Forest cover disturbances in the South Taiga of West Siberia

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Abstract

Analysis of vegetation cover and tendencies in forest cover changes at a typical site in the south of West Siberia was performed using remote sensing observations from Landsat. The Northern Eurasia Land Cover legend was used for the assessment of unsupervised classification results. The land cover maps constructed have shown that about half of the study area is occupied by wetlands with several distinctively different vegetation types. The area studied is typical for the South Taiga zone (ecoregion) of Western Siberia from the Ob’ river to the Irtysh river, where loamy and clayey soil forming rocks are widespread. Similar vegetation structures dominate over 600 000 km², or about 20%, of the West Siberia area. Analyses of the forest cover changes show that the forest cover loss is not very significant. The area of forest disturbed in 1990–9 is equal to 16 008 ha. The area of forest disturbances during the 2000–7 period was about twice as high (30 907 ha). The main reasons for the forest reduction are intensive forest harvesting and strong windthrow. The high sustainability of the region studied against anthropogenic impacts is explained by the high overall wetness of the territory, the small population density, and the prevalence of deciduous forests at different succession stages with rich vegetation cover.

Keywords: boreal forest, land cover change, deforestation, remote sensing

1. Introduction

Forest cover changes due to intensive interaction of humans and environment is an important global environmental issue. All over the globe, forests are subject to enormous pressure, resulting in deforestation and land cover degradation (Krankina et al 2004a, 2004b, Lepers et al 2005, Achard et al 2006, Vygodskaya et al 2007, Newton et al 2009, Hansen et al 2010, Panigrahy et al 2010). The consequences of deforestation include the loss of biodiversity, destruction of the livelihood of native communities, soil erosion, change in land surface albedo, inadvertent impact on regional climate, disturbances in regional carbon balance, etc. Deforestation alters and fragments natural landscapes into ‘biodiversity semi- or non-habitable’ areas (Newton 2007).

Boreal forest is one of the largest terrestrial ecosystems of the Earth. It covers 33% of the global forest area (Sabine et al 2004) and up to present has been one of the terrestrial ecosystems that is less impacted by humans. An important feature of forest dynamics in temperate and boreal zones is natural reforestation and expansion of forests (Hassan et al 2005). Intensification of human activity, logging and human-caused fires, against the background of actual climate changes, may lead to significant disturbances in boreal forest functioning. For example, these disturbances can lead to significant emissions of stored carbon to the atmosphere (Achard et al 2006, Vygodskaya et al 2007, Pimm et al 2009, Potapov et al 2011). Therefore, there is an urgent need for tools that can provide an integrated assessment of the human impact on forest biodiversity and support decision making related to forest use. Forest cover changes can by documented locally through forest inventories that document forested areas and wood storage information. These inventories are not very reliable for different reasons (Alekseev and Markov 2003). Therefore, at regional and global scales, forest cover changes require an approach based on remote sensing (Bartalev et al 2003, Cohen and Goward 2004, Krankina et al 2004a, 2004b).
Independent satellite-based monitoring of boreal forest is an important tool that provides transparent information on forest change. Furthermore, observation of forested landscapes using remote sensing data gives a more complete understanding of the historical and current factors driving forest dynamics and trajectories of forest cover changes. Interpretation of the possible causes of these changes is quite difficult and remote sensing products should be combined with ground data.

Recent studies used remotely sensed observations to analyze the present structure of forest cover over boreal zones (Aksenov et al. 2002, Schvidenko and Nilsson 2002, Hese and Schmullius 2009). They provide evidence of forest cover changes (Achard et al. 2006, Bergen et al. 2008, Peterson et al. 2009, Potapov et al. 2011). Studies of the succession dynamics of forests in the South Taiga zone have shown that the primary forests had a large proportion of dark coniferous forest through the 19th century, whereas the late-20th century forest is dominated by light coniferous, mixed, or deciduous forest types and the deciduous type appears to be increasing (Hytteborn et al. 2005). The forest cover transformation occurs both naturally and due to human activities. The main processes causing forest cover changes in boreal Eurasia are logging and increase of fire frequency. Annual forest cover change rates ranged from 0.26% for diffusive logging activities to around 0.65% for areas affected by intense clear-cutting activities, and up to 2.3% for areas affected by fires (Achard et al. 2006).

Rates of observed forest cover changes are nonhomogeneous and have high spatial and temporal variability. The highest rates of forest cover loss occur in most populated regions (Potapov et al. 2011). Changes in landscape patterns and trends over Soviet and post-Soviet socioeconomic and forest management eras (Peterson et al. 2009) have shown that while some patterns are associated primarily with environmental variables, other differences in land cover patterns and trends are likely related to the institutional and social changes. The early post-Soviet era was characterized by low rates of logging, some agricultural abandonment, regrowth of the forest especially near access routes, increases in the fraction of deciduous trees in land cover, and continued increase of the frequency of fire events in mixed and conifer forests (Peterson et al. 2009).

The objectives of our study were to detect the spatial patterns of land cover and reveal tendencies of and reasons for forest cover changes at a typical site in the south of West Siberia. Development of technological procedures for automatic and routine satellite image processing for analysis of vegetation patterns and robust analysis of changes was also among the study objectives. Landsat space images were used for these regional analyses of land cover and its changes.

2. The study area

The study area is located in the southwest part of West Siberia in two different bioclimatic zones: South Taiga and Sub-Taiga. The study area is drained by the Chaya River and its tributaries: the Iksa, Bakchar, Teterenka, Andarma and Parbig rivers (see figure 1). The elevation varies from 110 to 130 m a.s.l. Watersheds are occupied by bogs. Bog massif formation began 4.5–5 thousand years ago and since that time the peat deposits have covered the initial relief roughness (Dyukarev and Pologova 2011). Watershed bogs have peat depth of about 3–4 m. Well and poorly drained areas are dominated by continuous cover of coniferous and/or deciduous species. A large part of the area is occupied by birch (Betula pubescens, B. pendula Roth.) and aspen (Populus tremula L.). Coniferous forests are composed of Picea obovata, Pinus sibirica, and Abies sibirica which are typical for the South Taiga zone but cover a very small area. Wetlands occupy about 36% of the West Siberia area (Sheng et al. 2004). Wetland types at the test site are represented by open sphagnum and sedge fens, ridge–hollow and ridge–lake complexes, and pine–shrub–sphagnum communities (or ‘ryams’). Ryams with different tree height

Figure 1. Location of the study area.
The above described vegetation structure exists over large areas of Western Siberia from the Ob’ river to the Irtysy river within the South Taiga zone (ecoregion) and a part of Middle Taiga where loamy and clayey soil forming rocks are widespread. The results obtained for the key area site can be extrapolated to an area of about 600 000 km², or about 20% of the West Siberia area.

The climate of the area studied is continental with cool wet summers and long cold winters. The population density is less than 0.5 persons ha⁻¹; the agricultural developed area is less than 2%. Widespread grassland deciduous forest dominated by aspen and birch is a modern feature of the area formed due to the high wetness and massive fires during the beginning of the 20th century. Intensive migration to Siberia after the Stolypin agrarian reform coincided with dry periods that resulted in enhanced fire activity. In the dry years 1900–8 more than half of the taiga on the left bank of the Ob’ river was burned. The area of forest that remains intact is 30–40%. In 1915, fires lasted all summer, covering the territory from Lake Baikal to the Urals. The forest burned area was about 1600 000 km² (Yevseyeva 2001). After that time, regrowth of conifer species was slowed by the high wetness and soil richness. Native dark coniferous stands have formed during the last hundred years only at well-drained sites. Most of them were cut during the second half of the 20th century.

3. Data

3.1. Satellite imagery

The Landsat 7 (ETM+) and Landsat 5 (TM) data obtained via the Global Visualization Viewer (GloVis) web interface (http://glovis.usgs.gov/) were used for analysis of vegetation and mapping of changes in forest cover. Each image consisted of six spectral reflective bands, a thermal band, and a panchromatic band. Six spectral bands were used in processing. The thermal infrared band was used for the cloud screening model, but was not included in the vegetation cover analysis. The study area is covered by satellite images obtained for path 150 row 20 in the Worldwide Reference System-2 (WRS-2) of path and row coordinates. We have selected three almost cloud-free images for the area studied, dated 30 Aug. 1990 (TM), 16 Sept. 1999 (ETM+), and 20 July 2007 (TM). The Landsat scenes used refer to the end of summer. Seasonal vegetation development can cause errors in land cover change analysis. To reduce uncertainties connected with vegetation phenology, we used a special normalization procedure described in section 6.1.

3.2. Ground data

A number of datasets, including aerial photos from GoogleEarth™, expert information on the landscape types, fieldwork data (stationary and track observations, botanical descriptions, and landscape-typological maps) were used as reference materials for selecting training points. The total number of ground points used for image classification and accuracy assessment is 691. An additional 350 ground points were used for forest change detection.

Field data were obtained by two of this article’s authors during last 20 years, when in the Tomsk region studies of soil and vegetation cover, dynamics of wetlands development, and the structure of forests were made using reconnaissance surveys, route studies and field station data. Such detailed knowledge of the area studied allows one to construct quality maps of the vegetation cover and forest disturbances.

4. Methods

The Landsat image pre-processing workflow included: cloud/shadow masking, atmospheric correction and radiometric calibration, masking of settlement areas, and applying tasseled cap transformation. The cloud mask was constructed on the basis of unsupervised classification of the composite images, including the thermal infrared band. Settlements located in the area studied are represented by small villages and hamlets. They were manually mapped within images and combined into masks used to exclude settlement areas from further analyses.

The image-based COST method for dark-object atmospheric correction (Chavez 1996) combined with radiometric calibration and conversion from Landsat image digital numbers (corresponding to the magnitude of energy being measured by each of the sensor elements in the satellite) to reflectance for Landsat multispectral data (Skirvin 2000) was applied for image processing. Finally, the six reflectance bands were transformed into tasseled cap indices (Crist 1985). Tasseled cap indices are effective combined characteristics in forest vegetation mapping and change detection (Healey et al 2005).

Each tasseled cap image was classified into 62 land cover classes using ISODATA (Iterative Self-Organizing Data Analysis Technique) unsupervised classification after applying cloud and settlement masks. Thereafter, each classified image was filtered to the minimum mapping unit ~0.7 ha (3 pixels × 3 pixels) with the use of ‘clump’ and ‘eliminate’ procedures.

5. The land cover map

5.1. The land cover map legend

The Northern Eurasia Land Cover (NELC) legend (Sulla-Menashe et al 2011) was used for the assessment of unsupervised classification results. The legend was developed during the Northern Eurasia Land Dynamic Analysis, NELDA (Sulla-Menashe et al 2011), project. The goal of the NELDA project was to provide a comprehensive characterization of land surface properties in the Northern Eurasia region in support of science questions ranging from climate controls on vegetation productivity to the socioeconomic causes and ecological consequences of land use and land cover change within the Northern Eurasia Earth Science Partnership Initiative, NEESPI (Groisman et al 2009). The NELC legend of the land cover map is hierarchical, and the nested structure of the legend provides a flexible representation of ecologically complex classes by including three levels of successively refined detail.
The NELC legend describes vegetated land as being composed of trees, shrubs, and herbaceous vegetation. Trees are distinguished from shrubs on the basis of a height threshold of 5 m. For vegetation under 5 m, perennial woody shrubs are distinguished from annual herbaceous plants. The dominant layer is defined as closed if the canopy closure is greater than 60–70%; otherwise the canopy is defined as open. Tree dominated land cover classes can include: evergreen broadleaf, deciduous broadleaf, evergreen needleleaf, deciduous needleleaf, and mixed forests (Sulla-Menase et al 2011). Expert knowledge of the area studied allows fixing eight classes available over the area. The primary classes include Tree.Needleleaved.Evergreen.Closed (TNEC), Tree.Mixed.Closed (TMC), Tree.Broadleaved.Deciduous.Closed (TBDC), Shrub.Closed (S), Herbaceous.Closed (H), water bodies (W), Barren (B), and Settlements (Set).

In addition to the land cover types described above, the NELC legend can include additional classes: urban, cultivated land, wetlands, and tundra. Wetlands occupy about 36% of the Western Siberia area (Sheng et al 2004) and should be included in the legend for the study area. We have selected five classes related to wetland areas: Tree.Needleleaved.Evergreen.Closed.Wetland (TNECW), Tree.Needleleaved.Evergreen.Open.Wetland (TNEOW), Tree.Mixed.Closed.Wetland (TMCW), Shrub.Closed.Wetland (SW), and Herbaceous.Closed.Wetland (HW).

### 5.2. Class interpretation

We use ground data to find classes of unsupervised classification corresponding to classes from the selected NELC legend. For each NELC legend class, there were selected from 24 to 43 points as training data on the basis of the ground data. The total number of points used for interpretation was 414. The compliance matrix was created to find classes of unsupervised classification corresponding to known classes of ground data. Some unsupervised classes clearly correspond to a single class from the map legend (e.g., bare, water). However, spectral characteristics of some classes are very close. For example, we cannot exactly separate grassland (herbaceous vegetation) from sedge–sphagnum fens (wetland herbaceous vegetation). Wetlands contain specific objects (water flow lines, forested islands) and can be easily recognized manually. After class assessments, we manually process the image to correct the classification results. Wrongly determined upland classes (H, S, TNEC) located on wetlands were marked as corresponding wetland classes (HW, SW, TNECW). Wrongly determined wetland classes (HW, SW) located in well-drained areas were marked as corresponding upland classes (H, S).

### 5.3. Accuracy assessments

To estimate the quality of the vegetation classification we selected 277 ‘accuracy assessment’ ground points (cf section 3.2). These accuracy assessment points differ from the points used in class interpretation in the previous step. The results of the accuracy assessment analysis are presented in table 1. The overall accuracy for the land cover classification is 84% of correctly classified pixels. The major error of classification is related to the wetland classes. The average accuracy of wetland pixel classification (72%) is 20% lower than the classification for the upland pixels (92%). Correct wetlands mapping with remotely sensed data still remains a difficult task, which requires interdisciplinary efforts of wetland ecologists, biochemists, and remote sensing experts (Krankina et al 2008).

### 5.4. Class distribution

Figure 2 shows the landscape pattern of the land cover distribution. The primary geomorphologic surfaces include river valleys, watershed wetlands and the left-side terrace of the Ob’ river. The study area has a typical Ob’—Irtysh interfluve combination of boreal forest and large wetland systems. Forest dominated areas are elongated along river valleys and separated by large wetlands located in the central parts of the interfluves. The forest cover of the study area is weakly fragmented and disturbed by human activity. Part of its area was developed for cultivated lands and settlements. Land use has transformed about 9.8% of the area, including areas of settlements (0.4%). The area is weakly populated due to the large fraction of swamps. Settlements and agricultural lands (plowed fields, grasslands and hayfields) are located on upland areas along rivers. The average density of population for the study area is 1.4 people km^-2.^ A According to the last census (in 2000), the total population of the area was 16,600, but it was reduced by 10–14% during the 2000–5 period (Yuzaminov and Rykun 2009).

About half of the study area is occupied by wetlands with distinctive vegetation types. They are located in the watershed areas and left-side river terraces. Well-drained areas are filled with mixed and deciduous forests with relatively small patches of herbaceous dominated land. Dark coniferous forest is rare due to the fact that this forest was considerably disturbed by fires at the beginning of the 20th century and logging by the timber industry. Some forest areas were disturbed by road and power line construction.

Analysis of the distribution of land cover classes (cf table 1 and figure 3) shows that the total wetland area is

| Table 1. Distribution of land cover classes. |
|------------------------------------------|
| Area (ha) | Area (%) | Ground data points | Accuracy (%) |
|-----------------|----------|------------------|-------------|
| TNEC | 251 358 | 7.8 | 30 | 96.4 |
| TNECW | 184 654 | 5.7 | 32 | 68.6 |
| TNEOW | 326 156 | 10.1 | 23 | 74.1 |
| TMC | 685 926 | 21.3 | 43 | 86.1 |
| TMOW | 75 484 | 2.3 | 32 | 86.8 |
| TBDC | 148 080 | 4.6 | 26 | 65.6 |
| TNECW | 441 090 | 13.7 | 37 | 94.4 |
| S | 151 382 | 4.7 | 27 | 80.0 |
| SW | 370 784 | 11.5 | 28 | 75.0 |
| H | 301 474 | 9.4 | 34 | 96.8 |
| HW | 243 496 | 7.6 | 30 | 84.6 |
| B | 11 629 | 0.4 | 24 | 100 |
| W | 19 277 | 0.6 | 32 | 97.0 |
| Set | 4 736 | 0.1 | 16 | 100 |
| Total | 3215 527 | 100.0 | 414 | 84.1 |
Figure 2. Land cover map for the key area. Legend: TNEC—Tree.Needleleaved.Evergreen.Closed, TNECW—Tree.Needleleaved.Evergreen.Closed.Wetland, TNEOW—Tree.Needleleaved.Evergreen.Open.Wetland, TMC—Tree.Mixed.Closed, TMCW—Tree.Mixed.Closed.Wetland, TMOW—Tree.Mixed.Open.Wetland, TBDC—Tree.Broadleaved.DECIDUOUS.Closed, S—Shrub, SW—Shrub.Wetland, H—Herbaceous, HW—Herbaceous.Wetland, B—Bare Land, W—Water, Set—Settlements, UC—Unclassified.

41.9%. Wetlands occupy vast areas in the southern and western parts of the study area in upper course of the Chaya river basin. Well-drained areas near river junctions have fewer wetlands. Eutrophic peatlands are located on left-side river terraces. About half (54%) of the wetlands are covered by trees with different composition and structure. Open wetlands with herbaceous vegetation have an area of 243,496 ha (18% of the total wetlands). Water objects (19,277 ha) are represented by the Ob’ river (located at the northeast corner of the study area), its tributaries, and a number of small inner wetland lakes.

A part of the Bakchar Bog located in the southwest edge of the study area was drained by the open channels method in 1965–70. The drained area is 22,000 ha. Drainage was done without peat excavation and the subsequent channels were gradually filled over time. Now areas along the channels are covered with deciduous species (birch, willow), and adjoining ryams with increasing tree growth.

Upland areas of the study site are mostly covered with forest with closed tree cover structure. Mixed forests (21.3%) prevail in the area. The deciduous forest (13.7%) consists of birch and aspen. Needleleaved evergreen forest can be found inside deciduous and mixed forest. In the tree stand structure, needleleaved trees are represented by Pinus sylvestris L. with the addition of Pinus sibirica. Historically, fire has been an essential factor in the natural disturbance dynamics of boreal forest ecosystems. The forest stand structure was formed during mesoscale cycles of disturbances due to large fires at the beginning of the 20th century. The primary forests are of dark coniferous type; they relate to long-term successional communities. Succession in dark coniferous forest is a very slow process that occurs on the centuries scale (Nikolov and Helmisäari 2005). Small patches of primary dark coniferous forest remain in the northern part of the study area. They are surrounded by deciduous and mixed forest. Forest in the southern part of the study area is deciduous. Mixed forest is usually paludificated and consists of Pinus sylvestris, Pinus sibirica and Betula pendula. According to official forest inventory data for the Bakchar region for 2003, forest occupies 17,460 ha (Alexeyev and Zimnitsky 2006).

Fractions of herbaceous vegetation (9.4%) and shrubs (4.7%) in the study area are rather low. Barren areas (0.4%) are represented by sand banks on river sides and burned areas of drained peatland.

6. Land cover change
6.1. The approach
Analysis of relevant literature shows that there is no single, generally applicable change detection technique, but different algorithms are used for each specific purpose. Our approach chosen for the forest change analysis is based on the use of multi-temporal disturbance index (DI) maps. The DI was designed by Healey et al (2005) to highlight the unvegetated
Figure 3. Distribution of land cover classes over the study area.

spectral signatures associated with stand-replacing disturbance and separate them from all other forest signatures. The DI is a linear combination of the three tasseled cap indices: brightness (B), greenness (G), and wetness (W):

\[ DI = Br - (Gr + Wr), \]

where \( Br, Gr, Wr \) are rescaled values of the brightness, greenness, and wetness normalized for the forest area. For example, \( Br = (B - Bmf)/STDBf \), where \( Bmf \) is a mean forest brightness, and \( STDBf \) is a standard deviation of this brightness (Healey et al. 2005). The formulation of the DI takes advantage of the assumption that recently cleared forestland exhibits high B and low G and W compared to undisturbed forest. The DI simply quantifies how close in tasseled cap space a pixel is to the areas in the scene having the highest brightness and lowest greenness and wetness. However, when viewed in sequence, DI images provide a direct way to highlight pixels that move from an average forest condition to a disturbed forest condition (Healey et al. 2005).

Three Landsat images obtained in 1990, 1999 and 2007 were pre-processed as described above (in section 5.1). Tasseled cap indices were transformed into disturbance indices. Three DI images were stacked into a one combined DI image. The disturbance information presented at three dates of imagery can then be visualized in a standard RGB display. The areas with significant changes in forest cover are clearly identified by changes in color, texture and sharp boundaries of forest clearings.

To identify areas with disturbances in forest cover, an unsupervised classification of the combined DI image was made and 32 classes were revealed. The class attribution procedure was similar to the procedure used for the vegetation cover classification (cf section 5.2). A new set of manually interpreted training points were created using visual analysis of the forest cover changes. All change events, including logging, road/pipeline construction, windthrows, stand replacement by forest fires and severe insect outbreaks were mapped together and no discrimination between change types was made in our analysis. Within low intensity selective logging sites, only areas with severe forest damage (clearings) were included for change detection training.

The resulting classification was compared to the ‘true’ layer created by manually digitized disturbances, and a comprehensive error matrix for the change classification was estimated. It was found that two classes emerged from the unsupervised classification results corresponding to forest disturbance areas. Additionally, 212 ground points were manually selected for the accuracy assessment analysis. Among them, 121 points were from undisturbed classes and 91 points represented the forest cover disturbed during different (recent) time intervals. Accuracy assessment analysis shows that the overall accuracy of the disturbed forest determination is about 95%. Our approach differs from those of the currently used algorithms based on post-classification comparison of vegetation maps obtained for different time intervals (Bergen et al. 2008, Hese and Schmullius 2009, Potapov et al. 2011). Its advantage is that intermediate steps of single-date forest mapping are not required and other land cover categories do not need to be determined. Potential errors of single-date forest and land cover classification are therefore avoided (Healey et al. 2005).

6.2. Results and discussion

Our results from classification and change detection analysis showed that the calculated area of forest cover loss from all disturbance factors (including logging, wildfires and windthrows) from 1990 to 2007 is 46,915 ha. The area of forest disturbed in 1990–9 is equal to 16,008 ha. The area of forest disturbances in 2000–7 is about double that (30,907 ha). The fragment of the map with the forest areas disturbed in 1990–9 and 2000–7 is shown in figure 4. Figure 4 shows only a small part of the studied area and for this particular part the amount of forest disturbed in the first period is a bit larger than that in the second one.
The forest cover loss from 1990 to 2007 is about 3.4% from the total forest area. Forest reduction occurs primarily due to intensive forest harvesting and strong windthrows.

According to official forest inventory data (State Forest Management Service, www.tomskles.ru) for the Bakchar region, during the 2003–8 period the forest cover area decreased by 0.02% for fir forest, and by 0.13% for spruce forest. The Siberian pine forest area increased by 0.39% and the deciduous forest area decreased by 0.11%.

Logging is thought to be the most important factor of gross forest cover loss connected with the human activity over the studied area (Yevseyeva 2001, Resource and ecological atlas of Tomsk region 2004, Ecological monitoring 2007). Forest logging areas have a specific shape and can be recognized manually in the space images. We have separated all disturbed forest areas into areas clearly eliminated by human activity and the areas damaged for all other reasons. We found that for both study periods (1990–9 and 2000–7), the area of forest decrease due to human activity does not change significantly. During the second period, logging efforts were shifted toward more accessible areas in the basic dark coniferous forests near villages and edges of the old logging sites.

The primary natural reason for forest damage at the study test sites was trees falling/breaking due to strong winds (windthrow). Strong winds have damaged forests between 1990 and 1999 in stripes up to 15 km × 1 km oriented from southwest to northeast in the prevailing wind direction. Such stripes are clearly detectable in figure 4. Significant forest cover disturbances remain in the forest pattern for a long time. The forest cover disturbances due to vast windthrows were 2822 ha in the first period and 15 455 ha for the second period of study. The windthrow areas during the 2000–7 period are about five times greater than those during the previous period. During the second period, strong windthrow occurred in the northeast part of the study area and some disturbances of diffusive type are observed in the areas adjacent to the areas of windthrows registered during the first period. It is possible that these changes are related to trees dying off and falling after the initial damage of the crown and to the broader open stretches after the initial windthrow. Other reasons for forest cover changes include logging, natural tree successional changes and diffusive changes for different reasons which resulted in a reduction of the total forest cover by 13 186 and 15 452 ha during the first and second periods respectively. Forest fires play a comparatively small role in gross forest cover loss in the study area (Ecological monitoring 2007, Alekseeva 2008). Bergen et al (2008) studied the neighboring key area of ‘Tomskaya Oblast’ and have noted that in 1999 there were no fires in the study area.

Some parts of forested wetlands were burned out during years with dry weather conditions coupled with the increased human visiting of wetlands. These wetlands had been drained during the 1960s. We did not take into account these small fires in our study, because disturbances of forested wetlands are not discussed here. Also, forest cover loss as a consequence of extensive insect outbreaks or increased tree mortality was not quantified in this study due to the diffuse spatial pattern of such disturbances and the absence of training and reference datasets.

In a number of areas, forest regrowth is observed. Natural forest regrowth generally takes place when land remains forested, in particular after logging, but there is also a phenomenon of spontaneous ‘afforestation’ as a result of abandoned agriculture fields. After 1990 many agricultural lands were abandoned, transformed to unmanaged meadows (grassland), and are now occupied by young birch. This afforestation corresponds to the overall slight increase of forest land in the Russian Federation in the 1990s (Achard et al 2006). The monitoring intervals using space images are relatively short compared to local forest recovery rates and, therefore, the areas of forest regrowth cannot be estimated with reasonable accuracy.

7. Conclusions

This analysis provides an insight into present landscape patterns and tendencies of forest cover changes in a typical humid region in the south of West Siberia. In contrast to other studies of West Siberia forest cover, ours used a classification system that clearly separates wetlands with different vegetation (cf Krankina et al 2008). Wetlands occupy about 42% of the study area. About half (54%) of the wetlands are covered with trees with different compositions and structures. Open wetlands with herbaceous vegetation cover 18% of the total wetlands area. Thus, during the satellite image classification, wetlands should be considered and assessed as a separate landscape element with completely different structure and functioning.

The results show an insignificant loss of forest cover in the study region over the 17-year period. The main reasons for forest reduction are intense forest harvesting and windthrows. These forest cover disturbances are not dramatic, because they shift a forest ecosystem to a first succession stage, and in the future forest regrowth will occur here. Reafforestation of clear-cutting areas results in closed forest communities, where all tree species are represented mainly by the first generation.
Forest fires with complete destruction of vegetation were not registered in the area studied during the past two decades. Dark coniferous forests in the study area were burned at the beginning of the 20th century and are now restored as deciduous forests. Intervals between fires are much longer than in the pine forests of Middle Taiga and the larch forests of North Taiga. On an annual basis, an average of 1.2% of the Russian far east boreal forest burns each year (Bergen et al. 2008). Forest lands in the Krasnoyarsk Krai is some of the most “fire prone” in Russia and in addition forest harvesting often leaves slashing fuels which may feed back into fire disturbance patterns. The area studied in the present development stage is more stable against fire disturbances than the east boreal forests. Relatively small disturbances in forest cover change the structure of forests. Minor changes happen all the time and return the vegetation to the first successional stage, and hamper the development of dark coniferous forests. There is a prolonged stage of forest cover development. The present landscape pattern and tendencies of the forest cover changes revealed could be used as base for regional ecological monitoring and analysis of successional changes in boreal forests.

The present letter can be seen as a study at a regional level, situated between global environmental projects and local studies at the ecosystem level. Regional studies of landscape patterns and tendencies of the forest cover changes can be used as a basis for regional ecological monitoring and analysis of successional changes in boreal forests. The study presented gives information on areas of wetlands, which is important for actual carbon pool analysis and precise estimation of CO₂ fluxes in terrestrial ecosystems. The West Siberia area covers seven bioclimatic zones (ecoregions) and has very varied landscapes. For realistic mapping of vegetation cover at the regional scale, researchers should take into account local specifics of the territory. The results obtained for one bioclimatic zone should not be simply expanded to other regions. This is one of the important points for environmental studies using remote sensing data.

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References

Achard F, Mollicone D, Stibig H-J, Aksenov D, Laestadius L, Li Z, Popatov P and Yaroshenko A 2006 Areas of rapid forest-cover change in boreal Eurasia Forest Ecol. Manage. 237 322–34

Aksenov D et al 2002 Atlas of Russia’s Intact Forest Landscapes (Moscow: Global Forest Watch Russia)

Alekseev V A and Markov M V 2003 Statistical Data in Forest Resources and Changes in Forest Productivity in Russia at the Second Half of XX Century (Saint-Petersburg: Forest-ecological Center) p 272

Alekseeva M N 2008 Ecological–geographical mapping of vegetation cover of Vasjugan plain on the base of space images PhD Thesis Tomsk 18

Alexeyev V A and Zimnitsky P V 2006 Biodiversity of Russian Wood Resources in Forest Statistical Data (St Petersburg: SBPNILH) p 161

Bartalev S, Belward A S, Erchov D and Isayev A S 2003 A new land cover map of Northern Eurasia Int. J. Remote Sens. 24 1977–82

Bergen K M, Zhao T, Kharkov V, Blum Y, Brown D G, Petersen L K and Miller N 2008 Changing regimes: forested land-cover dynamics in central Siberia 1974 to 2001 Photograph. Eng. Remote Sens. 74 787–98

Chavez P S Jr 1996 Image-based atmospheric corrections—revisited and improved Photograph. Eng. Remote Sens. 62 1025–36

Cohen W B and Gowd S N 2004 Landsat’s role in ecological applications of remote sensing Bioscience 54 535–45

Crist E P 1985 A TM tasseled cap equivalent transformation for reflectance factor data Remote Sens. Environ. 17 301–6

Dyukarev A G and Pologova N N 2011 Soils with complex organic profiles on the Vasyugan plain Eurasian Soil Sci. 44 480–92

Ecological Monitoring 2007 State of the Environment in Tomsk Region in 2006 Department of natural resources and environment protection of Tomsk region administration Tomsk:Grafika 148 (in Russian)

Groisman P Y et al 2009 The Northern Eurasia Earth science partnership: an example of science applied to societal needs Bull. Am. Meteorol. Soc. 90 671–88

Hansen M C, Stehman S V and Potapov P V 2010 Quantification of global gross forest cover loss Proc. Natl Acad. Sci. USA 107 E146

Hassan R, Scholes R and Ash N (ed) 2005 Ecosystems and Human Well-being Current State and Trends vol 1 (Washington, DC: Islandpress) chapter 21 (Forest and Woodland Systems)

Healey S P, Cohen W B, Yang Z and Krankina O N 2005 Comparison of Tasseled Cap-based Landsat data structures for use in forest disturbance detection Remote Sens. Environ. 97 301–10

Hese S and Schmullius C 2009 High spatial resolution image object classification for terrestrial oil spill contamination mapping in West Siberia Int. J. Appl. Earth Obs. Geoinf. 11 130–41

Hytteborn H, Maslov A A, Nazimova D I and Rysin L P 2005 Boreal Forests of Eurasia, Ecosystems of the World: Coniferous Forests ed F Anderssen (Amsterdam: Elsevier) pp 23–99

Krankina O N, Bergen K M, Sun G, Masek J G, Shugart H H and Kharkov V 2004a Northern Eurasia: remote sensing of boreal forest in selected regions Land Change Science: Observing, Monitoring, and Understanding Trajectories of Change on the Earth’s Surface (Remote Sensing and Digital Image Processing) vol 6, ed G Gutman (Berlin: Springer) (E-book)

Krankina O N, Harmon M E, Cohen W B, Oetter D R, Zyrina O and Duane M V 2004a Carbon stores, sinks, and sources in forests of northwestern Russia: can we reconcile forest inventories with remote sensing results? Clim. Change 67 257–72

Krankina O N, Pflugmacher D, Friedl M, Cohen W B, Nelson P and Baccini A 2008 Meeting the challenge of mapping peatlands with remotely sensed data Biogeoscience 5 1809–20

Lepers E, Lambin E F, Janetos A C, Defries R, Achard F, Ramankutty N and Scholes R J 2005 Asymmetry of information on rapid land-cover change for the period 1981–2000 BioScience 55 115–24

Newton A C 2007 Biodiversity Loss and Conservation in Fragmented Forest Landscapes: The Forests of Montane Mexico and Temperate South America ed A C Newton (Oxford: CABI) p 461
Newton A C et al 2009 Toward integrated analysis of human impacts on forest biodiversity: lessons from Latin America Ecol. Soc. 14 2
Nikolov N and Helmisaari N 2005 Silvics of the circumpolar boreal forest species A Systems Analysis of the Global Boreal Forest ed H H Shugart, R Leemans and G Bonan (Cambridge: Cambridge University Press) pp 13–84
Panigrahy R K, Kale M P, Dutta U, Mishra A, Banerjee B and Singh S 2010 Forest cover change detection of Western Ghats of Maharashtra using satellite remote sensing based visual interpretation techniqueCurr. Sci. 98 657–63
Peterson L K, Bergen K M, Brown D G, Vashchuk L and Blam Y 2009 Forested land-cover patterns and trends over changing forest management eras in the Siberian Baikal region Forest Ecol. Manage. 257 911–22
Pimm S, Roulet N and Weaver A 2009 Boreal forests’ carbon stores need better management Nature 462 267
Potapov P, Turubanova S and Hansen M C 2011 Regional-scale boreal forest cover and change mapping using Landsat data composites for European Russia Remote Sens. Environ. 115 548–61
Resource and Ecological Atlas of Tomsk Region 2004 Tomsk. Pechatnaya Manufaktura 28 (in Russian)
Sabine C L, Heimann M, Artaxo P, Bakker D C E, Chen C T A, Field C B and Gruber N 2004 Current status and past trends of the global carbon cycle Global Carbon Cycle: Integrating Humans, Climate, and the Natural World ed C B Field and M R Raupach (Washington, DC: Island Press) pp 17–44
Schvidenko A and Nilsson S 2002 Dynamics of Russian forests and the carbon budget in 1961–1998: an assessment based on long term forest inventory data Clim. Change 1–2 5–37
Sheng Y, Smith L C, MacDonald G M, Kremenetski K V, Frey K E, Velichko A A, Lee M, Beilman D W and Dubinin P 2004 A high-resolution GIS-based inventory of the west Siberian peat carbon pool Glob. Biogeochem. Cycles 18 GB3004
Skirvin S M 2000 Notes on COST ETM7 Atmospheric and Radiometric Correction Script http://arsc.arid.arizona.edu/resources/image_processing/landsat/ Sulla-Menashe D, Friedl M A, Krankina O N, Baccini A, Woodcock C E, Sibley A, Sun G, Kharuk V and Elsakov V 2011 Hierarchical mapping of Northern Eurasian land cover using MODIS data Remote Sens. Environ. 115 392–403
Vygodskaya N N, Groisman P Ya, Tchebakova N M, Kurbatova J A, Panfyorov O, Parfenova E I and Sogachev A F 2007 Ecosystems and climate interactions in the boreal zone of northern Eurasia Environ. Res. Lett. 2 045033
Yevseyeva N S 2001 Geography of Tomsk Region (Tomsk: Izd-vo TGU) p 222
Yuzanianov K M and Rykun A J 2009 State of rural labour market and strategies for population adaptation Vestnik Tomskogo gosudarstvennogo universiteta. Filosofiya, Sociologiya. Politologiya vol 1, pp 80–127 (in Russian)