Changing Regimes: Forested Land Cover Dynamics in Central Siberia 1974 to 2001

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Abstract

The twentieth century saw fundamental shifts in northern Eurasian political and land-management paradigms, in Russia culminating in the political transition of 1991. We used the 1972 to 2001 Landsat archive bracketing this transition to observe change trends in southern central Siberian Russia in primarily forested study sites. Landsat resolved conifer, mixed, deciduous and young forest; cuts, burns, and insect disturbance; and wetland, agriculture, bare, urban, and water land covers. Over 70 percent of forest area in the three study sites was likely disturbed prior to 1974. Conifer forest decreased over the 1974 to 2001 study period, with the greatest decrease 1974 to 1990. Logging activity (primarily in conifers) declined more during the 1991 to 2001 post-Soviet period. The area of Young forest increased more during the 1974 to 1990 time period. Deciduous forest increased over both time periods. Agriculture declined over both time periods contributing to forest regrowth in this region.

Introduction

Fundamental shifts in human-driven land-cover change regimes can significantly change the amount, type, and successional state of forests on a landscape, and over large spatial and temporal scales, this may result in long-term impacts on regional forest ecology and carbon dynamics (Foster *et al*., 1998; Houghton and Goodale, 2004). As a monitoring method, satellite remote sensing data, which became broadly available starting in the 1970s, has contributed to more accurate characterization of the legacy of such trends to forest ecology and forest carbon (Cohen and Goward, 2004)

The Twentieth century was an era of fundamental shifts for northern Eurasia, where large-scale political and economic transformations have occurred and where forest and land-management paradigms have changed (Korovin, 1995; World Bank, 1997). In the vast and largely remote forested region of Siberian Russia, the end of the former Soviet Union in 1991 also ended decades of centralized state-supported economy. While the middle twentieth century saw the height of Soviet-era agricultural collectivization and logging, shortly after 1991 timber harvest and lumber production had dropped to approximately one-quarter of the former annual rate and had not substantially recovered by 2001 (Krankina and Dixon, 1992; Blam, 2000). The abandonment of collective farmlands began before the 1991 transition.

In the absence of consistent and available statistics, remote sensing data are advantageous for directly observing and characterizing long-term changes on the Siberian forested landscape. To be most useful, remotely sensed data collected over a span of years, at spectral and spatial scales capturing both natural and human-driven change are required. Landsat is a strong candidate for this given its now over 30-year period of operation and characteristics suitable for vegetation analysis (Goward and Masek, 2001). The goal of our project was to observe and characterize trends in forest- and land-cover change before and after the 1991 political transition in case study sites representative of regional forest- and land-cover changes in Tomsk Oblast, Krasnoyarsk Krai, and Irkutsk Oblast using the 1972 to 2001 Landsat archive. Our specific objectives were to (a) use Landsat to map and quantify forest- and land-cover for three dates bracketing the political transition with one of the scenes at the transition date, (b) quantify 1972 to 2001 forest- and land-cover change trends and compare those from the Soviet-era with those from the post-Soviet era, and (c) analyze how these trends are changing the landscape in terms of forest amount, type, and successional states.

Background

The climate in the central Siberian study region (Figure 1) is continental with January and July mean temperatures of −22°C, and +18°C, respectively. Fifty to sixty percent of precipitation as rainfall occurs between July and September, and snow cover begins in October and remains for six to seven months. Physiography includes the eastern reaches of the west Siberian lowlands, the central Siberian plateau dissected by major rivers, and low mountain areas near Lake Baikal. Soils consist of sands, clays, and podzols. In wintertime, soils may be frozen to a depth of 2 to 3 meters, with local cases of permafrost.

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Photogrammetric Engineering & Remote Sensing
Vol. 74, No. 6, June 2008, pp. 787–798.

0099-1112/08/7406–0787/$3.00/0

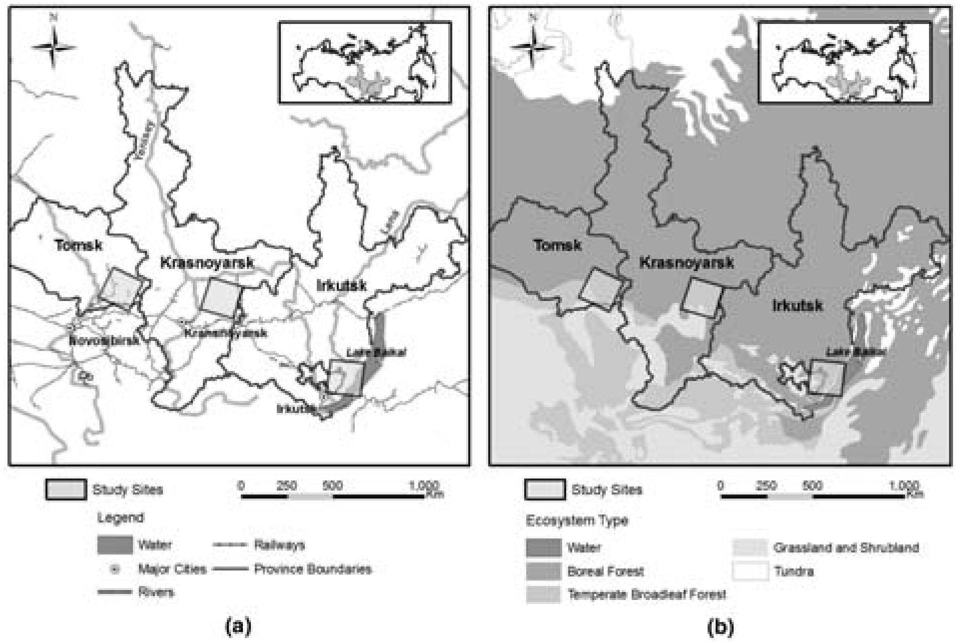

Figure 1. Study regions and case study sites with respect to infrastructure (a) and ecosystem types (b) and location within the Russian Federation (Olson *et al.*, 2001; Environmental Systems Research Institute (ESRI), 2006).

Ecoregions in the study area are dominated by boreal forests (taiga). The forest is a mosaic of several types at various successional states and with characteristic disturbances (Farber, 2000; Hytteborn *et al.*, 2005; Nikolov and Helmisaari, 2005). The "light-needle" coniferous forest includes Scots pine (*Pinus sylvestris* L.) and larch (*Larix sibirica* Ledeb.). The "dark needle" forests of spruce (*Picea obovata* Ledeb.), fir (*Abies sibirica* Ledeb.), and Siberian pine (*Pinus sibirica* Du Tour) exist typically as late successional forests or as accompanying species in light-needle dominated communities. Deciduous birch and aspen (*Betula pendula* Roth and *Populus tremula* L.) occur in pure stands as young forests on post-disturbance sites or as accompanying species in mid-successional mixed forests.

Human settlement in the region started in the Seventeenth century, but did not have significant impact until the latter half of the Nineteenth century. A few large urban centers are present (Irkutsk, Krasnoyarsk, Tomsk, and Novosibirsk), but much of Central Siberia is removed from significant urban infrastructure, with settlements consisting primarily of small towns and villages. A number of ethnic groups are represented in the region although, as groups, indigenous peoples are found to the north of the study region. Logging started intensively in the 1940s and 1950s, staffed in early decades by prison labor, and peaked in the 1960s to 1980s (Kortelainen and Kotilainen, 2003). Between 1930 and 1957 the Siberian silkmoth (*Dendrolimus superans sibiricus* Tschetw.) damaged and killed about 7 million ha of forests. In the 1994 to 1996 outbreak in Krasnoyarsk Krai 0.7 million ha of forest were affected, and about 0.3 million ha experienced complete mortality (Kharuk *et al.*, 2001; Kharuk *et al.*, 2003). Fires are a natural part of boreal ecology (Conard and Ivanova, 1997) and before humans came to dominate disturbance regimes, they were caused primarily by lightning. Most are now thought to be human-caused (Goldammer and Furyaev, 1996), often fuelled by the debris left from the clear-cutting of trees or insect mortality (Korovin, 1996).

Landsat Remote Sensing in Siberia

The Landsat program began in 1972 with the Multi-Spectral Scanner (MSS; 1972 to 1983). This sensor was followed by the Thematic Mapper (TM4 and TM5) beginning in 1982 and by the Enhanced Thematic Mapper (ETM+) in 1999. The Landsat-5 TM and Landsat-7 ETM+ continue to acquire imagery, though each has experienced technical failures that have degraded their quality (NASA Landsat Project Science Office, 2006).

A general challenge in using Landsat data for long-term studies is that the information archived from the succession of satellites (MSS, TM, and ETM+) differs to varying degrees in its spatial, spectral, and radiometric resolutions plus noise content, complicating attempts to create consistent classifications over time or apply change-detection methods. More specific to Siberia, the availability of historical Landsat data for the study region was not well-documented, boreal regions are frequently cloud-covered, and Russian and Western scientists have only recently begun to collaborate on use of environmental remote sensing (Bergen *et al.*, 2003), so data archives and networks remain scarce.

Recent work, however, has demonstrated application of Landsat data to land-cover studies in Central Siberia, and also in western Russia and Far East Siberia. In Central Siberia research has focused on combining Landsat ETM+ and radar sensor data for mapping boreal forest types and disturbance (Kharuk *et al.*, 2003; Ranson *et al.*, 2003). In far eastern Siberia, rates and patterns of forested land-cover change between 1972 and 1992 were analyzed using Landsat (Cushman and Wallin, 2000). In western Russia, Landsat has been compared with other sensors (Bartalev *et al.*, 1995) and used to document forest disturbance and carbon content (Krankina *et al.*, 2004).

Methods

Case Study Sites Selection

Case study sites were selected from Tomsk Oblast, Krasnoyarsk Krai, and Irkutsk Oblast. These three administrative units are the three most important in central Siberian forest sector in terms of forest reserves, timber removal, and lumber production (Blam *et al.*, 2000). Criteria for site selection were: (a) availability of cloud-minimized Landsat images for each of three dates between the 1972 and 2001 endpoints, with a middle date at or near 1990, (b) geographic distribution, with a case study site located in each of the three administrative units, (c) representative land-cover and change as understood from the literature and prior studies (Bergen *et al.*, 2000; Farber, 2000; Kharuk *et al.*, 2001), and (d) interest to Russian study team members and availability of reference data sources.

The Landsat United States Geological Survey (USGS), Beijing, China and Kiruna, and Sweden archives were searched to locate all useable scenes in each World Reference System (WRS) path/row location that fell within the entire extents of the three administrative units, and for all years 1972 to 2001. All potentially usable scenes were recorded into an Access® database; the database searched for all potential locations with three or more time-series scenes that met the study objectives, and three case study sites were selected (Figure 1).

Case Study Sites

Tomsk Site

Landsat path/row 147/20 (WRS-2) is in eastern Tomsk Oblast (Figure 1). This westernmost site is centered on 57° 17' 57" N, 86° 33' 18" E. The Tomsk site is comprised of boreal taiga forest (72 percent), northern temperate forest (27 percent, now primarily agricultural lands), and forest-steppe (<1 percent) ecoregions (Olson *et al.*, 2001). Eastern Tomsk Oblast lies at the transition between the west Siberian lowlands and central Siberian plateau and has minor topographic relief with elevation ranging from approximately 100 to 200 m above sea level (ASL) (USGS, 1996). Tomsk Oblast is approximately 90 percent forested (Shumilova, 1962).

Krasnoyarsk Site

Landsat path/row 141/20 is in Krasnoyarsk Krai and is centered on 57° 19' 27" N, 96° 05' 01" E. The site is comprised of boreal taiga forest (91 percent) and forest-steppe (9 percent) ecoregions. The site lies on the central Siberian plateau with relatively minor topography ranging from approximately 150 m to 500 m ASL, but largely between approximately 200 to 400 m ASL (USGS, 1996). Krasnoyarsk Krai was first among all regions of the Russian Federation in timber reserves as of 1995, and in the top three in logging and lumber production (Blam *et al.*, 2000). Krasnoyarsk forests were where some of the most extensive logging by prison labor in the mid-twentieth century occurred.

Irkutsk Site

Landsat path/row 133/23 is in Irkutsk Oblast. This easternmost study site is centered on 53° 06' 47" N, 106° 06' 25" E. Part of the autonomous region of Ust-Orda Buryatsky is in the site southwest. The site is comprised of boreal taiga forest (88 percent), northern temperate forest (2 percent) and forest-steppe (10 percent) ecoregions. Topographic relief is greatest in this site, ranging from approximately 450 m ASL at the Lake Baikal surface to approximately 2,055 m ASL in the Baikal range (Peterson, 2004) north and west of Lake Baikal. Irkutsk Oblast was second after Krasnoyarsk Krai in timber reserves in 1995 (Nilsson and Shvidenko, 1999).

Landsat Data

While it was possible to find time series for each administrative unit with scene dates of approximately 1972, 1990, and 2001 (Table 1), even to meet study minimum requirements it was necessary to combine two or more scenes for at least one of the dates in each of the case study sites (i.e., if a large area of clouds was present in a corner of the otherwise most cloud-minimized primary scene).

Other Spatial Data

In addition to Landsat data, a digital elevation model (DEM), and ancillary GIS datasets (e.g., water, transportation, and urban) were needed. At the time the Landsat data were processed, high-resolution DEM (i.e., Shuttle Radar Topography Mission (SRTM) data were not available for this region, and therefore a 1 km DEM was extracted from the USGS GTOPO30 data (USGS, 1996). High-resolution GIS data were not available, and so hydrology, transportation, and urban features were digitized by project staff from Russian 1:200 000 topographic maps held at the University of Michigan (Federal Geodesy and Cartography Service of Russia, 1991).

Landsat Data Preparation

Georectification

Definitive ephemeris processing had been used to obtain coordinates of the study ETM+ images, and these data were geometrically corrected with the coordinates available in the header files (Masek *et al.*, 2001; NASA Landsat Project Science Office, 2002). The radiometrically and systematically corrected ETM+ data in Space Oblique Mercator were imported into ERDAS Imagine® and orthorectified (Leica

TABLE 1. LANDSAT TIME SERIES SCENES USED IN THE STUDY. THE PRIMARY SCENES FOR ALL SITE/DATE COMBINATIONS ARE INDICATED WITH AN "*". USEABLE AREA REFERS TO THE PERCENT AREA AVAILABLE FOR LAND-COVER CLASSIFICATION AFTER CLOUDS AND HEAVY HAZE WERE REMOVED FROM ALL THREE DATES IN A STUDY SITE COMPARED TO THE TOTAL AREA OF THE WRS 2 PATH/ROW

WRS 2 Path/Row		Path 147, Row 20	Path 141, Row 20	Path 133, Row 23
Study Site		**Tomsk**	**Krasnoyarsk**	**Irkutsk**
Images	ETM+	09 July 1999*	18 August 2000*	13 August 2001*
	TM	07 September 1989*	(1) 14 May 1991* (2) 07 July 1990 (e) (p140r20) (3) 02 July 1989 (w) (p142r20)	(1) 21 August 1989 e (p132r23)* (2) 19 August 1989 w (p134r23)
	MSS	(1) 30 August 1975 (p159r20)* (2) 08 July 1975 (w) (p160r19)	26 June 1974* (p152r20)	(1) 21 June 1975 (e) (p143r23)* (2) 28 July 1975 (w) (p144r23)
Useable Area		100%	99.5%	91.7%

Geosystems, 2005) using the Landsat-7 geometric model and the 1 km DEM, and resampled into the project coordinate system (Krasovsky Spheroid, Pulkovo 1942 datum, Albers Conical Equal Area projection). This procedure was applied to the MSS and TM images which were then registered to the ETM+ images (RMS error between 0.5 and 0.85 pixels). Images were resampled, ETM+/TM images to 30- and 60-meters, and MSS images to a 60-meter resolution. Each time-series was subset to the common image area of the three dates.

Clouds, Haze, and Sensor Anomalies
Noise occurred in the some MSS and TM data (primarily blue bands) in the form of line dropout. As much noise as possible was removed from classification features by either not using the blue bands with noise, or identifying areas with line dropout and replacing them with values based on a neighborhood majority. Clouds and cloud shadows were segmented into spectrally similar objects using eCognition® (Definiens, 2002), and then masked from the datasets. If a cloud pixel was present at one of the image dates, it was removed from all image dates for that site (Table 1). Standard de-hazing algorithms proved unsatisfactory with spatially-varying haze patterns. Heavy haze was removed along with clouds during the cloud-masking stage, and areas of light haze containing potentially usable data were addressed later during the classification process.

TABLE 2. CATEGORIES USED IN LANDSAT CLASSIFICATIONS (COLUMN 1) AND FOREST AND LAND-COVER/LAND-USE TYPES OF THE STUDY SITE (COLUMN 2)

Category Number	Landsat Classification Category	Forest and Land-cover/ Land-use
1	Conifer	Spruce/fir forest, upland Spruce/fir/Scots pine forest, lowland Siberian pine forests Scots pine or Scots pine-larch forests
2	Mixed	Mixed pine-deciduous forests Mixed pine-larch-deciduous forests
3	Deciduous	Deciduous forests (birch-aspen)
4	Young	Post-cut or post-fire with deciduous (birch-aspen) or conifer regeneration Regeneration from agriculture
5	Cut	Fresh cuts
6	Burn	Fresh fire scars
7	Insect	Insect infestation
8	Wetland	Wetlands, flood-lands
9	Agriculture	Agriculture (crops, hay, pasture)
10	Urban	Built-up areas
11	Bare	Bare ground
12	Water	Water

Forest- and Land-cover Classification
A test using the Tomsk imagery of the potential for use of radiometric-based change detection for this study resulted in limited success, primarily due to spatially-varying haze, although the lack of exact anniversary dates and the different MSS, TM, and ETM+ data also reduced radiometric compatibility. Given similar characteristics in other sites and scenes, individual image classification and post-classification change detection were selected as the overall methods.

Forest- and Land-cover Classes
A set of classes applicable to each of the nine Landsat scenes to be classified was arrived at by (a) assessment of the ecology of the region, (b) examination of spectral plots and separability in MSS/TM/ETM+ data during initial classifications, and (c) testing and refinement of classifications. Forests compositions (including community mixes) are provided on text accompanying the Russian topographic quadrangles. Prior studies provided information on the Insect disturbance class (Eastern Siberian State Forestry Enterprise, 1996). Floodlands and wetlands were not separable and were combined and assigned to the Wetlands class; pure larch (rare, with exceptions in the Irkutsk site) and bogs were assigned to the Conifer class. Conifer and Deciduous are maturing or mature mostly closed forest canopies. Several different compositions of mixed forest were assigned to one Mixed class, including those with and without larch and those representing mid-successional stages. The final classes included: Conifer, Mixed, Deciduous, and Young forest; Burn, Cut, and Insect disturbances; and Wetland, Agriculture, Bare, Urban, and Water (Table 2).

Training and Testing Data
Because of restrictions on use of global positioning system (GPS) and remoteness and size of the study area, we could not rely primarily on field data collection for reference data. Reference data were assembled independently by Russian study team members based on map and image datasets and limited field data (Table 3). Because these sources were not necessarily temporally coincident with all three Landsat image dates, all potential sites were compared *a priori* with the Landsat composites to provide the correct interpretation at the time of the image date. Multiple reference sites per class were selected over the geographic extent of each test site at each date to capture within-class variability; during the classification process, some additional sites were added as needed by classification analysts, i.e., >400 total were selected per scene. The selected reference locations were assembled as annotation layers in ERDAS Imagine® where annotations were points representing the central location of homogeneous areas. The reference sites were divided, with one half for use in classification training and the other for accuracy assessment.

Classification
Individual images of each date for each site were classified at 60-meter resolution, consistent with the MSS base resolution. The first step for each scene was an unsupervised classification using the ISODATA algorithm in ERDAS Imagine® (Tou and Gonzalez, 1974). Clusters were grouped into coarse categories (water, forest, disturbance, bare, wetland, agriculture, and urban) and labeled by referencing available ancillary data. Water, Bare, and Urban, were identified in this step also aided by GIS data and masked out of the imagery.

Remaining data were then classified using a supervised classification procedure. Prior to use for supervised classification training, polygons of multiple pixels exhibiting similar spectral properties were grown from seed pixels located at the training data annotation label, and these pixels used to develop signatures. At each step of the supervised classification, signature separability was evaluated through visual inspection of histograms, ellipse plots, and by calculating matrices of Jeffries-Matusita distance (Leica Geosystems, 2002). Where separability was not successful, classes were combined as discussed above. Image pixels were classified into categories using a maximum-likelihood decision rule.

The supervised classification procedure was iterative in that forest (Conifer, Deciduous, Mixed, and Young) and Insect categories were first classified, and masked out. The remaining area was then re-classified to Burn, Cut, Wetland, and Agriculture. The separate classified image layers were

Table 3. Primary Sources Consulted for Reference Sites Selection

Classes	Source	Date	Sites
All	*Topographic Map Series 1:200 000* Federal Geodesy and Cartography Service of Russia	1991	All
All	*Forest map of USSR*. State Forest Committee	1990	All
Forest	*Forest vegetation of South Predbaikalye 1:200 000* Academy of Sciences	1982	Irkutsk
Insect	*Map 1:200 000*. East Siberian State Forestry Enterprise	1996	Krasnoyarsk
Insect	Airborne false color infrared	1979	Krasnoyarsk
All	*Vegetation type map*, 1:2,500,000. Atlas of the USSR	1992	All
Forest	*Forest type map*, 1:2 500 000. Atlas of the USSR	1992	All
Forest, Disturbance	Selected field reconnaissance	2002	Irkutsk
All	Selected field reconnaissance	1999, 2000	Krasnoyarsk

spatially recombined using the ERDAS Imagine® Model Maker. In the Irkutsk site where spatially-varying haze affected parts of images, TM/ETM+ classification was also done at 30 m to attempt to improve results. Poorly classified hazy areas were identified using a distance image (Leica Geosystems, 2002) produced during preliminary classifications and classified separately before being recombined with the main portions of the imagery.

Accuracy Assessment

Prior to accuracy assessment, polygons of multiple pixels exhibiting similar spectral properties were grown from seed pixels located at the accuracy data annotation label. A subset of single non-contiguous pixels were then chosen randomly from the generated testing polygons, in order to ensure an adequate sample but to minimize spatial autocorrelation. Those classes expected *a priori* to be smaller by area were represented by fewer testing pixels than the expected larger classes, with classes varying somewhat by scene composition. Contingency matrices comparing testing data to classification results were created and producer's, user's, overall accuracy and Kappa statistics of agreement (KHAT) were generated.

Forest- and Land-cover Change

In addition to land-cover proportions provided for each of the nine site-date combinations, the classifications were used to aggregate meaningful types of land-cover change categories for the two Landsat time periods. Matrices and change images were created by comparing each temporal pair of images. Although most combinations did not occur or occurred minimally, with twelve land-cover categories, there were 144 changes possible. Based on the matrix output, forest- and land-cover change directions were grouped into: No Change, Logged, Burned, Insect Damage, Regenerated, Forest Succession, Development, and Noise/Error (Table 4). Regenerated Type I refers to Conifer or Mixed forest areas that were cut or burned at some time between the change pair dates and were forest at the earlier date; Regenerated Type II refers to areas that were labeled Cut, Burn, Insect, or Agriculture at the first date and were forest at the later date.

Change Accuracy

Assuming independence of errors in time series of land-cover maps, the estimated overall accuracies of subsequently calculated data on land-cover change for the two change periods was calculated by multiplying overall accuracies for each pair of dates, (Yuan *et al.*, 1998). The change matrices included a category of Error/Noise, pixels that transitioned to non-logical categories between the two image dates, and these were recorded for potential accuracy/error information.

Table 4. The Nine Change Categories and Their Change Components (1-Conifer, 2-Mixed, 3-Deciduous, 4-Young, 5-Cut, 6-Burn, 7-Insect, 8-Wetland, 9-Agriculture, 10-Urban, 11-Bare)

	Change Category	From Class (Time 1)	To Class (Time 2)
1	No Change	1,2,3,4,5,7,8,9,10,11	same as time 1
2	Logged	1,2,3,4	5
3	Burned	1,2,3,4,5,6,7,8,9	6
4	Insect Damage	1,2,3,4	7
5	Regenerated Type I	1,2,3	4
		1	3
6	Regenerated Type II	5,6,7	4,3,2
		9	4,3
7	Forest Succession	4	3,2,1
		3	1,2
8	Development	1,2,3,4,5	9,10
9	Other/Noise	Various combinations	Various combinations

Results

Forest- and Land-Cover Classifications

Results of classification included the nine maps and accuracy statistics (Table 5). Accuracy figures for individual classes in the text below are producer's accuracy.

Land-Cover Accuracy Assessments

All sites had overall accuracies 81 percent or greater (Table 5), but Tomsk and Krasnoyarsk were on average classified better than the Irkutsk site. Among the image dates, the MSS images had the lowest overall classification accuracies for all sites.

The three forest types Conifer, Mixed, and Deciduous, were generally classified well, with all (producer's) accuracies >80 percent for Tomsk and Krasnoyarsk but some lower accuracies for Irkutsk at the MSS date. Young forest was also well classified in the Krasnoyarsk and Tomsk sites (>82 percent), with most confusion occurring between Deciduous and Cut. Young forest at the Irkutsk site was the most difficult of all categories to classify, especially at the MSS date and was confused with Wetland. Wetland was well classed in Tomsk and Krasnoyarsk but posed problems at the Irkutsk site where it was confused with the Conifer (bogs), Agriculture, and Young. Cut was somewhat variable but moderately to well classified and where confused, generally with Young forest class. Burn was not present at all site-date combinations and was sometimes confused with bare, cut or agriculture and with accuracy higher for dates with larger burn area and patch sizes. Insect was present only at the Krasnoyarsk site and was classed less well at the TM date

TABLE 5. ACCURACY OF THE CLASSIFICATIONS FOR EACH OF THE NINE LANDSAT-DERIVED LAND COVER MAPS. SHOWN IS PRODUCER'S ACCURACY AND *N* of Testing Pixels for Each Class Plus Overall Accuracy and the KHAT Statistic

	Tomsk				Krasnoyarsk				Irkutsk			
Class	*N*	MSS	TM	ETM+	*N*	MSS	TM	ETM+	*N*	MSS	TM	ETM+
Conifer	220	89.0	99.5	90.0	220	93.6	91.8	99.1	150	94.2	93.3	98.3
Mixed	220	94.5	97.2	94.1	220	95.0	96.8	99.0	150	56.9	91.4	82.6
Deciduous	220	89.5	97.7	98.1	220	75.9	91.3	97.7	150	76.7	81.0	85.1
Young	220	82.7	92.7	95.0	220	95.4	97.2	95.5	55	30.4	66.4	75.0
Cut	110	65.4	87.2	98.1	110	90.9	93.6	79.3	55	81.8	95.4	81.4
Burn	55	72.7	53.6	n/a	110	71.8	100.0	60.0	55	80.0	92.4	98.4
Insect	n/a	n/a	n/a	n/a	110	n/a	45.5	98.1	n/a	n/a	n/a	n/a
Wetland	220	100.0	100	83.6	110	96.3	92.7	89.9	150	78.0	92.0	66.4
Agriculture	220	100.0	100	98.6	220	99.5	96.8	96.8	150	86.7	88.1	91.9
Urban	55	97.3	98.1	95.4	55	81.3	72.0	66.7	75	90.1	100	98.7
Bare	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	75	97.2	100.0	100.0
Water	55	99.0	94.6	97.3	55	88.0	98.7	98.7	150	100.0	100.0	100.0
Overall		***90.4***	***94.2***	***93.7***		***90.1***	***91.0***	***92.1***		***81.5***	***89.3***	***88.6***
KHAT		***0.89***	***0.93***	***0.96***		***0.88***	***0.89***	***0.91***		***0.71***	***0.83***	***0.82***

TABLE 6. FOREST- AND LAND-COVER COMPOSITIONS FOR EACH CASE STUDY SITE FOR EACH DATE. GIVEN IS PERCENT OF SITE TOTAL LAND AREA IN EACH CATEGORY

		Tomsk 147–20			Krasnoyarsk 141–20			Irkutsk 133–23		
	Class	MSS	TM	ETM+	MSS	TM	ETM+	MSS	TM	ETM+
Forest Type, Successional State, Disturbance Class (%)	Conifer	11.8	10.8	10.2	16.7	10.9	8.2	19.6	15.9	15.5
	Mixed	31.9	29.0	28.7	41.2	38.8	36.7	29.4	31.5	25.5
	Deciduous	13.7	14.3	19.4	3.6	10.9	23.8	7.8	8.3	11.9
	Young	8.9	11.0	11.2	13.7	21.0	8.6	1.4	1.4	1.5
	Cut	4.8	3.3	2.9	5.7	2.9	2.8	0.8	2.3	0.6
	Burn	0.07	2.40	0.00	0.77	0.79	0.70	0.18	0.32	2.54
	Insect	0.00	0.00	0.00	0.00	0.38	6.77	0.00	0.00	0.00
	Total Forest	***70.60***	***70.94***	***72.40***	***81.11***	***85.86***	***86.56***	***58.47***	***58.93***	***57.25***
Other Land Cover%	Wetland	15.60	15.68	15.48	1.94	1.95	1.97	19.83	18.95	23.69
	Bare	0.00	0.00	0.00	0.00	0.00	0.00	5.99	6.05	5.57
	Urban	1.33	1.33	1.31	0.33	0.34	0.34	0.44	0.63	0.40
	Agriculture	12.47	12.04	10.81	16.62	11.85	11.13	15.27	15.45	13.09
	Total	***100.00***	***100.00***	***100.00***	***100.00***	***100.00***	***100.00***	***100.00***	***100.00***	***100.00***

where insect outbreak was very minor, occurring in isolated small patches (<0.5 percent of the site area); it was very well classified in the ETM+ image where it represented a major regional outbreak (almost 7 percent of the study site).

Land-cover

Land-cover results describe the landscape in approximately 2000. (Table 6; Figures 2 and 3). The Tomsk image is bisected by the Chulym and Kiya Rivers (tributaries of the Ob River) and associated floodland Wetland. Agriculture is interspersed with small settlements and located in the southern part of the image coinciding with incursions of northern temperate forest and forest-steppe ecoregions. The remainder of the image is primarily taiga forest. Several patches of mature Conifer still exist within a mosaic of secondary successional forests and disturbance patches. The full resolution imagery shows continued logging, including small rectangular Cut patches (clear-cuts) following new prescribed size limits in the ETM+ image (Yaroshenko *et al.*, 2001). Fire in the first two image dates occurred in close proximity to these areas of Cut. A similar forest landscape is present in the Krasnoyarsk site. The image is bisected by the Chuna and Biryusa Rivers (tributaries of the Angara River which feeds the Yenisei River) with associated wetland areas. Agriculture is located in the southern third of the image. In the northern two-thirds of the image, patches of mature Conifer remain within a mosaic of secondary successional forest and disturbance patches. As in the Tomsk image, the Krasnoyarsk full resolution imagery reveals some active logging. Fire occurred in forested areas near the second (TM) date. Insect infestation occurred in Conifer and Mixed forest in the Krasnoyarsk images observed at the especially at the ETM+ date. In both the Tomsk and Krasnoyarsk images and over all dates Mixed is the largest forest category on the landscape. In the Irkutsk image this is also the case, however, known presence of significantly more

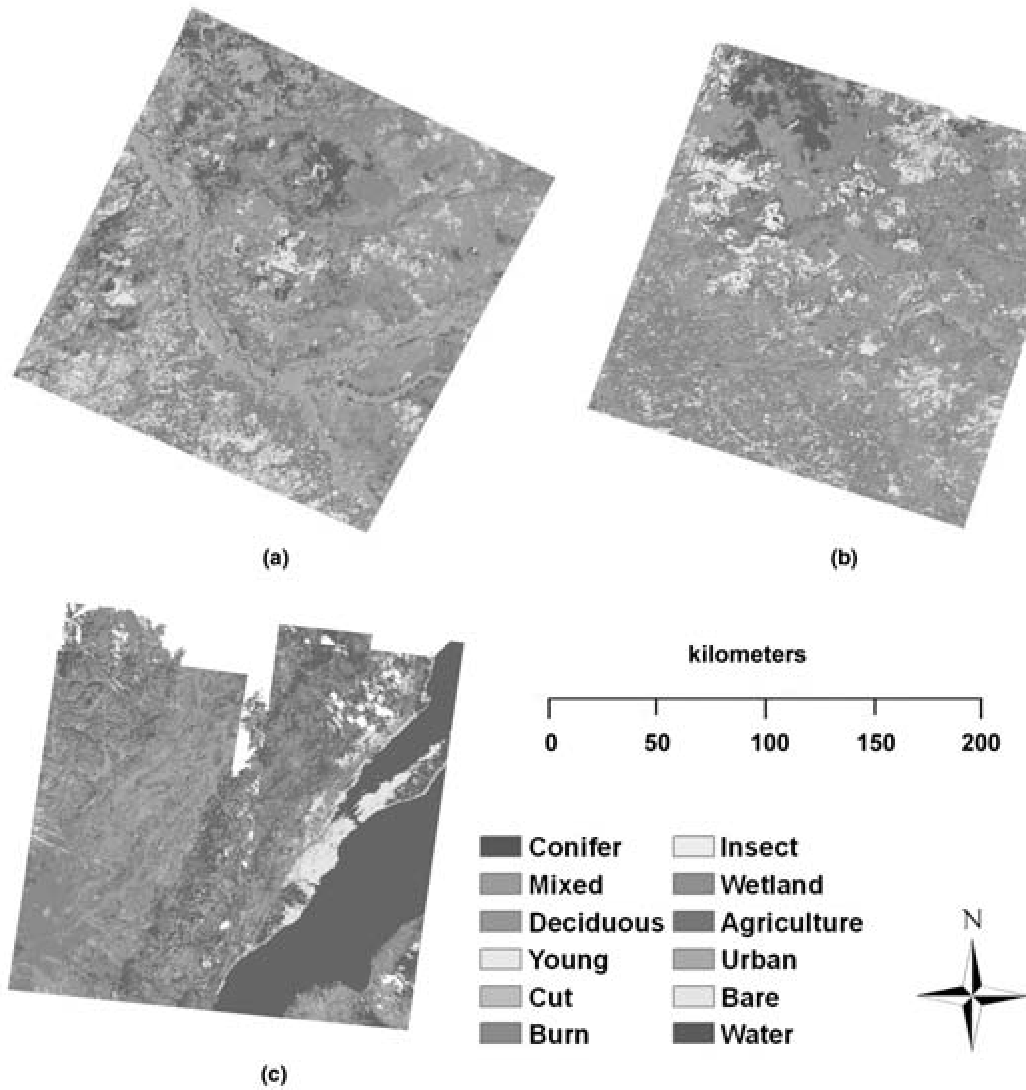

Figure 2. Landsat ETM+ land-cover of the three case study sites: (a) Tomsk, (b) Krasnoyarsk, and (c) Irkutsk. Missing data in the Irkutsk site data is from necessity to use combined non-contiguous images and removal of some areas due to clouds/haze. A color version of this figure is available at the ASPRS website: **www.asprs.org**.

larch means a somewhat different Mixed category composition (Peterson, 2004). Drier forested uplands occur to the west of Lake Baikal and Cut and active Fire classes were concentrated in this area in the ETM+ image. In the northwest, finely dissected physiography supports primarily Conifer or Mixed (with larch) forests on drier slopes and bogs and other wetlands in valley bottoms. The south central area is comprised of Agriculture and small Urban settlements. Bare ground occurs only in the Irkutsk image along Lake Baikal.

Forest- and Land-cover Change

Change Accuracy and Evaluation

Estimates of the accuracies of land-cover changes were all between 73 percent-83 percent (Table 7). These values are lower than the individual land-cover overall classification accuracies and represent the probability that both classes are correct, and by extension that the change class is correct.

Logical change directions potentially contain some error, but non-logical directions are assumed to be error. Change directions categorized as Error/Noise were less than or equal to 5 percent of area in the Tomsk and Krasnoyarsk sites, but were higher for Irkutsk, possibly resulting from Irkutsk lower accuracies and its lower accuracies generally occurring in classes with greater numbers of pixels than those in Tomsk and Krasnoyarsk.

Forest- and Land-Cover Change

Interpretation of the land-cover proportions (Table 6) shows two major trends consistent across all three sites over all dates. These are a decrease in the proportion of Conifer forest on the landscape, and an increase in the proportion of Deciduous forest. Agriculture also decreased over all three sites and over all dates except for the Irkutsk site, where the first two dates were nearly equal. Cut and Mixed forest also decreased over the three dates for the Tomsk and Krasnoyarsk sites and between the second and third date at the Irkutsk site. Young forest (regrowth from Cut, Burn, and Agriculture) increased over the three dates in the Tomsk and Irkutsk site and between the first and second date in the Krasnoyarsk site. Wetland was stable over the three dates in Tomsk and Krasnoyarsk, but problematic in Irkutsk probably due to classification error where wetlands were confused with forest classes and Agriculture. Other land covers were either stable (Urban, Bare) or more stochastic by nature (Fire, Insect).

Interpretation of the aggregated change categories shows two trends that are consistent across all three sites (Table 8). These trends are the decrease in the amount of the Logged category between the first and second time periods and the dominance of Forest Succession as the largest change category in the second time period. Forest Succession, was a greater proportion in the second time period than in the first in the Tomsk and Krasnoyarsk site and nearly the same in the Irkutsk site. In the Tomsk and Krasnoyarsk sites, there was a somewhat greater amount of total change in the second period (1990 to 2001) than in the first period (1975 to 1989), but primarily as Succession from earlier disturbance. In Irkutsk total change was slightly greater in the second period, but this is inconclusive due to classification error in its more problematic scenes. Given the higher amount of non-logical change at the Irkutsk site, it is expected that true No Change is underestimated.

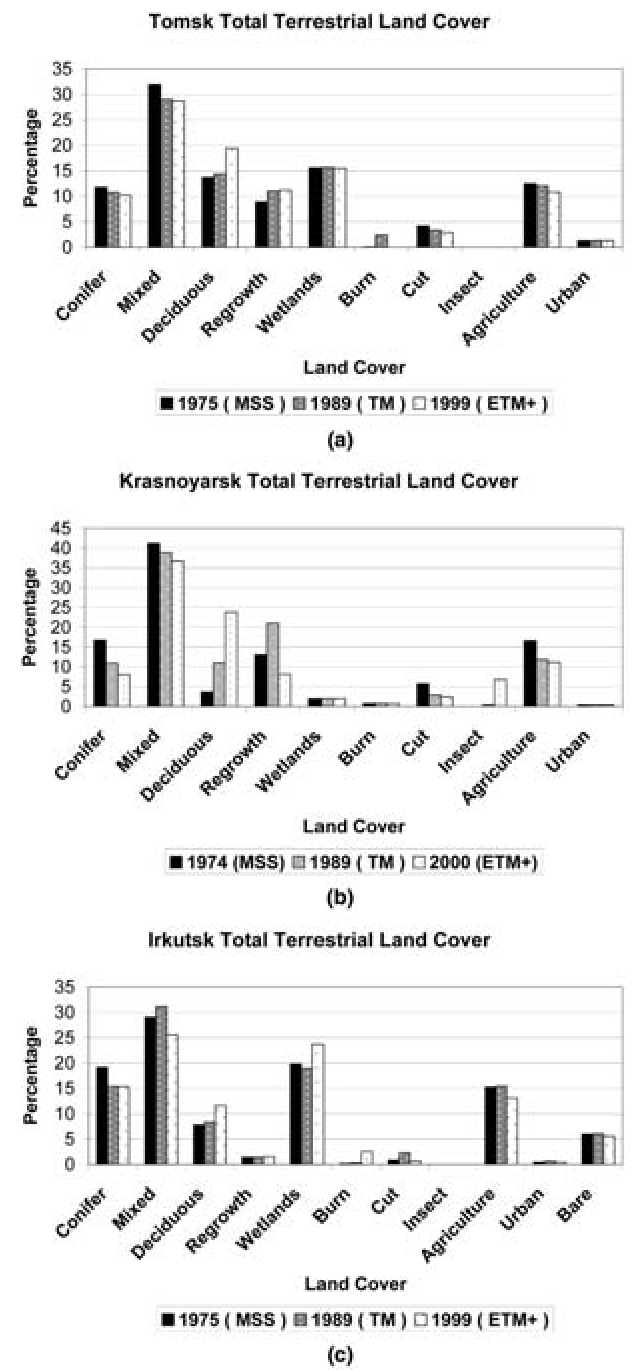

Figure 3. Forest- and land-cover compositions for each case study site for each date (water is excluded): (a) Tomsk, (b) Krasnoyarsk, and (c) Irkutsk.

Discussion

Forest Change in Central Siberian

Forest Type and Amount

Although the boreal forests of central Siberia have largely not been converted to other land uses, and many are still on the frontiers of human habitation, they are not by any means quiescent landscapes. Human and natural disturbance have long been changing the amount, type, and successional state of this forested landscape. The primary forest of this region had a large proportion of dark coniferous forest up through the nineteenth century, whereas the late-twentieth century forest is dominated by light-coniferous mixed or deciduous forest types and the deciduous type appears to be increasing (Hytteborn *et al.*, 2005). In the southern part of Krasnoyarsk Krai (including the vicinity of our case study site) for example, disturbance affected 62 to 85 percent of forests over the previous (twentieth) century (Sokolova, 2000).

The remote sensing analyses in the case study sites appear to corroborate and further illuminate these trends (Figure 3). The ongoing effects of disturbance prior to and into the early twentieth century are evidenced by typically mid-successional Mixed forest (light coniferous-larch-deciduous) as the largest category on the landscape. Mid-twentieth century change is evident from the relatively large amounts of forest in early secondary succession in the 1970s images (23 percent, 17 percent, and 9 percent in Young or Deciduous category in the Tomsk, Krasnoyarsk, and Irkutsk sites, respectively). These early- to mid-successional forest patches surround "islands" of remaining mature Conifer forests on similar underlying physiography.

Table 7. Land-cover Change Estimated Overall Accuracies and Error/Noise Proportions

	Tomsk		Krasnoyarsk		Irkutsk	
	1989–1999	*1974–1990*	*1990–2000*	*1975–1989*	*1989–2001*	*1975–1989*
Estimated Overall Accuracy	85.1	88.3	81.9	83.8	72.7	79.1
Error/Noise Proportion	2.44	4.52	5.10	4.82	16.44	13.73

Table 8. Terrestrial Land-cover Change Between Each Set of Change Pairs (Water is Excluded) as a Percentage of the Study Site Landscapes

	Tomsk		Krasnoyarsk		Irkutsk	
Change Category	*1975–1989*	*1989–1999*	*1974–1990*	*1990–2000*	*1975–1989*	*1989–2001*
No Change	85.20	75.35	69.80	64.17	62.02	67.52
Logged	2.42	1.48	1.80	1.10	1.94	0.50
Burned	2.39	0.00	0.79	0.67	0.30	2.47
Insect Damage	0.00	0.00	0.21	6.22	0.00	0.00
Regeneration I	2.17	2.83	6.35	1.19	1.05	0.59
Regeneration II	3.25	6.09	9.13	3.62	0.67	2.14
Forest Succession	1.70	9.16	6.29	16.63	8.24	7.20
Development	0.44	0.58	0.55	1.58	2.19	0.50
Noise Error	2.44	4.52	5.10	4.82	23.58	19.08

Logging

Forest harvest has occurred primarily in either remaining dark coniferous forests, especially in areas where desirable Siberian pine is a dominant component of that type, or in light-coniferous forest where Scots pine and larch are timber species. Approximately ninety percent of harvest has been through clear-cutting (Hytteborn *et al.*, 2005), most at the larger landscape scale prior to new size restrictions. Logging is often inefficient, leaving slash and logs susceptible to fire.

Russian forest statistics collected for Tomsk, Krasnoyarsk, and Irkutsk for this study confirmed that logging in the study region had peaked in the 1960s to the 1980s and dropped sharply in approximately 1990 to 1991 (Figure 4). This trend also mirrored the trends for the Soviet Union and Russian Federation as a whole (Figure 4). Based on the Landsat analysis, while some logging continued in the case study sites 1974 to 2001, the category of Cut decreased over all three dates in the Tomsk (by 40 percent) and Krasnoyarsk (by 50 percent) case study sites, and between the middle and last dates in the Irkutsk site, corroborating an overall trend of decreased forest harvest (Figure 4). The Landsat-observed reduction in the area of the Cut category in the Tomsk and Krasnoyarsk sites appears to have slightly preceded the sharp drop seen at about 1990 to 1991 in official statistics of the overall region.

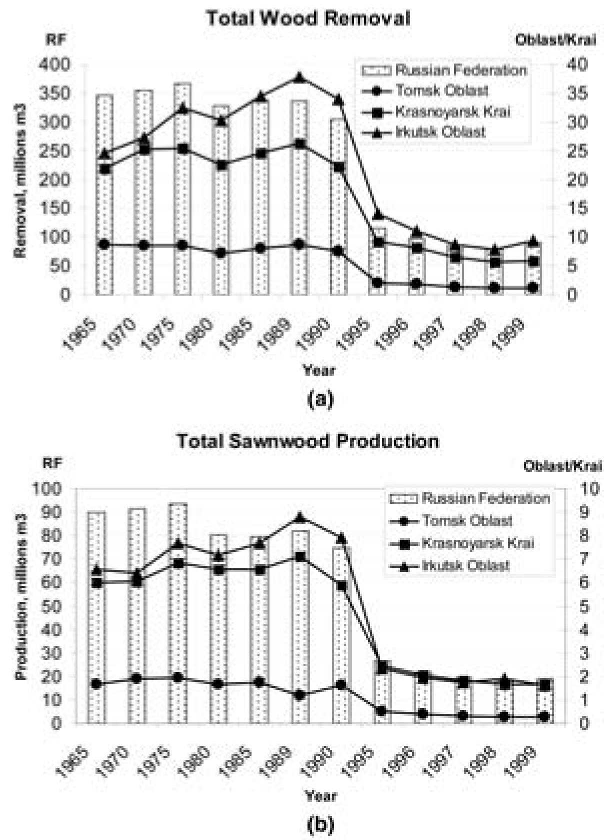

Figure 4. Russian official statistics showing forest sector trends from 1965 to 2000: (a) Total Wood Removal, and (b) Total Sawnwood Production. (All Union Scientific Research Institute of Economics, 1991; Goskomstat Rossia, 2007).

Fire

Forest lands in the study regions, especially those in Krasnoyarsk Krai are some of the most "fire prone" in Russia (Sokolova, 2000) and in addition forest harvest often leaves slash fuels which may feed back into fire disturbance patterns. On an annual basis, an average of 1.2 percent of the Russian far east boreal forest burns each year, with higher fire activity being found in the southern parts of this region than in the north; during years with large fires in the southern regions (such as 1998 and 2003), fires can affect 5 to 10 percent of the total land area (Sofronov *et al.*, 1998; Sukhinin *et al.*, 2004).

Based on the Landsat analysis, the area of new burns on the landscape appears to be similar to these reported in the literature. In the years that relatively severe fire occurred in Tomsk (1989) and Irkutsk (2001), approximately 2.3 to 2.4 percent of the case study site burned (Table 6). In Krasnoyarsk 0.70 to 0.77 percent of the landscape burned at all three dates. Because fire is a more stochastic event, three image dates are not sufficient for estimating change in rates of fire over time.

Insects and Other Animals

Siberian pine and fir are nutrition sources for pest caterpillars and are particularly susceptible to the caterpillars of the Siberian silkmoth, which damage or kill their needles. Insect-damaged areas may be susceptible to subsequent fire. In the Tomsk site, the insect damage that occurred in 1954 to 1957 is now observed in the form of long-term successional consequences. Severe insect infestation 1994 to 1996 in the Krasnoyarsk site was observed in the 2000 Landsat image as affecting 6.7 percent of total land cover primarily in Mixed and Conifer forests (Kharuk *et al.*, 2003). In such severe outbreaks where forests were defoliated or killed, the spectral signature of the Insect class was clearly distinguished. While outside the case study sites (northern extent of approximately 58°N), areas of central Siberia north and west of approximately 64°N are also impacted by wild reindeer (*Rangifer tarandus*) whose browsing influences recruitment dynamics of secondary forests (Webber and Klein, 1977).

Agriculture and Regrowth

The Landsat analyses indicate that conversion of agricultural lands to forest regrowth was a component of landscape change in central Siberia 1974 to 2001. Beginning before the dissolution of the government-run economy, some areas assigned to collective farms were vacated and area in production decreased (Figure 5). Once abandoned, agricultural areas can acquire tree regeneration, eventually succeeding to young deciduous or mixed forests. Study results show that agriculture decreased in all three case study sites over the time period, and that this began before the 1991 transition.

Forest Succession

Given this disturbance legacy, it is expected that forest secondary succession is a major component of the current central Siberian landscape. Fire or logging typically promotes young deciduous regeneration which grows into deciduous forests that may mature and remain dominant up to 70 to 100 years. For example, where Siberian pine occurs it is very susceptible to fire, and after-fire stands are typically colonized by young and deciduous birch-aspen forest (Hytteborn *et al.*, 2005). In mid-succession, mixed forests dominate. In some very xeric sites, light coniferous forests (Scots pine-larch) may regenerate directly after fire, also forming mature closed stands after 80 to 100 years. Succession to late-successional dark coniferous forests is a very slow process that occurs on the centuries-scale (Nikolov and Helmisaari, 2005).

Landsat image data over the 1974 to 2001 study period showed that Deciduous forest increased in all three sites over both periods. This is attributable to succession from Young forest during the study period, and the continued growth and succession of areas logged or burned prior to the earliest Landsat MSS date (Table 6). Succession to Deciduous also appears to have resulted from succession of Young regrowth on earlier abandoned agricultural lands. Some succession to Mixed (light-coniferous-deciduous) forest also occurred on the study landscape. Overall observed successional trends seem to follow logically for a landscape where disturbed forests are currently re-growing naturally at various stages.

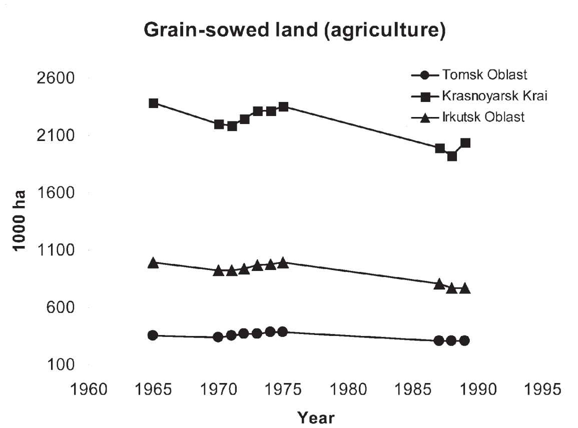

Figure 5. Russian official statistics showing an already decreasing trend in land-use for grain agriculture prior to 1990 (All Union Scientific Research Institute of Economics, 1991; Goskomstat Rossia, 2007).

Using the Landsat Archive in Siberian Forests

General challenges in using the Landsat archive in this study included the different spatial and spectral resolutions of MSS/TM/ETM+. While the use of the slightly coarser 60-meter versus 30-meter spatial resolution did not appear to negatively impact classifications in this landscape of relatively large grain-size, the more limited spectral resolution of MSS images probably influenced its somewhat lower classification accuracies.

Optical remote sensing issues characteristic of boreal regions include clouds and haze which were present to some degree in all case study sites, but in the Irkutsk site spatially-varying haze especially negatively impacted change detection. Cloud and haze issues for contemporary landscapes should be addressed by synergy of Landsat with radar; however radar data are not available for long-term change studies.

Classification results of the Irkutsk site were also impacted by topography. Use of finer spatial resolution DEM data for orthorectification such as 90 m SRTM (available for areas up to 60°N) may be advantageous (Farr *et al.*, 2007). Image ratio channels were explored to possibly normalize effects of Irkutsk site topography but tests resulted in little improvement, possibly because topography occurred in haze areas. Separation of boreal mixed forests whose conifer component is dominated by larch (primarily in Irkutsk) from those dominated by Scots pine was not generally possible. However, known larch areas coincided with hazy areas so lack of separation might be possible with better Landsat scenes. Several mixed forest compositions were subsumed under the Mixed class, however all represented a mix of conifer and broadleaf deciduous. Small rural settlements (Urban) in central Siberia are often interspersed with Agriculture and forest cover and difficult to distinguish. Future studies might consider exploring other spectral features to possibly aid such now identified separability issues.

Finally, challenges with Landsat availability in the region included lack of complete geographic coverage and lack of good *a priori* knowledge about coverage gaps. The survey of available data conducted by this study showed that early MSS and TM data over the northern half of Krasnoyarsk Krai and Irkutsk Oblast were not available. Selected TM data and ETM+ data were available for later years for the entire region. Change analysis relies on availability of good anniversary scenes at scientifically appropriate intervals. Our research shows that while availability of time series Landsat data is somewhat restricted for more than two dates, there exists selected availability of change pairs or series, for example as shown in Figure 6 for one and five year intervals.

Conclusions

Despite its considered remoteness, the central Siberian forest exists in a region that has experienced fundamental shifts in human-driven land-cover change regimes in the past century and in the most recent decades. As archives of remote sensing data have lengthened to over 30 years, interest in using them for long-term change analysis of such landscapes has increased. This study is one of the

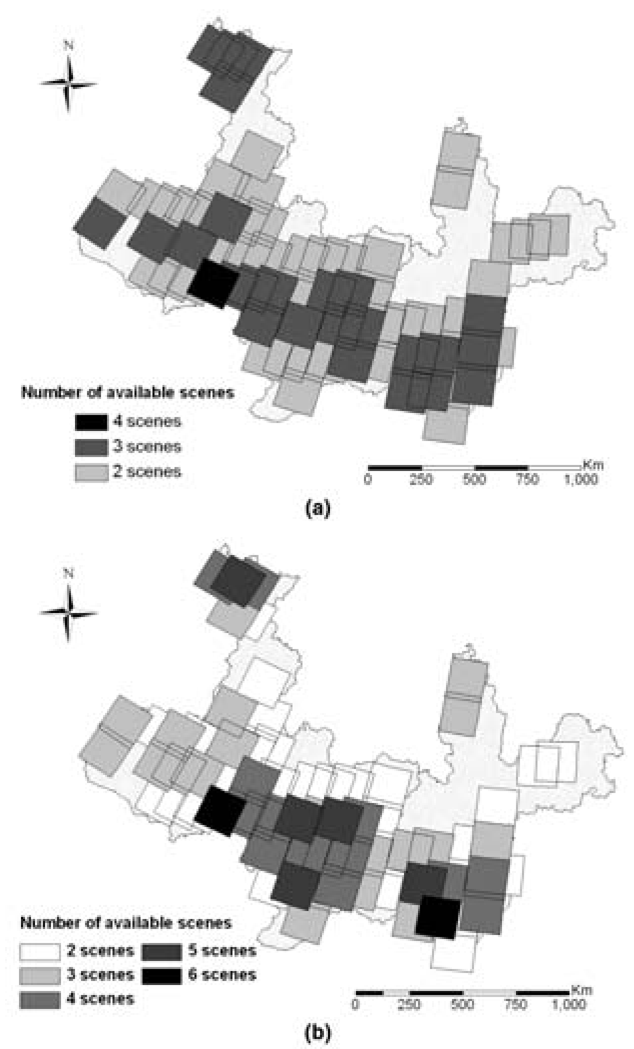

Figure 6. WRS-2 grid with the number of useable Landsat 1972 to 2001 time series scenes in (a) five year increments, and (b) one-year increments.

first to use the Landsat archive to investigate long-term forest- and land-cover change trends in Siberian forests. Our overall goal was to use the Landsat 1972 to 2001 archive to quantify and interpret trends in forested land-cover change in central Siberia at case study sites and bracketing the 1991 transition from the Soviet Union to the Russian Federation.

Results characterized changes in the amounts, types, and successional states of forests on the study landscape. Overall, and despite some challenges with the Landsat data, the observed land-cover and land-cover change patterns are reasonably consistent with expectations based on our summary statistical data and with published literature. The Landsat study results describe a dynamic central Siberian forest landscape, and one that between 1974 and 2001, appears to have been dominantly re-growing from earlier primarily twentieth century disturbance and which is continuing to undergo change in forest type and successional state. As expected, a decline in logging post-1991 was observed. Observation of regrowth of young forest from abandoned agriculture was not a specific expectation prior to this study, but very quickly its importance became evident. Overall, deciduous forest is currently increasing in area in this southern taiga region. Studies of understory regeneration are needed to predict longer-term successional trends, as are studies of the influence of climate change, and fire and insect disturbance. Research in areas further north in Siberia shows some evidence of evergreen conifer expansion into larch-dominated communities driven by climate change (Kharuk *et al.*, 2005) and expansion of wetlands due to thermokarst processes and fires (Chapin *et al.*, 2004). This suggests that what remains to be more fully known is how climate change as an agent might affect future forests of the region or how climate change combined with disturbance and successional forests, such as in the case study sites observed here, could impact the larger-scale biogeography of the central Siberian taiga.

Acknowledgments

This project was supported by NASA Land-Cover Land-Use Change (LCLUC) Program through Contract NAG5–11084. We extend appreciation to Dr. Garik Gutman, NASA LCLUC Program; RAS Academician E.A. Vaganov of the V.N. Sukachev Institute of Forest; and Shannon Brines, Stephanie Hitztaler, Iryna Dronova, and Bryan Emmett at the University of Michigan ESALab.

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