of several pioneer species. Pines were replaced by vegetation-free sands and barren ground, and after finishing the gas extraction process birches, larches and shrubbery populate the area again.

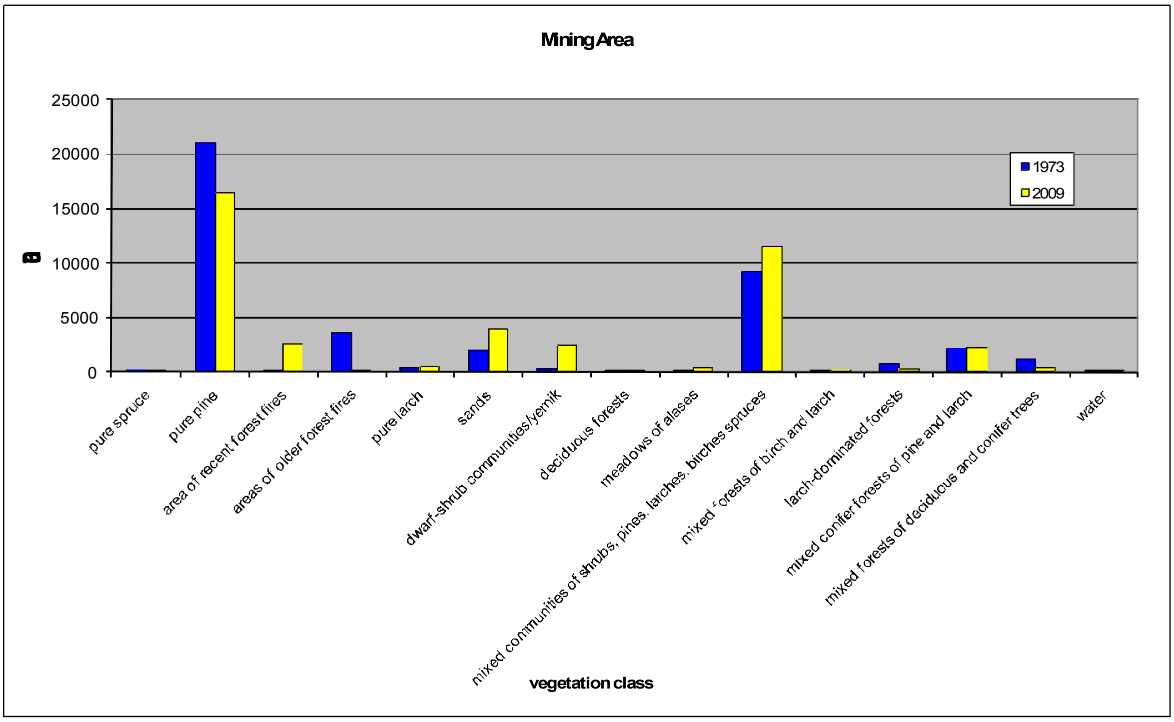

Fig. 15b: Chart of land cover changes in the mining area. (source: own scheme, land cover classifications of 1973 and 2009)

7.2.4 Reaction on Changed Water Regime

The next question to answer is the relationship between changing lake areas and the vegetation. Therefore two regions were chosen, one with a very rapid change of lake number and extent, and one with relatively moderate (→ Appendix B) The area with the considerably bigger lake change is situated in the middle of the study area (Fig. 16), in the north of the characteristic Viluy-meander near Verkhneviluysk. As example region with moderate changes the area in the north-eastern corner of the study area was chosen.

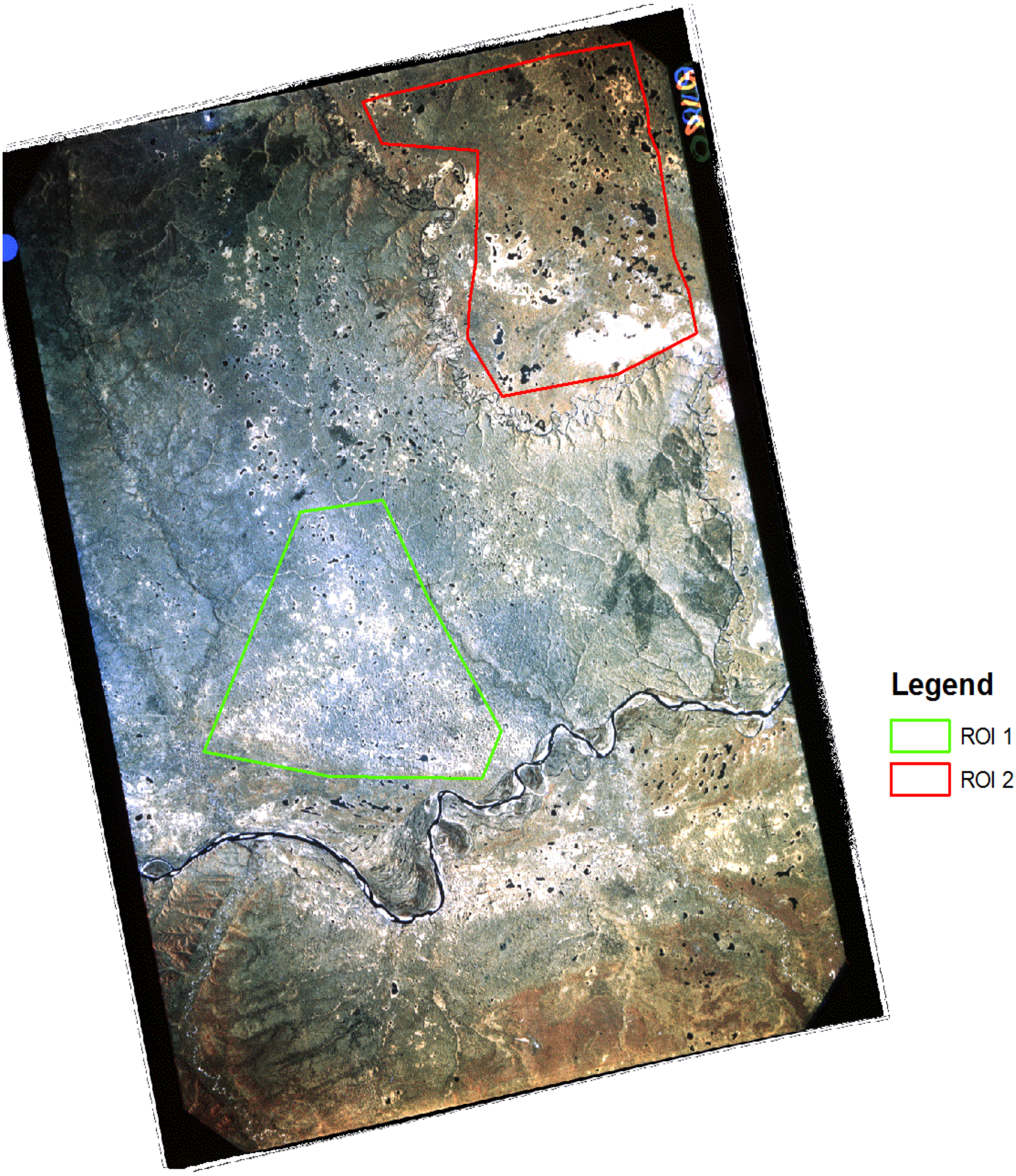

Fig. 16: Regions of different changes in lake area and count (source: own scheme, Regions of Interest over Soyuz-image 1976)

The results show differences in the vegetation development in the two regions.
Beside this an error probably caused by a cloud partly above the ROI in the Landsat-scene, which led to a calculated value for the mixed-community-class, which is twice the amount that was calculated for the 2009 and 1973-scenes, the vegetation coverage is relatively constant in the whole time of study. Minor replacements of pure larch stands and

mixed conifer forests by shrubberies had occurred in a smaller extent, while pure pine stands extended a little.
A significant contrast is the vegetation development in ROI 1. The larch-dominated forests were extensively replaced by pure larch-stands. The lake area increased about 563% from 1512ha to 10038ha during the 36 years. Pure deciduous forests disappeared nearly completely from the ROI, while the part of forests with conifers grew. Deciduous forests are often situated on more moist places, conifers on dry ones. So it is to assume, that moist stands became even more moist and so drowning the trees and forming the typical alas-lakes.

7.2.5 Differences of change in dependence to surface-near geological ground

For detecting links between surface-near geological ground (→Appendix A.b) and leading species, two groups of vegetation types were created by merging several land cover classes. The two classes with more than 90% larches have been aggregated to a single class, and the treeless alas meadows and shrub communities were also unified.
The part of the entire study area that is covered by pure larch and larch-dominated forests generally decreased about 6% between 1973 and 2009. Peculiar is an increase of larch coverage on sediments above chalk. This portion grew from 2% in 1973 up to 16% in 2009. Also on quaternary lacustrine sediments (mostly situated in alas depressions) the larch cover increases, while a decrease on younger quaternary and recent sediments was noticed. On the other bedrock types no significant changes had occurred.
At the same time the area covered by meadows and shrub societies expanded from 9 to 13%. The biggest increase was recorded on younger quaternary and recent sediments, as well as on Aeolian sands and on peaty grounds. The results or other classes only show smaller changes (Fig. 17a and 17b).

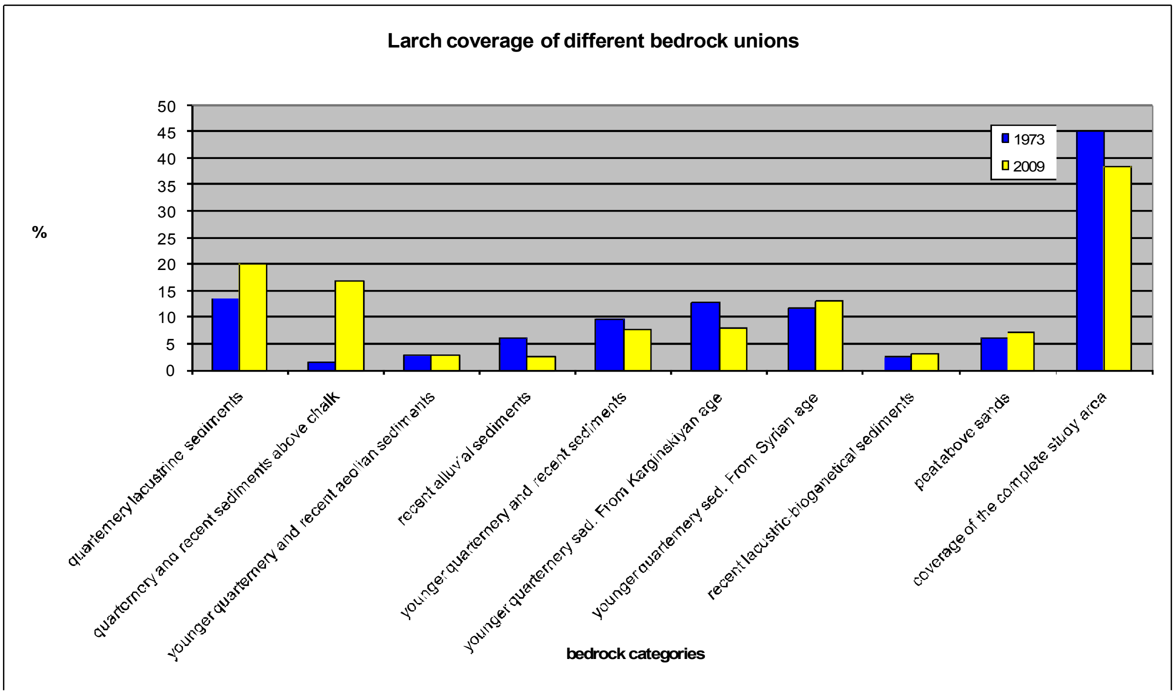

Fig. 17a: changes in larch coverage on different grounds (Source: own scheme)

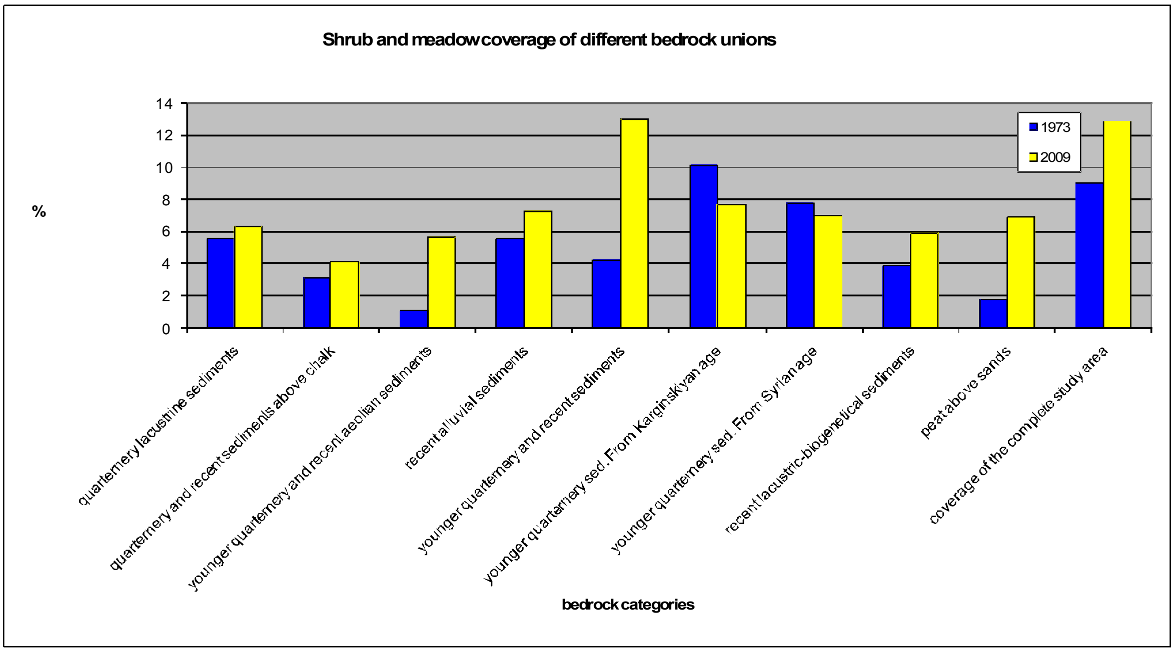

Fig. 17b: changes in shrub and meadow coverage on different grounds (Source: own scheme)

7.2.6 Development of Thermokarst Landscape Elements

As they are the element dominating the landscape in the study area, it put a special focus on the alas-depressions and their prevailing vegetation of meadows and (dwarf-) shrubs. Therefore, two questions will be discussed for the whole study area in more detail:

1. What kind of vegetation in depressions that were covered by meadows and shrubs in 1973 exists nowadays? What kind of replacement took place?

2. Which plant communities were transformed into present alas-meadows and shrub- communities?

7.2.6.1 Transformation of Alas-Meadows and Shrubs

Only a little more than one third of 1973s meadows and shrubs did not change their vegetation coverage and 8% of the former thermokarst-areas have been filled with water since 1973 (fig. 18). Especially the second aspect surprises, because this growth is much smaller than expected. It was assumed that this percentage has to be higher to explain the massive increase of the lake area. So the biggest part of the recently added lakes is not only of re-filled origin, numerous lakes must be created by later thermokarst-forming processes.

Fifteen percent of the former alas-meadows were populated by the typical pioneer species birch and larch, so that in sum of 65% of the meadows and shrub-covered areas are now forests with diverging larch parts.

Only four percent were transformed into sands or pure deciduous forests.

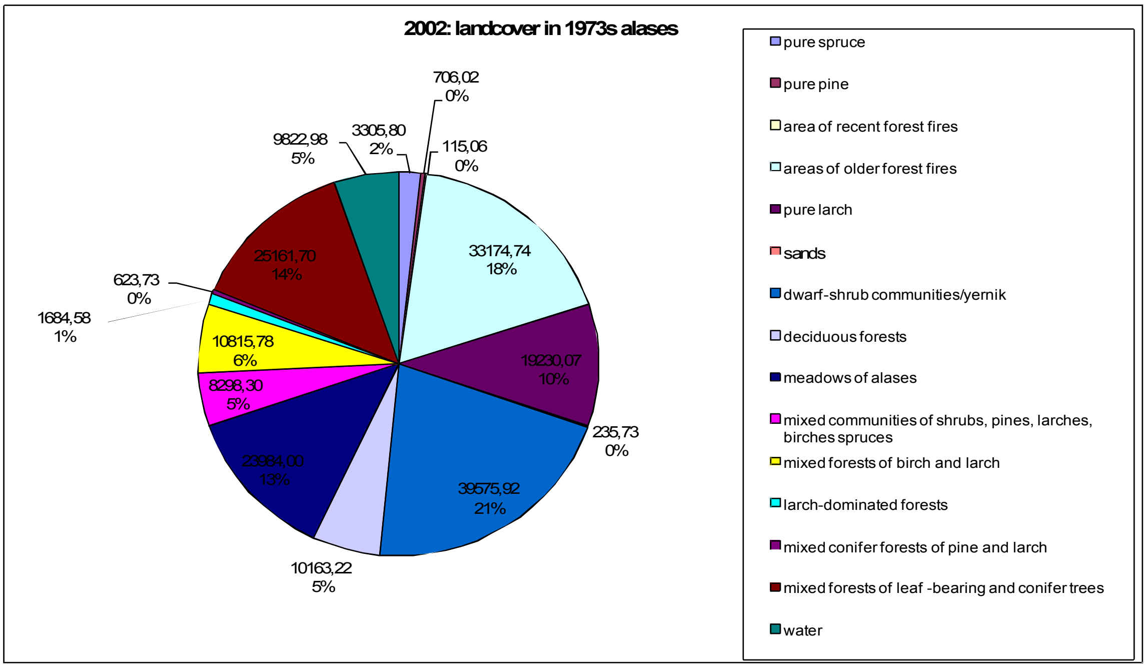

Fig. 18: Percentaged areas of vegetation units in 2002 in alas-meadows and shrubs of 1973. (Parts of the former alas meadows and shrubs that is covered by a vegetation class is represented in hectar and per cent.)

7.2.6.2 Transformation into Alas-Meadows and Shrubs

More than a half (58%) of the recent meadows and shrub-covered areas have been forests in 1973 (fig. 19). Especially the deciduous forests in the valleys of Viluy River and its tributaries were replaced, probably by systematic forest clearing. The conifer-dominated forests that have changed their vegetation cover are today new thermokarst depressions. Only 5% of the former lakes dried out and were populated by shrubs and meadows. Areas, in which changes in vegetation coverage have not occurred, make up 29% of the today's alases. The theory of forest fires as one main reason for starting the permafrost thawing process is verified on 13%.
That means in fact, that most of the recent alases are of younger stages of their development, and that only a minor part of them was refilled during the study period. Figure 18 could show the actual previous coverage of the recent alases a little inaccurate, because of the lower spatial resolution of the Landsat-1 scene. Thus it is impossible to georecetify the scenes absolutely congruent.

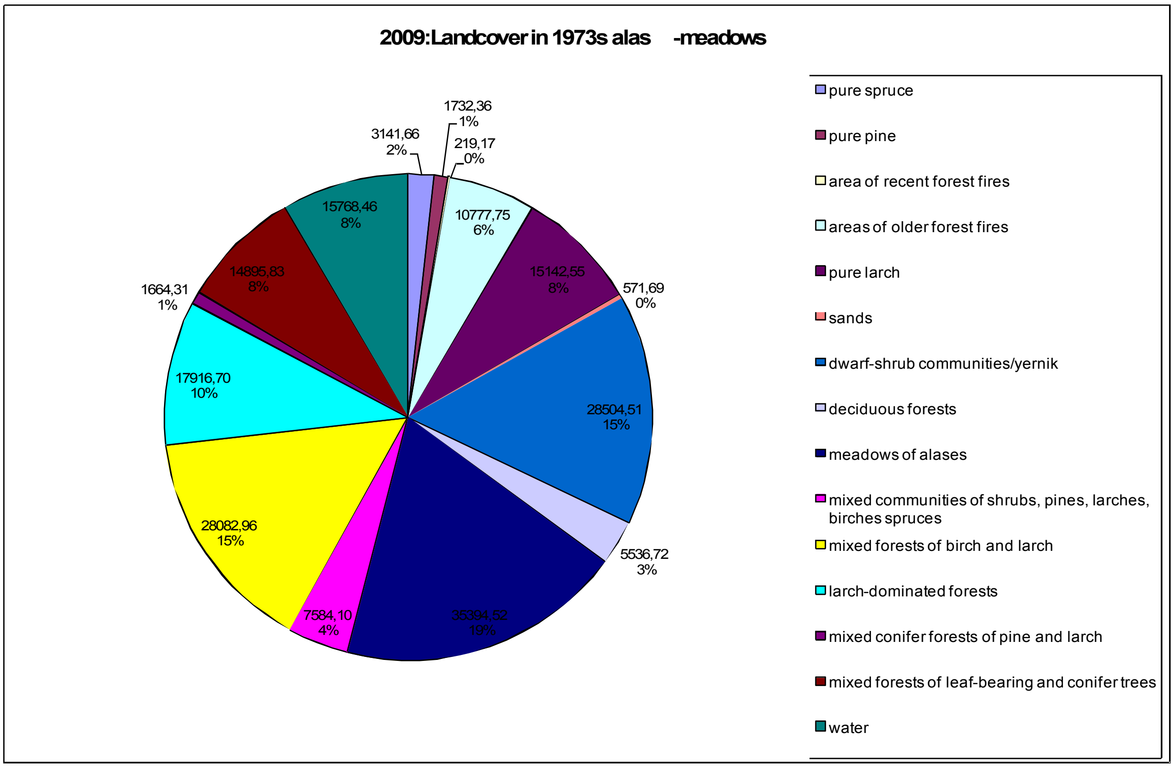

Fig. 19: Percentaged areas of vegetation units in 1973 in alas-meadows and shrubs in 2009. Area in hectar and percent of land cover classes that had covered the recent alas meadows and shrubs in 1973.

8 Discussion

Result quality

There are several factors that possibly derogate the quality and accuracy of the results.
The algorithms for supervised classification are not free of mistakes. Each algorithm has some advantages or disadvantages. The Maximum-Likelihood-Method is the algorithm with the best classification results, but it also has weaknesses. Every pixel is ordered to a specified class. If it is not to decide clearly, to which class one pixel belongs, it is classified to a random category.
Some algorithms define a new class with all pixels that cannot be ordered to a specified class, but the Maximum-Likelihood-approach does not. Transition sections between two classes, especially between water and land, were classified incorrectly. Another point is the similarity of spectral signatures of some completely different land covers, for example, some pixels that are situated in an area of recent forest fires, are assumed to be water. These problems can be minimised by some filter-matrices.

Additional problems occur because of the different ground resolutions of the Landsat scenes that lead to imprecise borders between two types of vegetation. Because the Landsat-scenes were not put under an atmospheric correction. This proved especially problematic in the scene of 2002, because parts of the scene were covered by clouds. This problem cannot be solved, but if band combinations are used, which consist of channels with longer wavelength-ranges that are not as much absorbed as the Landsat visible band combination, principal properties of the surface can be detected.
The ranges of wavelengths that could be sensed by the “Landsat visible” channel diverge between the different Landsat-generations. This involves problems in quality of spectral analyses, especially when calculating NDVI, as well as some imprecision in supervised classification. Those difficulties are determined by the unusual sensibility window of the MS-sensors. Basic indices like the NDVI or NVI are defined for using other borders of infrared and red spectral ranges. Furthermore it is impossible to combine the Landsat-1-channels in a way that visualises the scene in true colours.

The map that was used for the supervised classification is a hand-drawn one, so probably some shapes are not painted well, and even the georectification could not solve this problem. Another problem is that despite the coarse-scale spatial resolution of the multi-spectral photography, which served as a base for the used thematic map. Besides that, the generalisation grade is relatively high, so that some (possibly important) facts are not shown in the map.

The climate data is not complete. Values for 365 or 366 days per year are quite rare, for 1972 no data exists and for 1971 data was available only until July (→ Appendix A.3). Interpolation is one method to solve the problem, but micro-trends are left out when interpolating. The second approach to replace the missing data is to include values from neighbour-stations. For 1971 and 1972, the missing temperature and precipitation data gaps were filled by the average of the Yakutsk and Nyurba datasets. For Viluysk, the station in Nyurba is the next one. But the distance between these two towns is more than 200km, and especially precipitation is very variable, so that it is not sure, whether the values are meaningful or not.

Nevertheless the data allowed showing principal trends and it is assumed that the results are exact enough to answer the questions of this work.

Result substance

The higher average temperatures that are linked with higher precipitation sums and less days of frost have a direct effect on the vegetation in the study area. Although some alas lakes dried in the last 35 years, a significantly higher number developed newly. This induces massive changes on habitat properties, which means increasing moisture, deeper thawing depths in summer and an accretive salinity (caused by remaining salt after water had evaporated) in some parts.

Also the effect of human activity is visible by a decline of forest cover which is caused by forest cleaning, man-caused fires, mining and pollution.

The fact, that in ROI 1 the drained alases are not completely the same that were re-filled in the period of the study time, has been verified by detecting that closely 60% of the recent alases have been forests 30 years ago. This is an affirmation of the traditional theory of thermokarst relief development. But this theory has been refuted in an almost neighbouring part of the study area, the burned area. There, the replacement took place without forming of new thermokarst lakes though they had been expected.

Concerning the surface-near geological ground, no obvious connections to thermokarst development could be observed. The spatial scale is too high to allow clear statements regarding clear statements to its influence. The detected changes appear to be more depending on regeneration processes, because the biggest area of lacustrine sediments is congruent to the forests that changed their stage of development from post-fire communities to forests with higher larch-percentages.

The decline of pine forests in favour of larches can be explained with the lower competition ability of pines compared to larches. The second species is more competitive on moderate moist habitats, so it replaces the pines on sites that used to be drier. If the moisture continues increasing, the larches would be replaced on their part by birches or again pines, because larch competition ability alters faster on changed habitat conditions than the one of the pines.

Another surprising aspect is, that the sandy areas did not expand, that means that they also not refilled with water. This can be explained by different stages of development of meadow-alases and sand-alases. The sandy ones are drier than the vegetated ones, so a re-fill-process need a lot of more time than in younger, moister depressions.

The fact that the parts of the burned area of focus that is covered by pre-fire pioneer vegetation declines for more than 70% can be explained with a faster runtime than the theory of CHEROSOV (in TROEVA ET AL. 2010, p. 286) predicts. This theory stated that between 40 and 45 years after the fire event, the regeneration leaves the shrub stage to reach the so-called birch stage. In North America, “the area burned by forest fires has doubled during the last 20 years” (CHAPIN ET AL. 2000). This is contrarily to the results in the study area, where fire events of the same disturbance than in the 1970s did not occur during the period of time of these studies. A possible reason for this is the higher albedo of deciduous trees compared to conifers. Because wide parts of the study area burned in the 1970s, there are more forest communities with deciduous parts. The higher albedo causes a higher reflectance, more solar radiation gets reflected back into space. Another reason for the less fire events during the study time is the higher resistance of post-fire vegetation against new fires.

That permafrost landscapes, even in the boreal vegetation zone, is very dynamic. This was figured out by the analysis of the developments from and into alas vegetation communities.

As Ivanova 2008 postulated for the Verkhoyansk area in northern Yakutia forest parts that have been cleared to create new grazing areas, are the initiate alas development, with all consequences on vegetation. The higher sensitivity of this anthropogenic vegetation starts a chain reaction, because of the changed energy fluxes. Another disadvantage for the ecological situation is that those meadows are not only more sensitive to higher solar radiation income, but they react also faster and more negative on chemical exposure.
It is not to preclude, that pollutants in the rivers have an effect on the forests stands. The decline of the typical vegetation of river valleys like spruces and pure deciduous forests possibly is caused not only by forest clearing, but also by soil degradation because of the harmful substances. The loss of the protecting vegetation fastens this process. For the state of Iowa/USA, this had been previously proved (Zhang and Schilling 2006).
In North America, “the area burned by forest fires has doubled during the last 20 years” (Chapin et al. 2000). This is contrarily to the results in the study area, where fire events of the same disturbance than in the 1970s did not occur during the period of time of these studies. A possible reason for this is the higher albedo of deciduous trees compared to conifers. Because wide parts of the study area burned in the 1970s, there are more forest communities with deciduous parts. The higher albedo means a higher reflectance of solar radiation. Thus, less radiation and its energy can be transformed into warmth. This reduces the fire probability.
Another difference to comparable regions in America is that the soil moisture is assumed to be increasing, resulting the increase of lake number. For American boreal forests, Chapin et al. (2000) said that it remains constant and is not linked with increasing air temperatures and precipitation.

Probably the very high density of alas-shapes in the central parts of the Soyuz-scene was developed as a consequence of the last bigger fire event, that destroyed a high percentage of the forests in the photography. This chronological unknown fire event is responsible for the high percentage of forests on older and oldest fire affected areas in the forest stand map.

9 Summary and Conclusions

Land cover classifications using Landsat data is an often used method for change detection. The methodical concept was adequate for the aim of this work., that was to quantify changes in vegetation patterns or a large scale. For downscaled observations, this method is less adequate, then higher resoluted data has to be used. Significant changes in the land cover of the study area have been observed with multi-temporal data. Changes in issues of plant communities and forest combination, human impact like forest clearing and reactions of the ecosystem on fire events and climate change were observed and quantified. It is impossible to originate these changes only to a single influencing factor; they all interact with each other. The human activity, for example, starts forest fires as well as to limit them, too. Additionally, climate is also influenced by mankind, both at the global and the regional scale. The climate change occurs very rapid in central Eurasia, with dramatic increases of annual average temperatures. It cannot be stated definitely what the factor with the most responsibility on vegetation is, because direct signs that link them to climatic changes are overlayed by regeneration after fire events. The geological ground has the lowest impact on the vegetation.

Purchases for further work could be collecting more detailed data regarding to soil moisture and the impact on ecological properties in boreal forests. The role of the surface-near ground has to be put under a downscaled research to appraise, whether its influence is as surprising low as it was detected.

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A: Data Appendix

A.a The Remote Sensing Data

Because of the several generations of Landsat satellites that have taken the multi-temporal remote sensing data, it is necessary to collect the properties of each scene. Therefore it has to be especially mentioned, that the scene of in 2002 was taken by a satellite of younger generation than the 2009 scene.

Following table contains the basic information about the used remote sensing data:

	Landsat 1	**Landsat 7**	**Landsat 5**
date	24.07.73	13.08.02	24.08.09
sensor type	MSS	ETM	TM
spectral range (µm)	0,5 – 1,1	0,45-12,5	0,45-12,5
Number of channels	4	7	7
scene identifier	LM11390151973205AAA03	LE71280162002225SGS00 LE71280152002225SGS00	LT51280152009236MGR00 LT51280162009236MGR00
ground resolution/ pixel extent (m)	79 x 79	30 x 30	30 x 30
Cloud coverage (per cent)	0	10	0
Flight height	907-913 km	705 km	705 km

Table 1: Properties of Landsat images and satellites

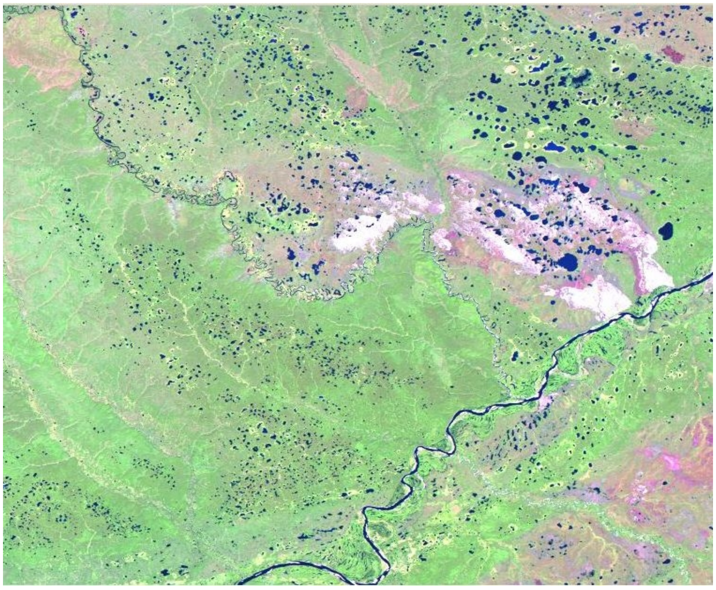


Fig. A.1: Part with the characteristic meander of the river Viluy of the Landsat scene taken in 2009 with band combination 4--2-1.

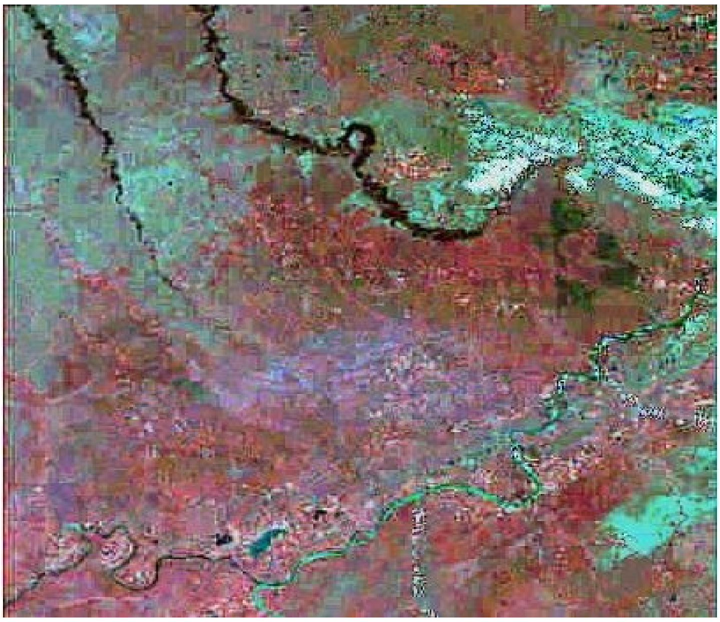


Fig. A.2: Landsat scene taken in 1973 in band combination 4-3-2.

A.b The Multi-Spectral Image Data and Deviated Maps

Some basic information about the Soyuz-photograph (fig. A.1) had been taken from Vostokova et al. 1982 are collected in the following table:

Date	18.9.76
Flight height (km)	400
Area	175km x 225km

Table 2: Properties of the Soyuz-image

In SAGDAYEV ET AL. (1982) the image is not georectified and printed at a scale of 1:400000. Therefore, the maps (fig. A.2 and A.3) that result from interpretation of the image are at the same scale.

The "Soyuz"-image from 1976 (georeferenced)

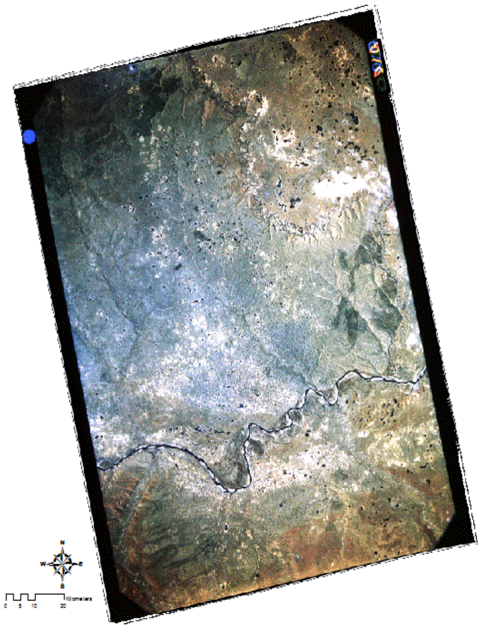


Figure A.3: The Soyuz image of Viluysk area (Source: SAGDAYEV ET AL. 1982)

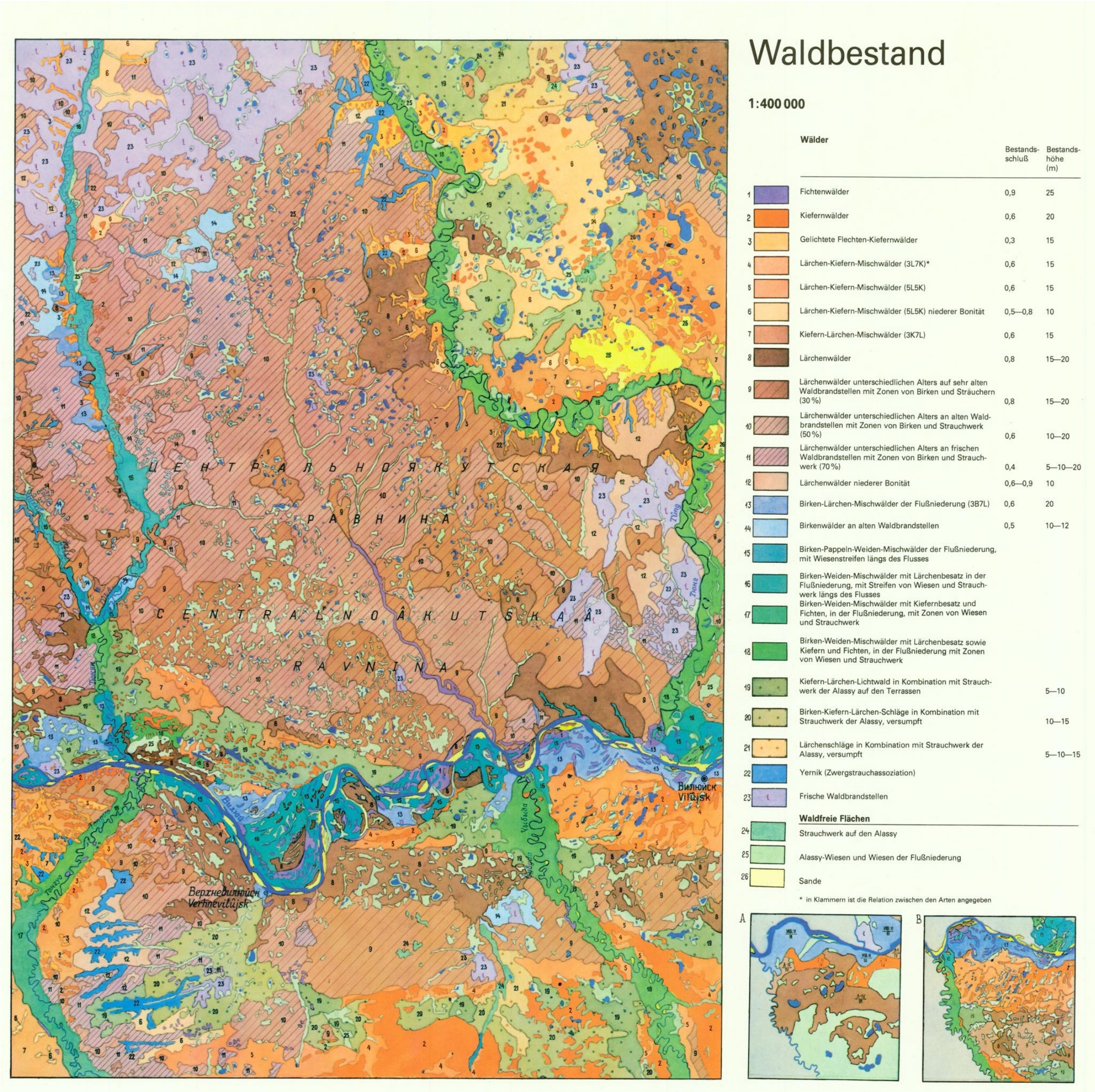
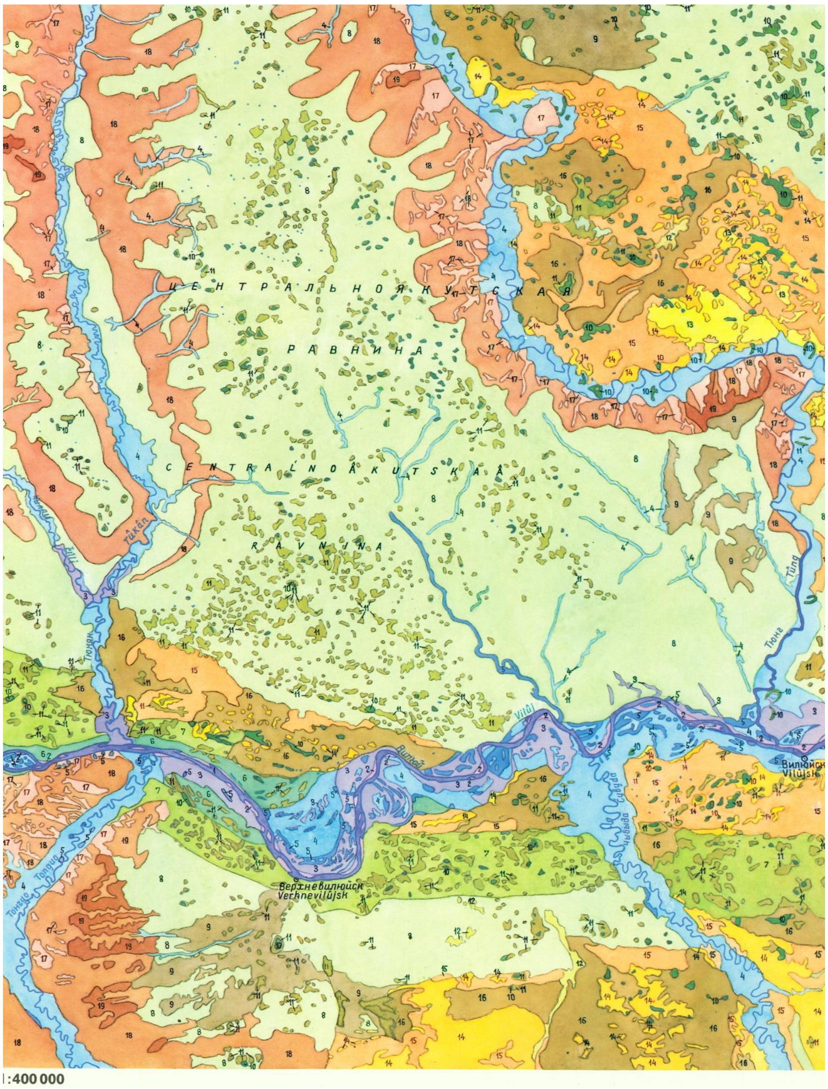


Fig. A.4: Map of forest stand, (Source: SAGDAYEV ET AL. 1982, p.35)



	Geologisch-genetischer Gesteinskomplex	Gesteinscharakteristik						
		Zusammensetzung	Zustand	Gefriertyp	Zeitpunkt des Gefrierens	Kryogene Texturen	Vereisung (%)	Monomineralische Eisbildungen
1	Komplex rezenter alluvialer Sedimente (a IV)*	Sand	getaut	—	—	—	—	—
2			gefroren, mit getauten Bereichen	syngenetisch	Spätholozän (IV_3)*	massiv	20 bis 30	—
3		Sand, Feinsand				massiv	bis zu 10–20	—
4	Komplex jungquartärer und rezenter Sedimente (a III_3–IV)	Feinsand, schluffiger Lehm	gefroren		Sartan-Kaltzeit bis Holozän (III_4–IV)	massiv, linsenförmig, geschichtet netzartig	von 10 bis zu 50–60	regenerierte Eiskeile 0,5–1/bis zu 6–8** Sand-Eis-Keile
5		torfig-schluffige Ablagerungen, Torf				linsenförmig, geschichtet	bis zu 60–80	regenerierte Eiskeile bis zu 3/bis zu 10
6	Komplex jungquartärer Sedimente Karginsker Alter (a III_3)	Feinsand, Lehm			Syrian-Kaltzeit bis Sartan-Kaltzeit (III_{2-4})	konkav- und horizontalgeschichtete Strukturen erster Ordnung; ataxitische, geschichtete, linsenförmige, massive Strukturen zweiter Ordnung	bis zu 90	regenerierte Eiskeile
7	Komplex jungquartärer Sedimente von Syrian-Alter (a III_2)	Feinsand, Lehm						
8	Komplex von alt- und jungquartären und pliozänen bis altquartären lakustrischen Sedimenten (a I–II + la N_2–Q_1)				zweite Hälfte des Altpleistozäns bis Mittelpleistozän (I_2–II)			regenerierte Eiskeile 3 bis 4 und mehr / bis zu 20–50
9		Feinsand und Lehm, vertorft				ebenso wie in den oberen Teilen des Profils – ataxitisch		
10	Komplex rezenter, lakustrisch-biogener Sedimente (lb IV)	Schluff	getaut	—	—	—	—	—
11		schluffiger Sand, Feinsand, Lehm	gefroren	epigenetisch	Spätholozän (IV_3)	geschichtet, netzartig, massiv	20 bis 30	Injektions- und regenerierte Eiskeile
12		torfig-schluffige Ablagerungen, Torf				geschichtet, netzartig	von 40–60 bis zu 80–90	
13	Komplex jungquartärer und rezenter äolischer Sedimente (v III–IV)	Sand	getaut	—	—	—	—	—
14			gefroren	syngenetisch	Syrian-Kaltzeit bis Spätholozän (III_2–IV_3)	kontaktartig	5 bis 7	—
15						massiv	bis zu 20	—
16	Komplex von jungquartären und rezenten äolischen Sedimenten, überdeckt von rezenten biogenen Ablagerungen geringer Mächtigkeit (bis 0,5–1 m) (b IV/v III–IV)	geringmächtiger Torf und torfig-schluffige Sedimente über Sand				linsenförmig, geschichtet, netzartig	bis zu 80	regenerierte Eiskeile
17	Komplex jungquartärer und rezenter alluvial/deluvialer Ablagerungen über Kreide (ed III–IV, d IV/K_2	Sand		epigenetisch		kontaktartig	5 bis 7	—
18		Sand, Feinsand, Lehm				massiv, geschichtet, netzartig	10 bis 60	regenerierte Eiskeile
19		Lehm und Feinsand, vertorft				geschichtet, netzartig	40 bis 80	

Fig. A.5. Map of Combination and Structure of Permafrost Ground (Source: SAGDAYEV ET AL. 1982, p.32)

A.c: Errors in Climate Data

Because the climate data is not free of missing values, it is necessary to show how many days are missing to estimate the correctness of the climate data analysis. A statistic of the annual distribution of errors has been created:

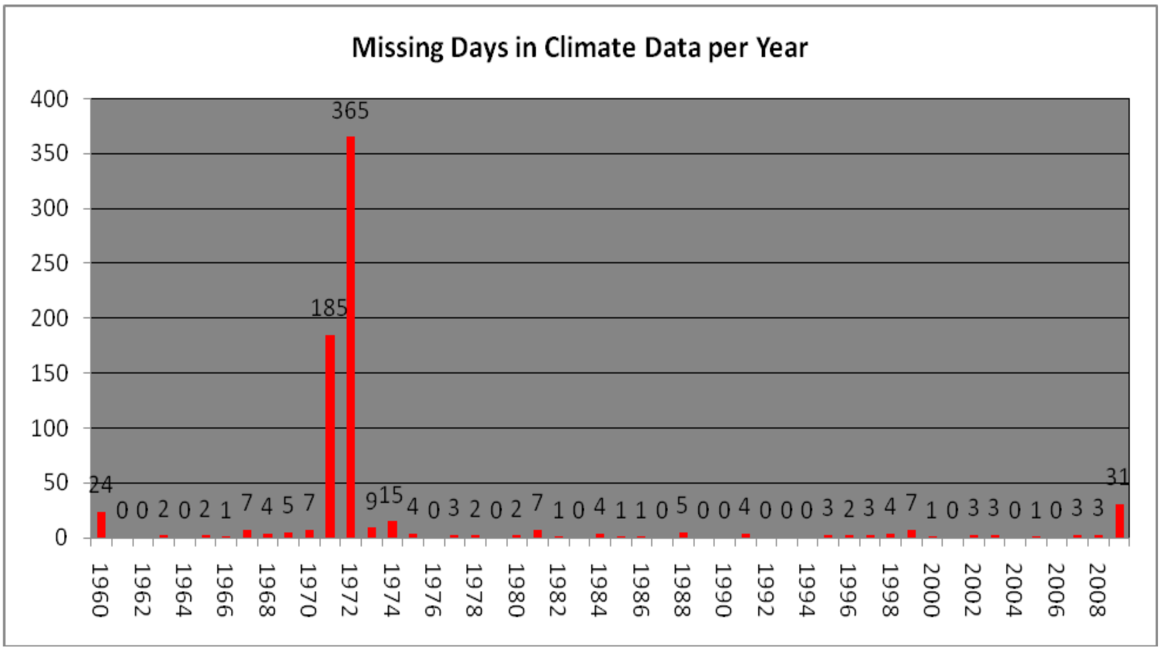


Fig. A.6: Number of datasets per year that have not been available for analysis (Source: own scheme)

B : Methodical Appendix

B.a: Criteria for Training Sites for the Supervised Classification

The training sites had to be defined by several criteria. The different vegetation classes of the map “Forest stands” (fig. A.2) were put into context with their spectral signatures. Then these spectral signatures had been used to classify the two younger Landsat-scenes.

class no.	name	True colours: 3-2-1	RGB: 4-3-2	NDVI
1	Pure spruce stands	very dark green	dark violet	low
2	Pure pine stands	green with high part of brown	light brown with green influence	low
3	Areas effected by recent fire events	dark brown to black	moderate green	around 0
4	Fire-effected areas with partly regenerated vegetation	light green, nerved by dark brown parts	light pink	high
5	Bare sands without any vegetation	light yellow or white	white or light blue	<0
6	Mixed deciduous forests in river depressions	light green	powerful pink	very high
7	Mixed forests of birches, willows, larches and pines	darker green than 7	darker pink than class 6	high
8	Pure larch forest	red-brown	moderate magenta	moderate
9	larch-dominated forests on oldfire-effected areas	lighter brown than class 8, more green	Effectual light purple	moderate, more than class 8
10	Communities of shrubs, pines, birches, spruces and larches, oftentimes getting marshy	Moderate green, inconsistent surface	Moderate magenta	lower than class 9
11	mixed forest of birches and larches	moderate green	Effectual pink	moderate to high
12	associations of dwarf-shrubs (Yernik)	brown-green	purple	moderate to low
13	mixed forests of pines and larches	red-brown, green brown dense vegetation	Moderate to light pink	moderate
14	meadows in dry alases	light green, tendency to yellow	light pink	moderate to high
15	lakes and rivers	blue or dark green	black	around 0

Table B.1. Spectral Characteristics of the Training Sites for Land Cover Classes

B.b: Used ArcGIS tools

ArcGIS was the software, which was mostly worked with. It was used to make it possible to work with the classification results, to improve quality and reducing the data amount.

ArcGIS tool/toolset	Function	Applied on	Result
Georeferencing	Converts scenes in unique projection and makes the different scenes congruently	Soyuz-Image and deviated maps, Landsat 1/5/7-scenes	Congruent datasets
Editor	Creates polygons to digitize analogue maps	Maps of surface-near ground and forest stand	Digital maps for overlay and ground information for classification
Majority Filter	Blanking noise	Land cover classification of Landsat-1/5/7-scenes	Clearer appearance of classification results
Clip (analysis)	Reshapes a dataset	Landsat scenes, final classifications for spatial analysis	Smaller extent of datasets, focus on specific topics
Raster to Polygon	Converts raster data into vector files	Land cover classifications, water masks	Selectable features in vector format
Eliminate (management)	Dissolves borders to merge small polygons with its largest neighbour	Land cover classifications	Bigger polygons, data amount reduced significantly
Merge	Unifies two datasets	Water mask, land cover classification	Corrected classifications,
Select by location	Selects features of a layer, which spatially intersect/contain etc. with features of another layer	Clipped regions of interest, burned areas, mining area combined with land cover classifications	Spatial intersections to create time series

Table B.2: Used ArcGIS tools with function, data on which it was applied on and result

B.c: Created Datasets

To get a concentrated overview of all datasets that were created during these studies, the following table lists all of them with their name, their source data and the software that was used to create.

Description of created Dataset	Name of Dataset (XY: 73/02/09)	Programme	Source Data
Subset of Landsat scenes	SubsXY.img	ENVI	Landsat scenes
Land cover classification in raster format	MaxLikeXY.bsq	ENVI	Subset of Landsat scenes
Simplified classification in raster format	maxLikeXY_fil.im	ArcGIS	Rough classifications
Land cover classifications in vector format	vegeXY.shp	ArcGIS	Filtered classifications in raster format
Simplified classification in vector format	vegeXY_elim.shp	ArcGIS	Land cover classification shapefiles
Water mask	waterXY.mask	ENVI	Landsat scenes
water classifications (raster format)	MaxLikeXY_water. bsq	ENVI	Water mask and Landsat scenes
Water classifications (vector format)	waterXY.shp	ArcGIS	Water classifications (raster)
Corrected land cover classifications	vegeXY_merge.shp	ArcGIS	Water classifications (vector) and land cover classifications (vector)

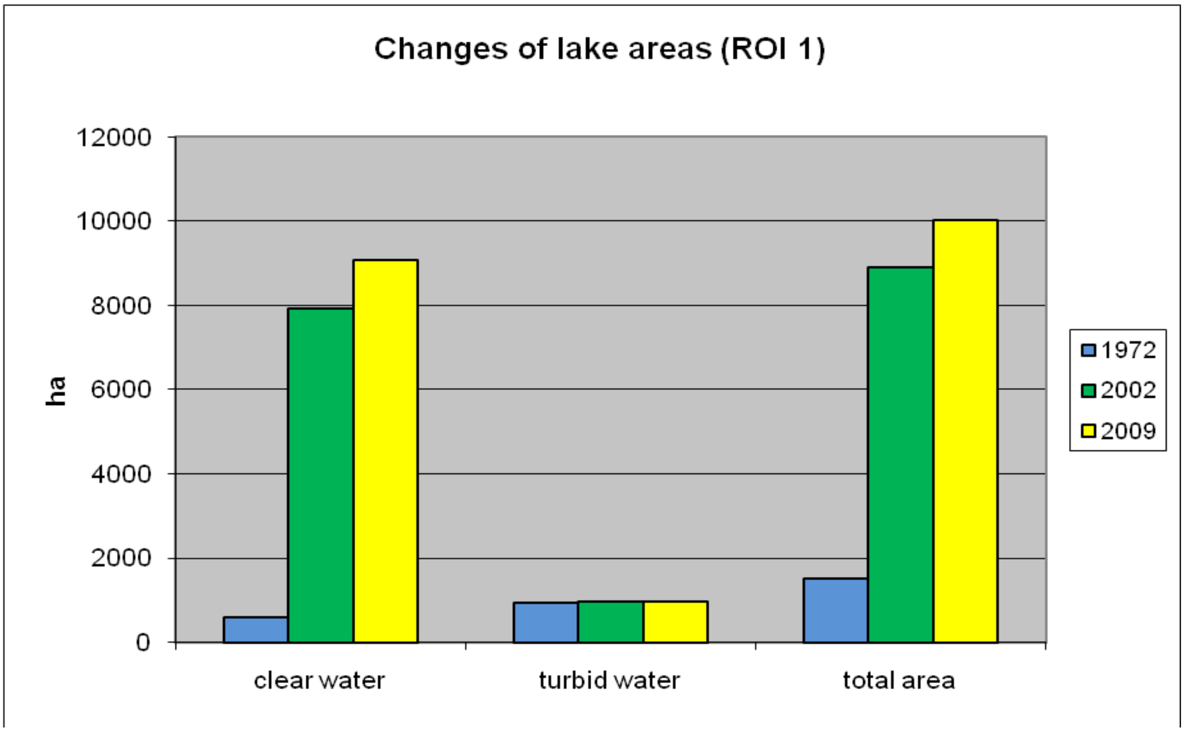
Table B.3: Description and Properties of the Created Datasets

B.d. Thematic Analysis

For different thematic aspects, 4 regions of special focus were defined. The Areas “ROI 1” and “ROI 2” are the areas with different tendencies according to the changed hydrologic situation of thermokarst-lakes (concrete values → fig. B.2a and B.2b): . The chosen burned area was preferred to the other region in the north-western part o the study area that was affected by forest fires. The choice was taken because the smaller burned area is situated completely in the study area and was to detect even in the Landsat-1 scene. The other fire must have been occurred between 1973 and 1976.

Focus Regions for spatial analysis

Figure B1: Localisation of the regions of interest for detailed thematic analysis. (source: own scheme with Soyuz-image as basis)



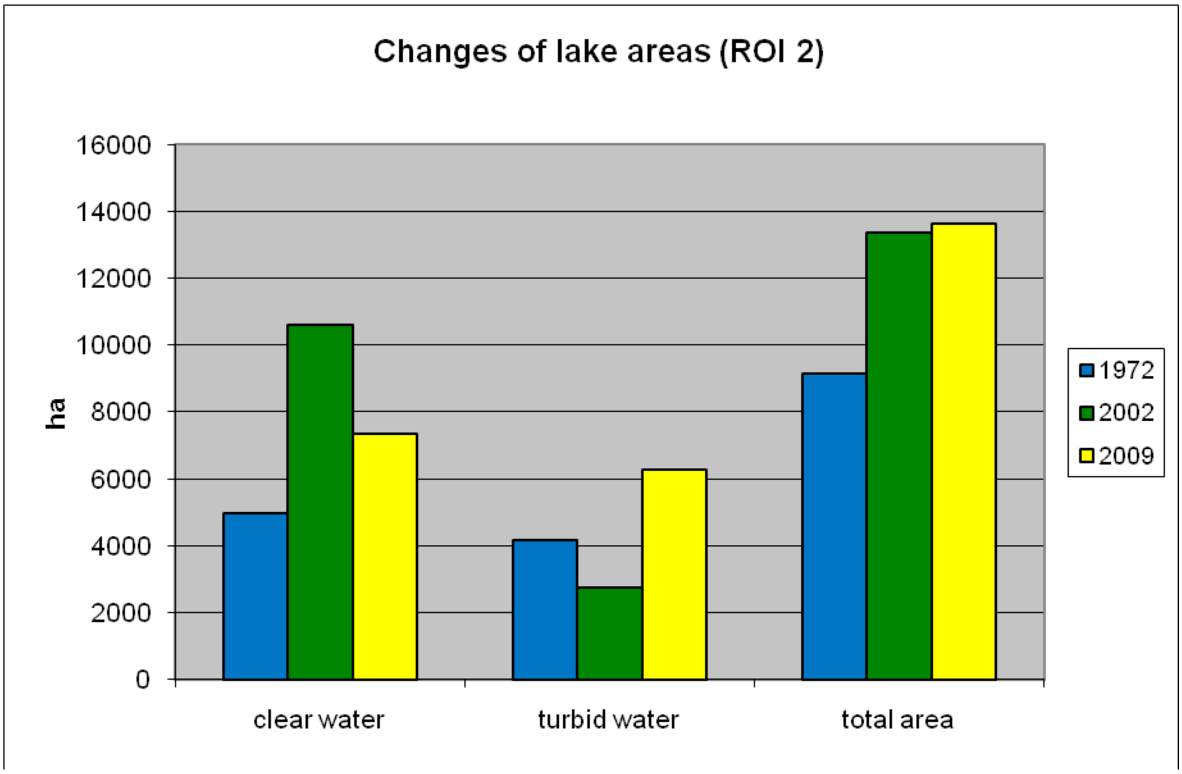


Figure B.2a and B.2b: Change of the size of areas covered by thermokarst lakes between 1972 and 2009 in the two regions of interest (Source: Land Cover Classifications 1973, 2002, 2009 →fig. C.1 to C.3).

C Classification Results

To present the final land cover classification for the three generations of Landsat-Data, the created maps are pictured below:

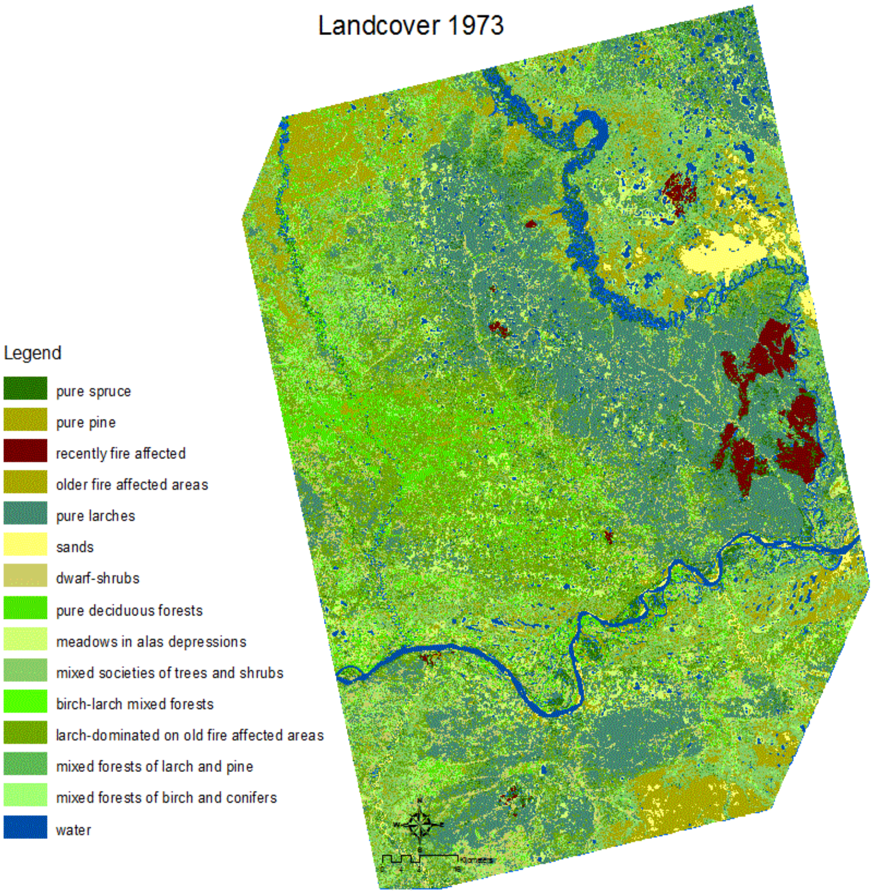


Figure C1: Land Cover Classification of the Viluysk area 1973. (source: own scheme)

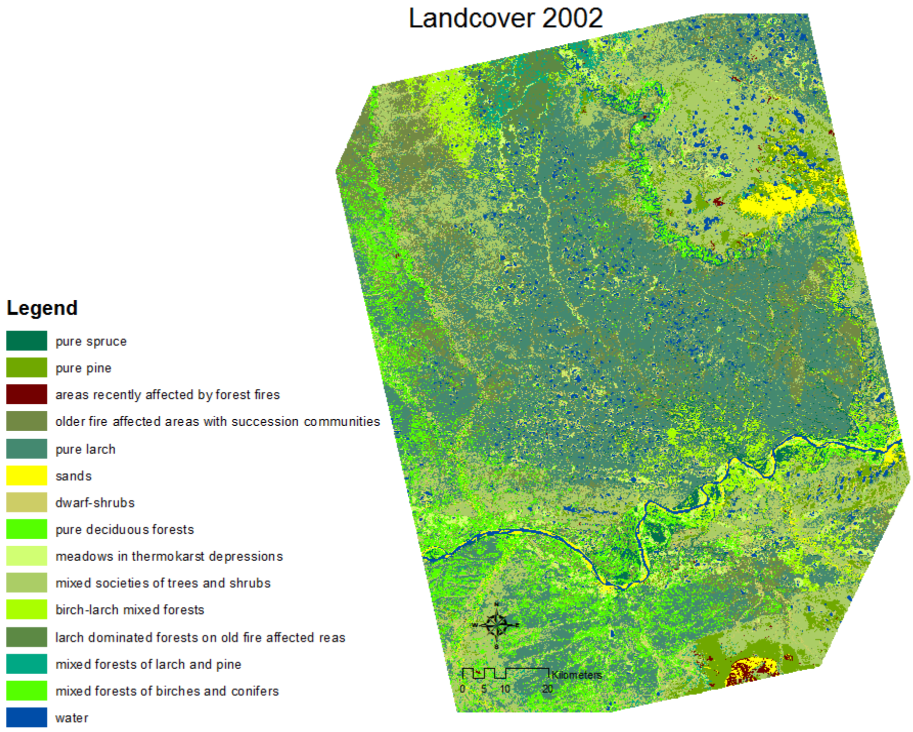


Figure C2: Land Cover Classification of the Viluysk area 2002 (Source: own scheme)