Disturbance and forest cover change mapping in Siberia with Earth observation

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1. INTRODUCTION

The EC-project SIBERIA-II (Multi-Sensor Approach for Full Greenhouse Gas Accounting in Siberia) (Schmullius and Hese, 2002; Hese et al., 2002; Santoro et al., 2002) represents an evolution from its predecessor SIBERIA (SAR Imaging for Boreal Ecology and Radar Interferometry Applications), where algorithms were successfully developed to produce maps of growing stock volume for 1 Mio km^2 Siberian boreal forests.

The scientific objective of SIBERIA-II is to integrate Earth Observation and biosphere process models such that a full greenhouse gas (GHG) accounting within a significant part of the biosphere may be quantified to a much greater degree of certainty than before. To achieve SIBERIA-II´s objective a variety of Earth observation (EO) sensor systems that are operational are utilized in order to derive the needed biophysical properties as input for two Dynamic Vegetation Models (the Lund-Potsdam-Jena and the Sheffield DVM) and a landscape-based accounting approach (IIASA-GIS). The IIASA-GIS also contains the necessary ground truth information for regional applications while local verification is supplied by the Russian forest enterprises. The project region stretches from 52 to 72 degrees N and 88 to 110 degrees E. The area of over 3 Mio sqkm embraces steppe and tundra biomes, and taiga forests (Fig. 1).

2. SIBERIA-II EO PRODUCTS

For the derivation of the EO products, SIBERIA-II makes use of of a lot of current orbiting satellites taking into account the data availability and the temporal and spatial resolution requirements set by the DGVMs and the accounting approach. As a result, the following products are derived: land cover and change, biomass (on testsites), FPAR, LAI, phenology, freeze-thaw, wetland map, snow cover depth and extent, forest fires, Af- Re- Deforestation (ARD) only for testsites.

Land cover is fundamental for carbon cycle observation or assessment. In SIBERIA-II the land cover product has two main objectives: 1) provide initial conditions for DVM calculations and 2) provide a land cover map to update the current information in the GIS database. To satisfy the spatial and temporal resolution requirements as well as the quality and time period of its acquisition, land cover and change maps are produced using MODIS and MERIS data.

Biomass is a very important parameter for carbon accounting and is expected to improve the corresponding GIS layer in the landscape approach. Biomass can currently only be derived indirectly from other EO-based parameters. Nonetheless, repeat-pass winter ASAR coherence is tested for direct retrieval.

FAPAR, LAI and phenology are not inputs to DVMs, but can give information on how well the models reproduce actual vegetation seasonal functioning. In the landscape-based approach LAI and phenology are used as GIS layers to characterize vegetation. From MODIS, thematic

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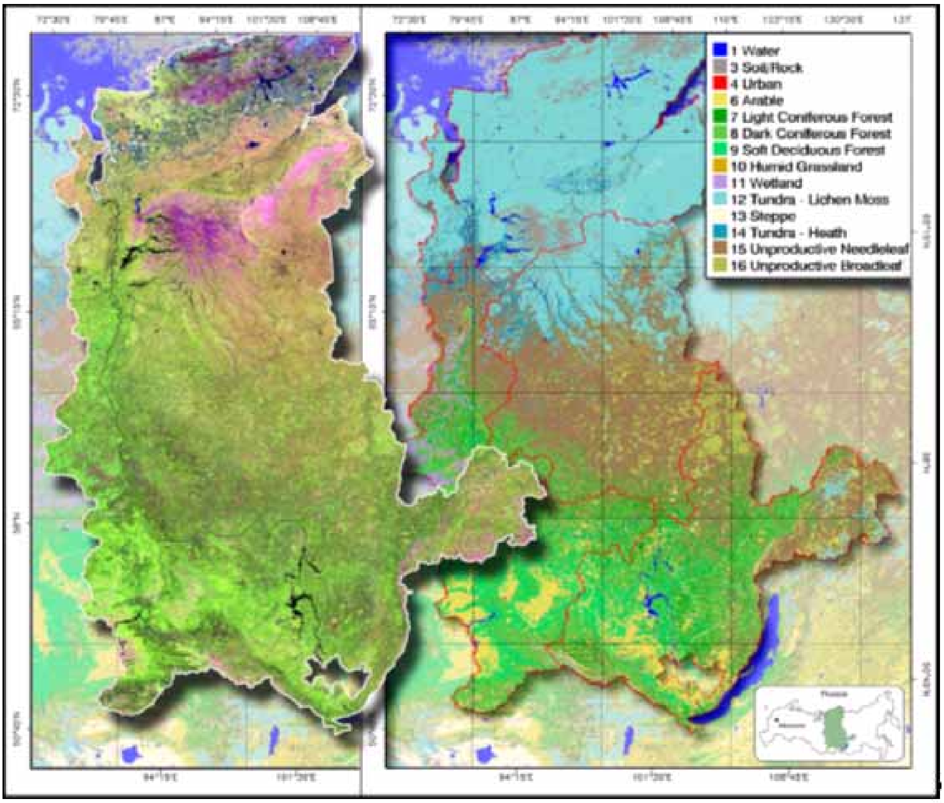

Fig. 1. The SIBERIA-II project region in central Russia. Left: 16-day MODIS cloud-free composite for summer 2002 (days 225-241). Right: adopted MODIS-landcover product to Siberian ground truth (courtesy: L.Skinner/A.Luckman, University of Wales, Swansea, SIBERIA-II Project Team). This new developed landcover map is being implemented in Dynamic Vegetation Models and a GIS-approach for a realistic account of greenhouse gas fluxes over a 3 mio sqkm transect through the Eurasian boreal zone.

maps of FAPAR and LAI on an 8-days basis have been generated for the whole Eurasia. Phenology can be derived by integrating temporal series of FPAR, LAI and radar images.

Both DVM approaches require the indication of start and cessation of freeze/thaw periods (switch-on/switch-off of photosynthetic activity), and the maximum depth of the thawing averaged at a cell level. For the observation of freeze and thaw effect time series derived from QuikSCAT data are investigated and an initial parameter for onset and duration of thaw is operationally being derived.

Wetlands are wet areas intermediate between land and water. The extent of wetlands is important in CO, CO_2, CH_4 accounting and for plant functioning. ASAR WS data is used to produce masks of water bodies. These results may be integrated with soil maps to understand and derive more information concerning wetland areas.

Snow cover can be included both as a hydrological parameter and as a parameter controlling photosynthesis in the DGVMs. Refinement of the snow product retrieval methodology using passive microwave radiometers and application on archived SSM/I data over Siberia is currently ongoing.

Disturbances in form of forest fires represent one of the main threats to Siberian forests. Within SIBERIA-II a fire scar product based on NIR and SWIR data from several sensors (SPOT/Vegetation, MODIS, ATSR-2 etc.) has been developed.

ARD (Afforestation, Deforestation, Reforestation) defines different transitions between forest and non-forest in the Kyoto Protocol. Landsat ETM+ and TM imagery have been chosen for ARD maps at selected test sites between 1990 and 2003.

3. ARD FOREST COVER CHANGE MAPPING

The scientific objective of the SIBERIA-II project is to integrate Earth observation and biosphere process models such that full greenhouse gas accounting within a significant part of the biosphere can be quantified. Global estimates of the net carbon flux due to land cover changes are complicated by critical uncertainties like distribution and rate of deforestation and biomass burning, conversions from natural land cover and rate of reforestation and re-growth of deforested or burned land. The Kyoto Protocol (KP) carbon emission inventory is related to land cover changes with respect only to areas directly affected by human action through ARD (Afforestation, Reforestation, Deforestation) (Scole and Qi, 1999).

It is important to differentiate the needs by the KP and by full carbon accounting (FCA). FCA accounts for all possible sources and sinks and not only for those related to ARD under a specific and restricting definition of forest.

Differentiation between natural and human induced forest changes (as required by the KP) is a complex task and asks for an analysis of underlying causes of disturbances. As noted already in Scole and Qi (1999) forest management practices which change growth rates of forests and selective logging are not considered in the KP. Interpretation of the possible causes of forest changes is often impossible with Earth observation. Analysis of contextual and structural information using post classification analysis with contextual GIS analysis systems in multiple scales can however improve the potential of remote sensing for Kyoto ARD mapping. There will however remain restrictions to extract underlying causes of land cover changes with remote sensing. A combination of Earth observation with extensive ground truth and local forest enterprise information to deliver precise information to these questions is essential.

3.1 Data

Ground truth information from some test territories with extensive forest inventory data from forest enterprises in Russia is used for this analysis (on ground forest inventory and planning (FIP) for intensively managed forests). These datasets cover different regions in Siberia (compare with Table 1 and Fig. 2). Multi-temporal Landsat ETM and TM5 data stacks for these areas were acquired from 1989 and 2000 covering areas in the Krasnoyarsky Kray and Irkutsk Oblast (Landsat path and row: 140/20, 141/20, 142/20, 143/20, 135/21, 136/21). To correct for path radiance in multi temporal data atmosphere correction algorithms were employed using algorithms following Richter (1996). Some Landsat TM5 data sets showed a “salt and pepper” effect which appeared randomly at different places in the image geometry and without correlation between the different sensor bands. This noise was corrected using a threshold based selective filter technique that changes the effected pixels to the mean of the surrounding 8 pixel values if a defined threshold is exceeded. Adjacent Landsat scenes were relative corrected to an atmosphere corrected multi temporal master scene using histogram matching techniques to allow the application of training areas and signatures to larger areas. Reprojection to the specific Siberia-II “Albers Equal Area Conical WGS84” projection was performed for all datasets.

3.2 Deforestation Mapping Methodology

Different forest cover change detection approaches have been proposed in the past. Coppin and Bauer (1994) analyzed vegetation indexes using standardized differencing and selective

Table 1. Forest inventory enterprises in Siberia for the forest cover change analysis (IIASA - International Institute for Applied Systems Analysis - GIS ground truth database).

Test Territories	East	North	East	North
Krasnoyarsky Kray				
Bolshe-Murtinsky	91.83	56.83	94.00	57.33
Chunsky	95.17	57.42	98.25	58.08
Irkutsk Oblast				
Primorsky	102.09	55.58	102.56	55.99
Shestakovsky	102.94	56.10	104.51	56.68
Juzhno-Baikalsky	103.08	51.33	104.75	51.83

Fig. 2. Ground truth test sites in the SIBERIA-II project

principal component analysis. 14 change features were generated and the Jeffries-Matusita distance for best minimum separability was used as a measure of best statistical divergence to select the best change feature dataset. Coppin and Bauer (1994) concluded that the most promising change features are the standardized difference of brightness, the second principal component of greenness, the second principal component of brightness, the second principal component of the green ratio and the standardized difference of greenness. This pointed towards the Kauth-Thomas brightness and greenness indexes and the green ratio as the vegetation indexes with the most relevant forest cover change information. It was also noted that analysis of change that is beyond the spectral-radiometric information would need the incorporation in a GIS framework with artificial intelligence capabilities. Other studies used direct multi-date classifications or “hyper clustering” (Leckie et al., 2002), change vector analysis, parcel-based change detection procedures, artificial neural networks (Gopal and

Woodcock, 1996), cross-correlation analysis (Koeln and Bissonnette, 2000) and various post classification change detection methods. Important reviews of change detection methods have been published by Singh (1989) and Coppin and Bauer (1996).

The object-based strategy for data classification (Baatz and Schäpe (1999) and Benz et al. (2004)) uses as a first stage a segmentation into different scales of image object primitives according to spatial and spectral features. This segmentation is a bottom up region merging technique starting with one pixel sized objects. In numerous subsequent steps smaller objects are merged into bigger objects (pair wise clustering) minimizing the weighted heterogeneity of resulting objects using the size and a parameter of heterogeneity (local optimization procedure) (Benz et al. 2004). This concept has the advantage to account for contextual information using image objects instead of the pixel based concept used frequently as the basic element in image processing. In a second stage rule-based decisions can be used to classify the multi scale image objects. Class based feature definitions (integrating post classification analysis) are possible as well as the inheritance of class descriptions to form a complex class hierarchy. Image processing tasks can be performed using vector shape and other vector characteristics. Results can be also analyzed and presented in vector polygon format with attributes instead of the raster cell format. This increases the flexibility of this image processing concept and integrates GIS-like data queries in an attribute database directly into the image processing and analysis approach. New attributes (like object shape or structural characteristics e.g. distance to other objects) can be used.

Object based image analysis has been used since 2000 for different forest classification approaches. Halounova (2004) used the object oriented approach to classify B&W aerial photos with textural features. Yijun and Hussin (2003) classified tropical deforestation in East Kalimantan using the object oriented approach and Mitri and Gitas (2002) developed an object oriented classification model for burned area mapping. Flanders et al. (2003) tested the object oriented approach for cut block delineation.

Different advantages over pixel-based approaches have been published mainly using very high resolution airborne or orbital Earth observation data. The primary advantage of reducing spectral variability in high spatial resolution data sets (spatial resolution better 1 m) is only one aspect of object oriented image analysis. For the development of change detection procedures new GIS-like analysis concepts are important. Object shape in different scales based on a simplification through vectorisation can be used to differentiate clear cuts from other deforestation processes that do not show specific object shapes with a high rectangular fit (mainly fire scar objects) (Hese and Schmullius, 2004). This differentiation is however very much complicated by the high variability of object shapes. Important object shape characteristics like “rectangular fit”, “shape index” (linked to the fractal dimension) and “area” are not specific enough to allow a complete differentiation of logging activities and fire related landcover change processes (compare with Fig. 3 and Fig. 4). Multi-scale object information can be used to increase the classification accuracy of classes that have to be defined using textural information instead of spectral information (e.g. the spectral variability in urban areas is preferably classified using larger objects). Class related classification can be used to build rules for complex neighborhood relations to already classified image objects. This can be used to function as a classification of object structure. Such an approach can be applied e.g. to connect the classification of clear cuts to the classification of linear road objects beyond a parent change class. Transportation is prerequisite for logging activities and can be used as GIS-like context information. Road networks that were created in forested areas are secondary information for the detection of logging processes.

Using the class hierarchy with inheritance of features, simple change – no-change masks can be developed that provide a powerful global (inherited) approach for the adaptation to other data sets.

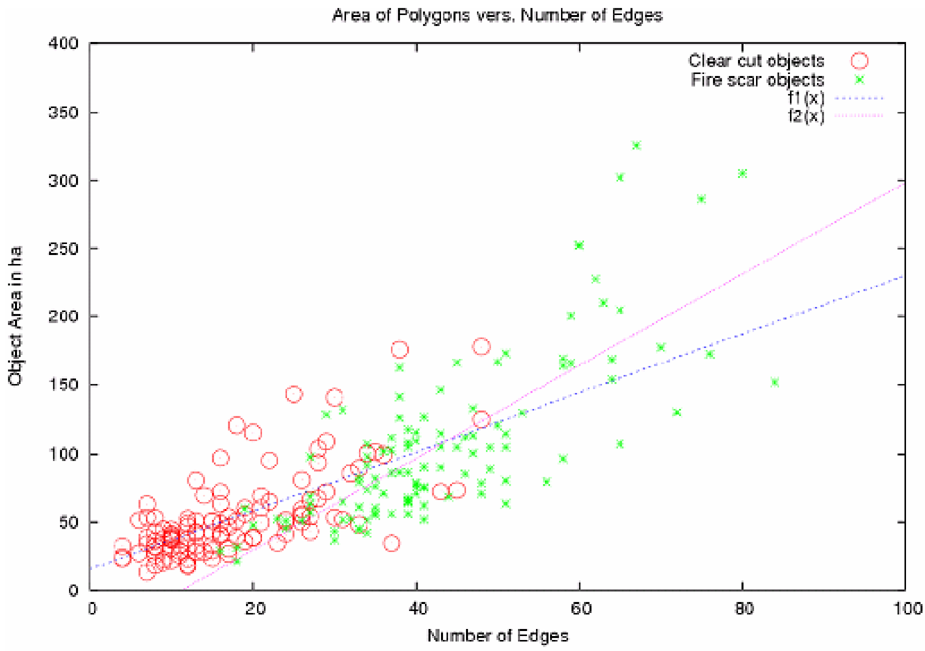

Fig. 3. Object features “object area” and “number of object border edges” for clear cut objects and fire scar objects.

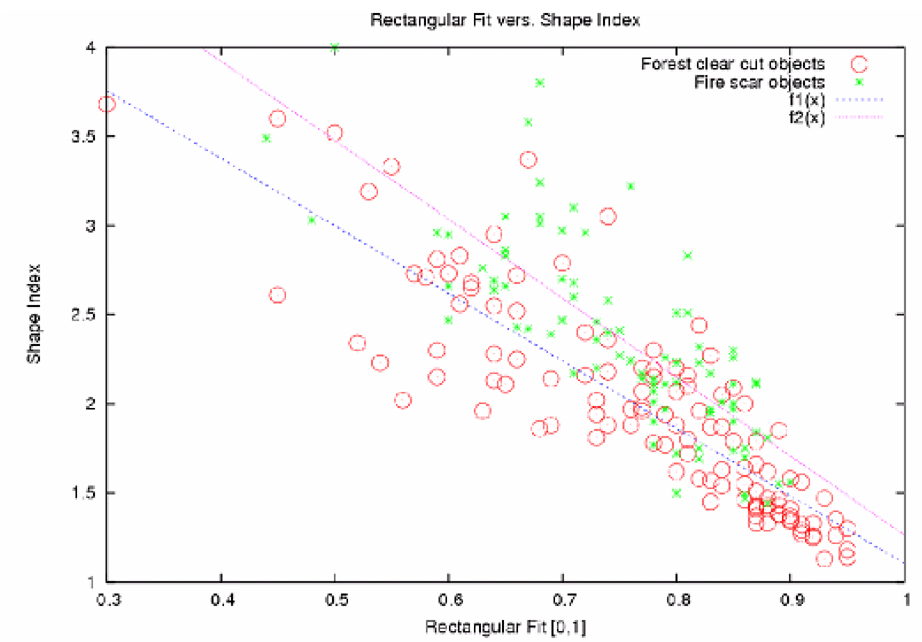

Fig. 4. Object features “Shape Index” and “Rectangular Fit” for clear cut objects and fire scar objects. "Shape Index“ = Smoothness of the image object borders. Ratio of border length to area (similar to the fractal characteristic). The "Rectangular Fit“ is the difference between a master rectangle and the considered object (1 = complete fitting object, 0 = no fit).

One drawback of the combined use of post-classification procedures using class related features and direct two-date change detection in one procedure is the complex error propagation logic that can lead to unstable classification results.

The first step in object oriented image analysis is the segmentation into object primitives using a bottom up region merging algorithm. Three different object levels are generated for the forest change detection approach using different thresholds for object merging based on multi temporal data from 1989 and 2000. The class hierarchy that is created is based on the primary segmentation levels. A change and no-change parent class is created using a simple standardized change ratio (Coppin and Bauer, 1994) of the red Landsat band. Clouds, cloud shadows and water objects are classified with the Brightness calculated for Landsat ETM and TM5. These classes are grouped together to form one class and are excluded from the change detection classification process. This is done by inheriting an inverted expression through the change – no-change parent class of the finest segmentation level.

The final forest change classification is done in the segmentation level with the smallest objects. Again a no-change and change “decision tree” is created using a standardized multi temporal change ratio of the red and the green channel. “Forestation on deforested areas” and “Deforestation” is classified using the multi temporal near infrared difference and NDVI thresholds. “Forestation on deforested areas” is defined as deforested in 1989 and reaching an age of 10 years in 2000. Deforestation is defined as not forested in 2000 but in a forest state in 1989. The classification is done using a NIR difference image and NDVI thresholds.

The human induced landuse conversion of agriculture land (that has not been forest before) to forested land is named “Afforestation”. For the classification of this specific change class differentiation of urban areas, agricultural used areas and forested areas in 1989 is important. In order to integrate this additional information into the change analysis system class related features are used. Using class related features a landuse change classification can be combined with a forest change mapping approach.

Table 2. Forest change area statistics for 3 Landsat scenes for the test territories Chunsky and Bolshe Murtinsky.

Class	**Area in hectares**
Path/Row: 142/20 (Bolshe Murtinsky)	
Deforestation	157668.53
Forestation on deforested land	74761.91
Forestation on non-forest land	1495.68
No change	2669942.00
Masked	178128.33
Path/Row: 143/20 (Bolshe Murtinsky)	
Deforestation	104981.10
Forestation on deforested land	101454.97
Forestation on non-forest land	1931.98
No change	2837849.50
Masked	68684.27
Path/Row: 140/20 (Chunsky)	
Deforestation	134878.34
Forestation on deforested land	124979.38
Forestation on non-forested land	6386.06
No change	2663196.25
Masked	189718.58

It should be noted that these definition do not follow exactly the definitions for Afforestation, Reforestation and Deforestation. The improvement of ARD classification with Earth observation is still subject of ongoing research using context information to classify human induced changes and differentiate different types of changes with probability estimations. The limitations to derive these class definitions using Earth observation (EO) have already been mentioned in this paper.

3.3 Results

Results of the forest cover change classification are provided in Table 2. Part of the analyzed data was masked due to cloud coverage and not used for the classification. Fig. 5 shows results of ARD mapping for one Landsat data set. Deforestation and Forestation are between 3 and 5 % of the classified area and the forestation on "non-forested areas in 1989" can be neglected with below 0.1 %.

Old fire scars and logging activities are not differentiated in these results. Although it is possible to differentiate these change classes using image object shape characteristics (as indicated in Fig. 3 and Fig. 4) this approach has proven to be not stable enough to be used with large datasets and is subject of ongoing research. The analyzed area shows only moderate forest changes. This is however not the case in other regions of Siberia where severe deforestation caused by pollution or fire occurred.

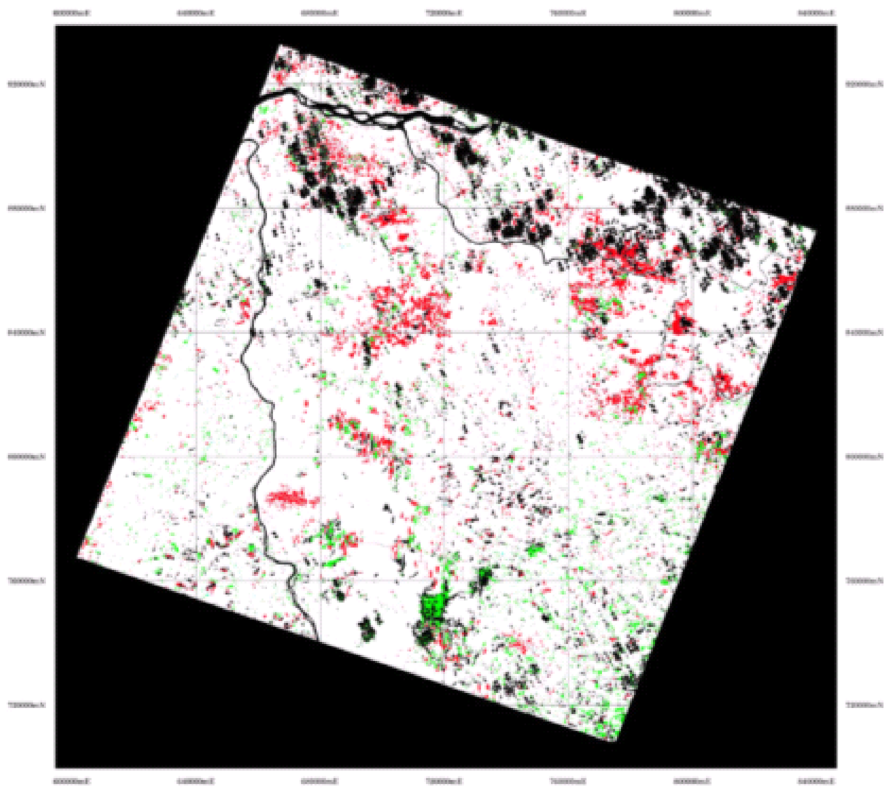

Fig. 5. Forest change map (Landsat scene, approximately 180x180 km) with deforested areas (in red), forestation on areas that have been forest before (in green) and forestation on areas that have not been forest before (in cyan) in the south of Siberia (Bolshe Murtinsky) Landsat 142/20. Masked clouded areas, cloud-shadows and water areas appear in black.

4. THE LANDCOVER PRODUCT IN SIBERIA-II

Several global land cover maps are available for example by the Joint Research Center (GLC2000), by the University of Maryland or by IGBP maps. However, they are not adapted to the needs of the IIASA landscape accounting system and the DGVMs used in SIBERIA-II.

The methodology used to obtain a landcover dataset in SIBERIA-II is based on a supervised technique (Skinner & Luckman 2003). The required landcover classes were identified by examining the needs of the end users for this product (the multilayered GIS landscape model (by IIASA) and two DGVMs (SDGVM and LPJ). As a consequence a 3-level hierarchical class definition system was defined that was at a later stage adapted to the GLC2000 class definition system. Two different sources of reference information were available: 1:50000 forest inventory test sites with information about species, stocking and age of forest stands and expert interpretation of Landsat data.

Reference polygons were selected using both data sources to identify areas were predictions of the landcover could be made.

The remote sensing data sets used were MODIS data sets (Strahler et al. 1999) and MERIS data (MERIS Team, 1997) (MOD09 EO 8-day 500 m data set and MERIS FR_L2 300 m data set). Data throughout the spring and summer 2003 was acquired.

The classification was performed using a c5.0 decision tree classifier following the method implemented by the MODIS landcover team at Boston (Fig. 6). This work was done partly at the University of Wales / Swansea (UK) and the Friedrich-Schiller University Jena (Germany).

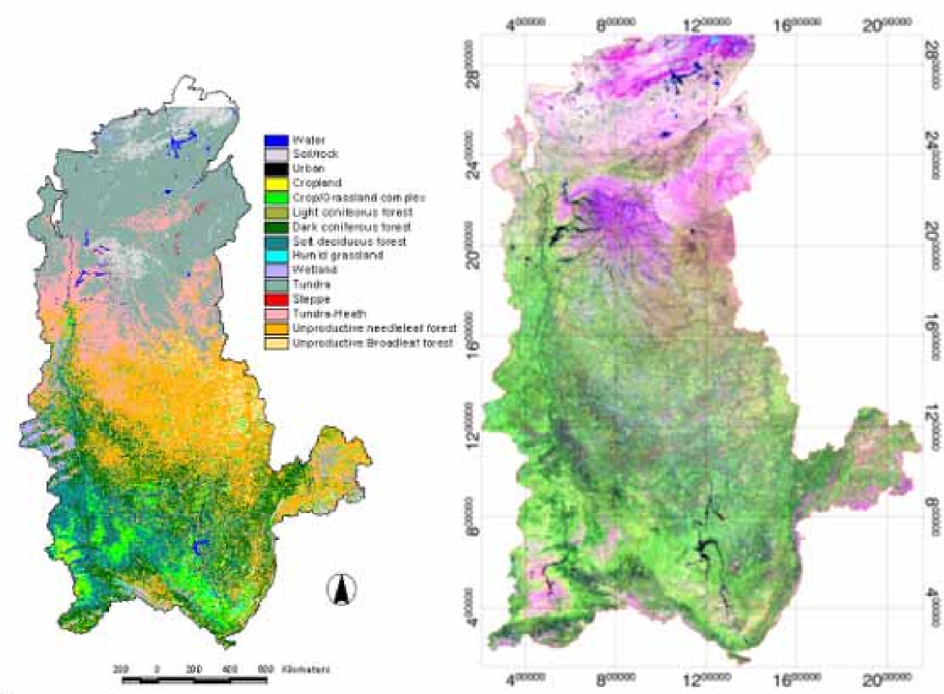

Fig. 6. Left: landcover classification product from Siberia-II (Level 2 landcover classification information with 15 classes) based on MODIS multispectral data. Right: MODIS 16-day multi temporal cloud free composite from summer 2002, days 225-241, bands 6, 2, 1, (SWIR, NIR, red) (Skinner & Luckman 2003).

5. CONCLUSIONS AND OUTLOOK

Result of the SIBERIA-II project – a set of EO based large scale biophysical datasets and their integration into biosphere models – have shown that Earth observation is an important tool to create a basis for biosphere process modeling approaches (both for calculation of the status of our biosphere and for modeling how the biosphere will react to changing atmospheric and climatic conditions). The value of EO-products as an extrapolation basis for other approaches to earth system modeling and understanding is clearly visible. In the framework of the JSPS (Japan Society of the Promotion of Science) Core-to-Core program “Upscaling the evaluation for the symptom of environmental change in Siberian permafrost region” the importance of Remote Sensing should be underlined and process knowledge about permafrost degradation should be directly linked to large scale Earth observation information.

Results of the SIBERIA (SAR Imaging for Boreal Ecology and Radar Interferometry Applications) and the SIBERIA-II projects will be stored in the “Siberian Earth System Science Cluster” (SIB-ESS-C). SIB-ESS-C will be the future structure and shell for all boreal large scale mapping results and will also integrate different biosphere modeling approaches. In the final stage SIB-ESS-C will act as both a database for EO-products and an interface for starting process based biosphere modeling tasks with the integration of EO-products. The interface between models and Earth observation data that has been created in SIBERIA-II will be used and new additional interfaces for other Earth observation products (freeze/thaw, biomass etc.) will be created in the future.

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