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ABSTRACT

Russian boreal forests are the largest forested zone on Earth and a tremendous pool of organic carbon. Current limited records on forest structure, composition, successional stage and disturbances contribute to large uncertainties in estimates of carbon stocks and fluxes in this zone. Our ability to monitor ongoing changes in forest cover has improved with the influx of remotely sensed data products since 2000 from multiple satellite platforms. Here we present a method aimed at reconstructing disturbance history from a known distribution of land cover. We developed and tested the method over a biologically and topographically diverse region of the Russian Far East. This method explores capabilities introduced through fusion of the long-term but spatially limited Landsat data archive and the spatially continuous but temporally limited 2000-present data record from the Moderate Resolution Spectroradiometer (MODIS). Landsat data from 1972 to 2002 were used to develop a reference disturbance dataset to train and validate a MODIS-based decision tree classification. The results showed a reliable differentiation of disturbed and mature forests with an overall accuracy of 88% (Kappa 0.73). Individual disturbances by type and decade were estimated with an overall accuracy of 70% (Kappa 0.64).

1. Introduction

Russian boreal forests occupy the largest forested zone on Earth and serve as a tremendous repository of organic carbon (Houghton et al., 2007; Nilsson et al., 2000; Soja et al., 2007; Stolbovoi, 2006). Events that occur within these forests and particularly those leading to changes in land cover composition have a pronounced impact on regional- and global-scale processes through abrupt and lasting changes in surface albedo, modification of the radiation balance and hydrological regimes, direct release of greenhouse gases into the atmosphere through fire occurrence, increases in soil respiration and accelerated rates of decomposition of the organic layer with retreat of permafrost, and changes in species composition and successional dynamics (Betts, 2000; Bonan et al., 1992; Soja et al., 2007). Over the past 30 years, these forests have experienced considerable changes under the combined influences of global climate change and abrupt and dramatic changes in socio-economic conditions of the Russian Federation since the dissolution of the Soviet Union in the early 1990s.

Available forest inventory data and records of natural and anthropogenic forest disturbance are either incomplete or cover only a short time period. The estimates of carbon stocks and fluxes differ greatly among various studies despite the fact that nearly all of these studies are based on the same basic Russian forestry inventory data (see Houghton et al., 2007 for a comparative assessment of various studies). Consequently, carbon flux estimates for Russian forests range from a source of 0.5 PgC/year to a sink of 1.02 PgC/year (Goodale et al., 2002; Shvidenko et al., 1996). Forest fire records maintained by the Russian Aerial Forest Protection Service (Avialesookhrana) are highly inaccurate in the reported amount of area burned and their geographic location (Conard et al., 2002). Accuracy of mapping forest extent and forest disturbances in Russia has improved since 2000 with increased data availability from multiple coarse and moderate resolution satellites. These include SPOT-Vegetation (Bartalev et al., 2003 and 2007; Tansey et al., 2004; Zhang et al., 2003), Moderate Resolution Imaging Spectroradiometer (MODIS) (Friedl et al., 2002 and 2010; Giglio et al., 2003; Giglio et al., 2009; Loboda et al., 2007; Roy et al., 2008), and Medium Resolution Imaging Spectrometer (MERIS) (Arino et al., 2007; Durieux et al., 2007; Gerlach et al., 2005). Multi-year assessments of forest dynamics are also available from global algorithms such as MODIS Burned Area products (Giglio et al., 2009; Roy et al., 2008) and multi-year records of percent forest

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cover (Hansen et al., 2003). In addition, data products fine-tuned to the specifics of Russian boreal forests such as MODIS forest disturbance mapping (Potapov et al., 2008) and SPOT-VGT circumpolar burned area mapping (Bartalev et al., 2007), a regionally focused MODIS-based land cover (Sulla-Menashe et al., 2010) and SPOT-Vegetation-based land cover of Northern Eurasia (Bartalev et al., 2003) are of particular value. Data from the Advanced Very High Resolution Radiometer (AVHRR) acquired at several ground receiving stations across Russia have allowed for the extension of the forest disturbance record back to the early 1990s over some regions of Russia (Sukhinin et al., 2004). The long-term archive of Landsat Multispectral Scanner (MSS), Thematic Mapper (TM), and Enhanced Thematic Mapper Plus (ETM+) data provides additional glimpses of boreal forest dynamics with considerable gaps in spatial and temporal coverage. Despite the multitude of potential sources of information, current multi-year observations of forest cover and forest change across the entire region of Russian boreal forests are limited to the MODIS era (~2000–present).

One of the notable specifics of boreal ecosystems is the slow rate of forest growth after disturbances. Slow rates of regrowth allow for delayed mapping of disturbances, as fire scars can frequently remain visible in the imagery for many years. The disturbed forested areas remain as grass- and shrub-dominated land cover for 10–30 years on average after the disturbance (Krestov, 2003; Nakamura & Krestov, 2005; Sheshukov, 1996). In many cases and particularly in the case of dark coniferous forests, initial successional forests consist of birch (*Betula spp.*)/alder (*Alnus spp.*)/aspen (*Populus spp.*)/willow (*Salix spp.*) communities, which present a stark contrast in the imagery to mature spruce (*Picea spp.*)/fir (*Abis spp.*) forests (Abaimov & Sofronov, 1996; Furyaev et al., 2008; Nakamura & Krestov, 2005; Sheshukov, 1996). Even within forest types where post-disturbance recovery resembles the mature forest species composition, the re-growing forests are frequently more open and can be distinguished from the mature stands with greater tree height and crown cover.

This paper presents an approach to reconstructing past disturbances in boreal and temperate forests over the past 30 years. This approach utilizes a suite of publicly available MODIS data products to identify and map the spatial extent and approximate timing of a disturbance event from present-day distribution of vegetation and land cover. We tested this approach in a biologically and topographically complex region of the Russian Far East (RFE) with the aim to reconstruct the past disturbance history within a region of biodiversity of global importance (Dinerstein et al., 2006; UNESCO, 2001).

2. Study area

In the context of this work, we refer to the RFE as a subset of the general geographic region limited to Primorsky and southern Khabarovsky Krai (administrative regions of the Russian Federation) (Fig. 1). This area ranges between approximately 43 °N and 55 °N and 130 °E and 142 °E. The region spans the Sikhote-Alin mountain range, which enhances the boundary of boreal forests in the northern and temperate forests in the southern part of the region, thus allowing the boreal coniferous forest stands to extend along altitudinal gradient much further south than in any other region of Northern Eurasia. At the same time the region's proximity to the warming effect of the Pacific Ocean supports the world's richest temperate forests, which are designated by the United Nations Educational, Scientific and Cultural Organization (UNESCO) as a world heritage site.

The transition between boreal and temperate ecosystems creates unique and challenging conditions for differentiating mature and successional forests. Mature forests in the RFE are represented by four dominant forest types: dark coniferous forests, light coniferous forests, mixed forests, and broadleaved deciduous forests (Krestov, 2003; Sheshukov, 1996). The first two forests types represent boreal ecosystems dominated by spruce/fir (dark coniferous) and larch

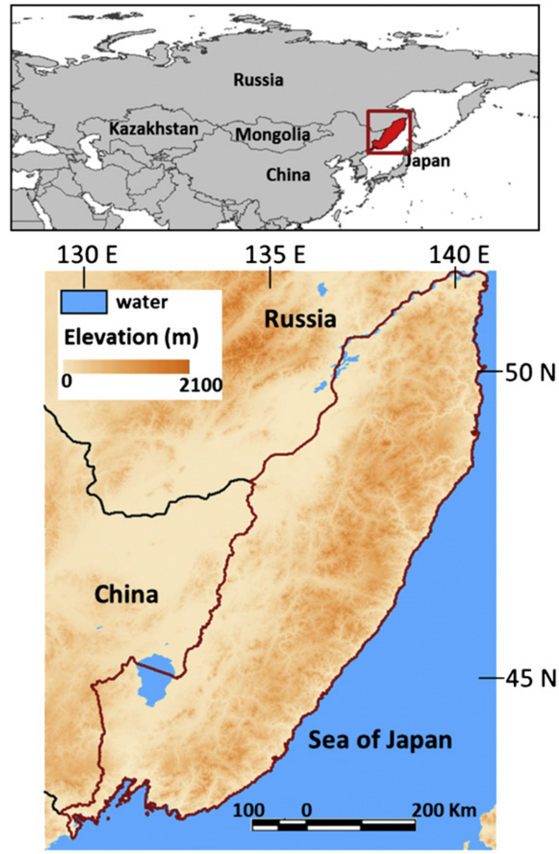

Fig. 1. Geographic position of the project study area in the Northern Eurasia (top) and in the Russian Far East (inset — bottom).

(*Larix spp.*) (light coniferous) stands. The successional forests in these boreal ecosystems are dramatically different from the mature forest state and are represented by birch and aspen species (typical of the dark-coniferous forest succession) or young and open larch stands. Mixed and broadleaved deciduous forests contain oak (*Quercus mongolica*) and pine (*Pinus spp.*) species with the Korean pine (*Pinus koraiensis*) being one of the most valuable forestry resources in the region (Miquelle et al., 2004). These forests have a successional pattern different from the dark coniferous stands, generally re-growing in the same species combination as the mature stands.

The major disturbances in this region are wildland fires and timber harvesting (Newell & Wilson, 1996). Although wildland fire is an essential ecosystem process, large fire occurrence has not been historically typical due to the influence of the East Asian monsoon bringing ample precipitation in the area during the hottest months of the year (June–August) (Kotlyakov, 2003). However, previous work has indicated that large (>1000 ha) fires occur in the RFE nearly every year and that during large fire years (e.g. 2003) nearly 973,000 hectares of forest can be burned during a single year (Loboda, 2009).

Anthropogenic disturbances are mostly limited to timber harvesting (Kondrashov, 2004; Newell & Wilson, 1996). The rate of timber harvesting increased considerably since the dissolution of the Soviet Union and the subsequent economic crisis (Achard et al., 2005). Visual assessment of the available Landsat imagery shows the prevalence of clear-cut logging; however, some selective logging has also been known to occur (Achard et al., 2005). Our brief visual analysis also showed that different types of disturbances overlap in space and the selectively logged areas in the earlier images can appear as clear-cut logging in later images.

3. Methodology

The presented methodology utilizes the opportunities offered by the biome-specific post-disturbance recovery trajectories in the RFE and the fused Landsat/MODIS data record to extend the satellite record for disturbances in the boreal and temperate forests of Northern Eurasia. This approach takes advantage of the nearly 35-year long but spatially incomplete Landsat MSS, TM, and ETM+ data record and the 10-year spectrally and temporally rich and more spatially complete MODIS data record. MODIS data-based products have been shown to differentiate well between coniferous and broadleaf forest types (Friedl et al., 2002 and 2010) as well as assess fractional vegetation cover (Hansen et al., 2003). Our approach builds on these previously defined capabilities to identify land cover categories associated with post-fire regrowth patterns characteristic for boreal and temperate forests of the RFE. We developed a record of disturbances from the Landsat archive to train and validate the MODIS-based classification. The specific methodological steps describing Landsat-based reference dataset development and the MODIS-based decision tree classifier are described in turn in the subsequent sections.

3.1. Landsat-based reference dataset development

We developed a moderate (30 m) resolution disturbance dataset for the RFE from 99 publicly available Landsat MSS, TM, and ETM+ images prior to the full release of the Landsat archive (Table 1). The imagery was pre-processed using the cosine approximation of atmospheric transmittance model (COST) for atmospheric correction (Chavez, 1996) and a topographic correction of reflectance values to minimize the impact of the complex topography of the Sikhote-Alin mountains on the forest canopy reflectance (Soenen et al., 2005). The full archive was divided into two categories: 1) the earliest available image for a given Landsat WRS-2 tile (adjusted for MSS WRS-1 tiles) and 2) subsequent images. The first group was used as a reference for subsequent forest change. The second group was used to develop the training and validation datasets.

Clouds, cloud shadows, and water were masked out from the pre-processed imagery in Group 2 using a combination of band thresholding and analyst-driven selection. The images then underwent a simple analyst driven classification using a decision tree classifier to select forest, bare/sparsely vegetated, shrub, and grass land cover. Shrub, bare, and grass categories were subsequently visually examined and compared to the previously available images to identify the areas of change and assign the identified areas to “burned” if the shape of the changed area was irregular or “logged” if the shape of the changed area followed a geometric pattern consistent with logging (Fig. 2). Areas which were not clearly identifiable were excluded from further analysis. Logging areas were not easily identifiable in the Landsat MSS imagery and therefore the sample areas for logging activities were limited to the Landsat TM and ETM+ period (mid 1980s–2002). Mapped disturbances were time-stamped using visual assessment of images in the Landsat archive of the US Geological Survey Global Visualization Viewer and grouped into decadal samples. A total of seven disturbance categories were identified from the available Landsat archive: 1) burned 2000–2002, 2) burned 1990–1999, 3) burned 1980–1989, 4) burned 1972–1979, 5) logged 2000–2002, 6) logged 1990–1999, and 7) logged 1980–1989. Prior to the release of the full Landsat archive, our holdings were limited to the publicly available data with the most recent images acquired in 2002.

Additional training data for evergreen needleleaf , deciduous needleleaf, deciduous broadleaf and mixed forest categories were identified using the MODIS Collection 5 Land Cover (MCD12Q1) product (Friedl et al., 2010) forest classes within undisturbed forested areas identified by the analyst as “unchanged” throughout the Landsat record. For mapping purposes, we considered forests as dense stands of trees taller than 5 m and with crown cover above 60% as defined by the Land Cover

Table 1
List of processed Landsat images.

Path_Row	Date	Inst	Path_Row	Date	Inst	Path_Row	Date	Inst
119_24	5/28/1975	MSS	111_26	9/17/1991	TM	111_23	9/7/2002	ETM+
119_25	5/28/1975		111_27	9/6/1993		111_24	5/18/2002	
119_26	5/28/1975		111_28	10/16/1990		111_25	5/15/2001	
119_27	2/28/1973		111_29	10/5/1992		111_25	5/18/2002	
120_24	1/6/1973		111_30	9/17/1991		111_26	5/15/2001	
120_25	1/6/1973		112_24	8/9/1992		111_26	9/4/2001	
120_26	1/6/1973		112_25	7/19/1990		111_27	10/1/1999	
120_27	9/20/1972		112_26	7/19/1990		111_27	9/7/2002	
120_27	9/20/1972		112_27	7/19/1990		111_28	5/15/2001	
120_28	3/18/1975		112_28	6/27/1988		111_28	9/4/2001	
120_29	10/8/1972		112_29	10/15/1987		111_28	9/7/2002	
121_25	1/7/1973		112_30	4/3/1992		112_26	9/22/1999	
121_25	6/11/1976		113_25	10/8/1988		112_27	7/19/1999	
121_26	6/29/1976		113_26	9/9/1989		112_27	9/22/1999	
121_27	6/29/1976		113_27	10/19/1992		112_27	9/22/1999	
121_28	6/29/1976		113_28	9/9/1989		112_28	6/7/2001	
121_29	5/12/1975		113_29	9/17/1992		112_28	10/29/2001	
121_30	5/13/1973		113_30	9/17/1992		112_29	6/23/2001	
121_30	5/12/1975		114_26	6/25/1988		112_29	9/11/2001	
122_26	6/30/1976		114_27	6/12/1989		112_29	10/29/2001	
122_27	7/12/1979		114_28	9/16/1989		112_30	10/10/2000	
122_28	8/18/1977		114_29	9/29/1988		112_30	9/11/2001	
122_29	9/17/1973		114_30	10/8/1991		112_30	10/29/2001	
122_30	9/17/1973		114_31	10/8/1991		112_30	5/9/2002	
123_29	9/17/1975		115_28	9/2/1993		113_27	8/12/1999	
123_30	7/19/1976		115_29	10/17/1992		113_28	7/13/2000	
110_24	6/16/1989	TM	115_30	10/17/1992		113_29	7/13/2000	
110_24	8/11/1992		110_24	6/22/2000	ETM+	113_29	5/16/2002	
110_25	6/16/1989		110_25	6/22/2000		113_30	7/13/2000	
110_26	5/18/1990		110_26	6/22/2000		113_30	5/16/2002	
110_26	10/6/1992		110_27	9/10/2000		114_29	9/25/2001	
111_24	6/29/1991		110_27	8/12/2001		114_30	5/17/2000	
111_25	8/13/1990		110_28	9/29/2001		114_30	9/25/2001	

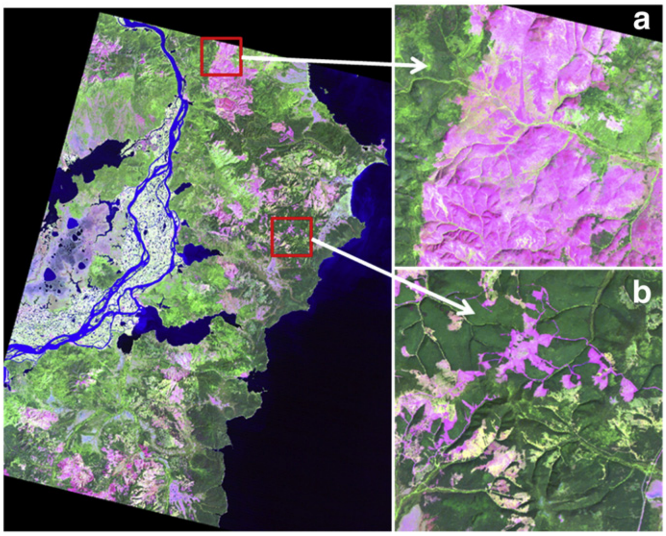

Fig. 2. Patterns of a) logging and b) burning in Landsat Thematic Mapper image (path 110 row 24 from 08/11/1992) in the northern section of the study area: bands 7:4:3 are loaded in the R:G:B combination; recent and severe disturbances appear in pink, restoring vegetation on disturbed sites appear in shades of yellow to light green, depending on the stage of regrowth, and mature forest appears dark green.

Classification System (Di Gregorio, 2005) and corresponding to other MODIS-based tree-mapping products (i.e. MODIS Vegetation Continuous Fields and Land Cover products). The MODIS Land Cover product was selected to provide the differentiation for these important training classes as it was built using the most recent observations of the surface parameters in the RFE (2005) and is mapped at a higher spatial resolution (500 m) compared to the other publicly available coarse resolution datasets (e.g. Bartalev et al., 2003).

3.2. MODIS-based classification

The Landsat-based reference data were aggregated to the MODIS ~500 m grid to create a "disturbed" training and validation dataset (≥50% of the grid-cell contain one of the disturbance classes in the Landsat-based reference dataset). We also added known burned areas between 2001 and 2008 mapped by the regional MODIS burned area algorithm (Loboda, 2009; Loboda et al., 2007) to the training and validation dataset to extend the burned 2000–2002 category to 2000–2008. Due to the lack of comparable record for forest change due to timber harvesting, training samples for logged areas remained limited to year 2002. The Landsat-based disturbance reference set allowed for spatially overlapping disturbances occurring over time. For example, an area logged or burned during the 1980s could be burned again during the 1990s. The classes were combined into a spatially unique disturbance mask with the most recent disturbances given precedence over earlier disturbances. Additionally, burning was given precedence over logging disturbances within the same decade. The latter precedence rule was established based on the fact that clear-cut logging has been found to support increased fire occurrence during summer fire events, which implies that fires frequently occur in previously logged areas and thus they generally occur later (Loboda, 2009).

One of the limitations of the developed training dataset stems from the opportunistic temporal sampling of various disturbances within the study area. For example, the areas within path 114 rows 26–28 were imaged only once and thus it remains uncertain if the areas were disturbed again later. However, because of the repeated mapping of the majority of the area of interest and a considerable overlap of individual path/rows of WRS-2 system over the RFE, the number of training and validation samples with a singular observation was very low in our dataset.

The training dataset was composed of a random selection of 70% of the "disturbance" cells. The remaining 30% of the cells with ≥50% "disturbance" were reserved for the validation set. Training and validation samples for the categories "burned 1990–1999" and "burned 2000–2008" were over-represented in the training and validation sets because of the emphasis on developing a comprehensive record for various disturbances and the overall data availability. Pixels belonging to over-represented classes in the training and validation samples were randomly filtered to limit any biases in the decision tree classification that might be caused by unequal class distributions (Table 2).

Decision tree mapping was developed from 46 MODIS-based variables obtained for 2008. The variables included the MODIS 16-day Bidirectional Reflectance Distribution Function (BRDF)-corrected Surface Reflectance product (MCD43A4) for MODIS bands 1–7 (visible, near-infrared, and shortwave infrared spectrum) at 500 m resolution (Schaaf et al., 2002) and the MODIS Land Surface Temperature (LST) product (MOD/MYD11A2) at 1 km resolution (Wan, 2007). Individual MCD43A4 composites were also used to calculate Normalized Difference Vegetation Index (NDVI), calculated as MODIS (band 2 − band 1)/(band 2 + band 1), and Normalized Burn Ratio (NBR), calculated as MODIS (band 2 − band 7)/(band 2 + band 7). The full year of information from the surface reflectance bands and NDVI and NBR indices was compressed into several variables: 1) "min", calculated as a mean of the three lowest values during 2008 per pixel, 2) "max", calculated as a mean of the three highest values during 2008 per pixel, 3) "meanJJA", calculated as the mean of June, July and August values during 2008 per pixel, and 4) "mean JF", calculated as a mean of January and February values during 2008 per pixel. The MODIS LST product was rebinned to match the 500 m resolution of the MODIS Surface Reflectance product. The full year of data was compressed into "min" (mean of the three lowest values), "max" (mean of the three highest values) and "meanJJA" (mean temperatures during June, July and August) parameters for daytime and nighttime temperatures during 2008 per pixel.

Similar inputs for surface reflectance and vegetation indices are frequently used to map vegetation from MODIS data (Friedl et al., 2002; Hansen et al., 2003). The NBR index is added as it has been shown to aid strongly in identifying burned areas (Loboda et al., 2007; Lopez Garcia & Caselles, 1991). Finally, several studies have shown that information provided by thermal bands improves land cover mapping and characterization in various geographic regions (Hansen et al., 2003; Ormsby, 1982; Southworth, 2004).

The resultant classification was masked to the study area of interest in the RFE. The MODIS Water Mask product (MOD44W) at 250 m (Carroll et al., 2009) was aggregated to 500 m resolution and applied to mask out water bodies in the study area. Additionally, MODIS Land Cover product classes "cropland", "crop/natural vegetation mosaic", and "urban" were grouped into the "other" category and used to

Table 2
The number of training pixels per class used for the decision tree classification. A random subset of pixels was selected from the total number of available training points for over-represented classes (burns between 1980 and 2008) to avoid suppressing identification of other classes of interest.

Class	Available (pix)	Used (pix)
Evergreen Needleleaf Forest	6254	6254
Deciduous Needleleaf Forest	2242	2242
Mixed Forest	4469	4469
Deciduous Broadleaf Forest	5978	5978
Burned 1972–1979	386	386
Burned 1980–1989	9843	3248
Burned 1990–1999	9017	2975
Burned 2000–2008	12311	3693
Logged 1980–1989	1989	1989
Logged 1990–1999	1744	1744
Logged 2000–2008	233	233

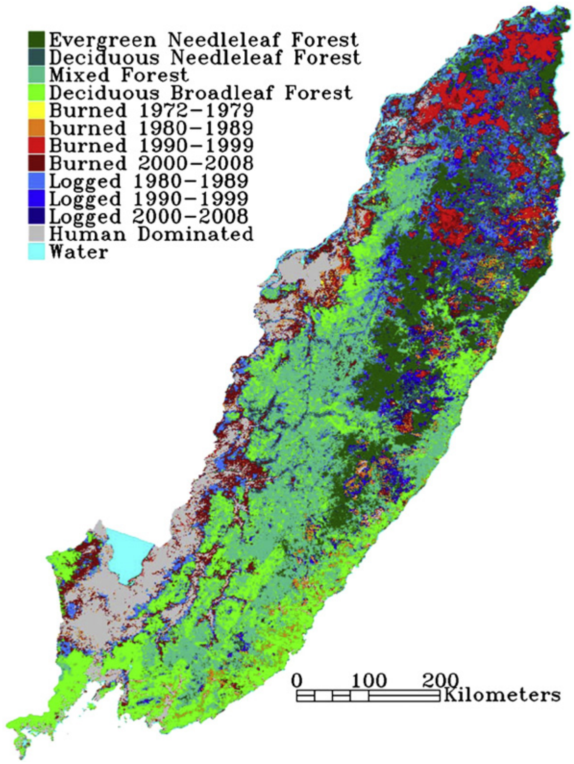

Fig. 3. Final classification results for mapping past disturbances in the RFE using the presented methodology.

mask out human activity-dominated landscapes. Fig. 3 shows the final result of past disturbance mapping.

4. Accuracy assessment

The accuracy assessment was conducted using the sub-sample of the Landsat-based reference dataset where more than 50% of a MODIS-based grid cell contained a single disturbance type. We selected the validation sample from those cells not included in the training of the decision tree. However, because the project was focused on developing the disturbance record, disturbance classes were considerably over-represented in the validation dataset. We ensured the appropriate representativeness by randomly selecting from the full validation dataset a sub-sample of ~0.2% (but no less than 30 pixels) of the total number of pixels mapped in each category by the decision tree.

We then used a confusion matrix to evaluate the resultant classification accuracy in a two-step assessment. First, we assessed the algorithm's ability to select disturbed and mature forests of any kind (Table 3). The results showed that we mapped disturbed and mature forests with 88% overall accuracy (Kappa ~0.73). The Kappa index shows the proportion of data classified correctly above the proportion which is assigned to a given class by chance (Cohen, 1960). We successfully mapped 93% of all forests and 79% of disturbances.

Table 3
Results of the accuracy assessment for generalized “mature” and “disturbed” forests.

	Class	Observed classes		Total (pix)	Omission (%)
		Mature	disturbed		
Predicted classes	Mature	93%	21%	1555	7.1
	Disturbed forest	7%	79%	726	21.19
	Total (pix)	1493	788	2281	
	Commission (%)	10.74	14.46		

Second, we assessed the ability of the presented method to identify all individual categories by type of disturbance and the approximate timing (Table 4). The overall accuracy for the full classification scheme assessment was lower at 70% (Kappa ~ 0.64).

5. Results

In general, burns are mapped more consistently than logged areas in both spatial and temporal domains. This is an expected outcome as burn scars in this region are frequently large (Loboda, 2009) and have a distinct spectral signature. In addition, the precedence rule accepted in this algorithm, which combined training data into mutually exclusive classes with the precedence given to burns over logging, may have attributed to a more robust representation of burned areas compared to logged areas in the training dataset. Areas burned prior to 1980 are mapped poorly and are frequently confused with deciduous broadleaf forest and deciduous needleleaf forests consistent with the two common trajectories of forest succession in the RFE. Areas that burned after 1980 are well-mapped in space but with a considerable amount of temporal confusion. Burns from the 1980–1989 period represent a transition gradient in forest recovery where some areas can be still identified as “disturbed”, but spectrally resemble logged areas with only slightly disturbed ground cover, while other areas have progressed in their recovery toward conditions more similar to mature deciduous broadleaf and deciduous needleleaf forests. However, nearly 20% of the burns from the 1980–1989 time period remain clearly discernable as burned in the imagery, potentially indicating a slower rate of forest recovery in those areas.

Burns from the 1990–1999 time period were mapped with the highest accuracy (72%) of all disturbance classes, partly due to the exceptionally large size of individual burned areas. Additionally, a field visit within one of those burned areas in 2006 indicated poor vegetation regrowth (Fig. 4). Burns from the 2000–2008 time period were frequently confused with burns from the 1990–1999 time period and previously logged areas. Ten percent of burns from the 2000–2008 time period were confused with deciduous broadleaf forests. This may be explained in part by the documented occurrences of management fires within broadleaf forests in the southern tip of the RFE, which clear the forest understory without noticeable damage to the dominant trees in the over-story canopy (Loboda, 2009).

Overall, logged areas were identified within individual categories poorly with the accuracy of 38%, 31%, and 17% for logging from the 1980–1989, 1990–1999, and 2000–2008 time periods, respectively. Logging from the 2000–2008 time period shows the lowest accuracy, likely due to the smallest training sample limited to 2000–2002 time period for which Landsat imagery was available. However, when combined over the 1980–2008 time frames, over 50% of logged areas were identified successfully. It was expected that logging areas would be less discernable in the imagery compared to burned areas due to only partial removal of vegetation, relatively light impact on ground cover, and considerably smaller footprints of logging concessions compared with burned areas. The temporal confusion between logged categories is likely due to the continuous growth of logged areas over time observed in Landsat imagery. Visual analysis of logged areas in Landsat TM and ETM+ imagery shows that the same areas where timber harvesting patterns were identified in the 1980s grew in size by the 1990s as adjacent areas to the previously logged sites were logged as well, thus adding to a potential confusion between areas logged in the 1980–1989 and the 1990–1999 time periods. Additionally, the artificial decadal grouping of data also is expected to have contributed to the temporal confusion in the decision tree results. Finally, the training and validation data points from the single-observation Landsat tiles (as described in Section 3.2) may have contributed to the uncertainty if they were re-disturbed after the initial mapping of disturbance type and timing.

Table 4
Results of the accuracy assessment for all categories within the full classification scheme: ENF — evergreen needleleaf forest, DNF — deciduous needleleaf forest, MF — mixed forest, DBF — deciduous broadleaf forest, burn70 — areas burned between 1970 and1979, burn80 — areas burned between 1980 and1989, burn90 — areas burned between 1990 and1999, burn00 — areas burned between 2000 and 2007, log80 — areas logged between 1970 and1979, log90 — areas logged between 1990 and 1999, log00 — areas logged between 2000 and 2007.

	Class	Observed classes											Total (pix)	Omiss (%)
		ENF	DNF	MF	DBF	Burn70	Burn80	Burn90	Burn00	Log 80	Log 90	Log 00		
Predicted classes	ENF	86	0	3	0	4	4	2	0	2	4	7	248	14
	DNF	2	62	1	0	26	8	6	4	9	9	7	183	38
	MF	0	8	88	4	0	7	0	2	9	3	10	602	12
	DBF	0	15	7	92	35	12	0	10	3	1	7	539	8
	Burn 70	0	0	0	0	4	2	1	0	1	0	0	8	96
	Burn 80	0	2	0	2	0	20	1	9	3	3	3	62	80
	Burn 90	0	0	0	0	0	10	72	17	9	20	7	180	28
	Burn 00	8	2	0	1	4	16	9	45	9	5	7	173	55
	Log 80	1	11	1	1	0	3	2	6	38	23	7	158	62
	Log 90	3	1	0	0	22	16	7	6	14	31	30	125	69
	Log 00	0	0	0	0	4	1	0	0	1	0	17	9	83
	Total (pix)	248	185	609	453	23	91	125	206	201	116	30	2287	
	Comm (%)	14	38	11	23	88	71	50	47	51	71	44		

6. Discussion

The presented method was carried out using the 2008 MODIS data specifically to test the limits of detecting past disturbances in the RFE. The results have shown that recent disturbances are identified more consistently than older disturbances. It is likely that the results of identifying the disturbances from the 1972–1989 time period can be improved if MODIS data from an earlier (e.g. 2001) season was used. However, our results also indicate that disturbances that occurred in the RFE more than 30 years ago are not likely to be mapped correctly using this approach, therefore limiting the overall reconstruction period to the 30 year time period prior to the year of MODIS imagery acquisition.

The direct comparison of the results received from the presented method to other disturbance mapping activities in the study area is challenging. On the one hand, official statistics regarding the area logged and the amount of timber removed are reported as incomplete or inaccurate by various Non-Governmental Organizations (NGOs) in the region who claim that illegal logging accounts for 10 to 50% of the timber produced while the official numbers from the Russian Federal Forest Agency and the Russian Federal Statistics Agency differ by ~50% (Newell et al., 2010). Similarly, official estimates of burned area, delivered by the Russian fire management agency Avialesookhrana, are also not representative of the total amount of area burned (Conard et al., 2002). Satellite-based maps of disturbance include percent change from the existing forest cover in 2000 over a 5 year period using MODIS data (Hansen et al., 2010) which differs from our approach where we mapped disturbance irrespective of the initial land-cover type, mapping of intact forested landscapes at a set period in time using Landsat data (Potapov et al., 2008), and the burned area mapping specific to the RFE using MODIS data (Loboda, 2009). Our estimates of mature forests overlap with the Intact Forested Landscapes (IFL) (Potapov et al., 2008) for 80% of the area. However, due to specific definition of IFL which does not preclude "naturally" occurring fires and selective logging, mapping errors, and other potential contributing parameters, the current approach estimates that 7% of the IFL have been burned and 13% have been logged at some point in time between 1970 and 2008. A more detailed analysis showed that these differences cannot be explained only by the mapping error in our algorithm as 910 training pixels for various fire events and 109 training pixels for logged areas validated by the analyst were located within the IFL boundaries. Finally, Loboda (2009) estimated that between 2001 and 2005 on average ~520,000 ha burn annually in our study area. The results of this method show a lower rate of burning (~390,000 ha annually). However, the present assessment excludes disturbances in croplands and grassland where fires reoccur frequently. Additionally, the disturbance hind-casting method accounts only for events which result in land cover conversion while burned area mapping in the RFE can identify surface burns which do not necessarily lead to dominant land cover type replacement (Loboda, 2009).

Fig. 4. Vegetation regrowth within areas burned in the RFE during 1998 fire events photographed in September 2006.

It is important to note that the presented method does not fully reflect the chronological sequence of disturbances in the RFE. This is a result not only of the mapping errors associated with the MODIS data and the mapping methodology, but it is also a result of the inherent obscuration of the previous disturbances by more recent ones and the dominance of burn signal over spectral signal from logged areas (even in the case of clear-cut logging — see Fig. 2). As a result, we established the rules that give precedence to burned signatures over logged signatures and more recent disturbances over past disturbances in our training dataset (see Section 3.1 Landsat-based reference dataset development) thus collapsing the multi-year disturbance history in some sites into a single disturbance snapshot. While this method will identify recent disturbances in non-tree dominated landscapes, it is not suitable for inferring a disturbance history in grass- and shrub-dominated landscapes because these land covers recovery quickly — frequently within the same season. Moreover, many burns which occurred between 2000 and 2008 appear along the "human-dominated landscapes" mask and reflect mostly burning that occurred in non-tree dominated landscapes including grasslands and croplands (Loboda, 2009). While we attempted to remove those areas using the "human-dominated landscapes" mask from further consideration, the mapping uncertainties in the MODIS Land Cover product, which provided the basis for this mask, and the lack of information regarding human management of grass- and shrub-dominated communities resulted in the "disturbance buffer" effect, where nearly all areas of "human-dominated landscapes" are fringed by disturbances which occurred between 2000 and 2008, visible in the map (Fig. 3).

The observed general patterns of distribution of disturbed areas in the RFE reflect the characteristics of disturbance regimes within the boreal forests in the northern part and the temperate forests in the southern part of the study area. Boreal communities experience larger amount of forest cover conversion compared to the temperate forests worldwide (Hansen et al., 2010). However, it is likely that this distribution also reflects a spatial trend in classification uncertainty related to the patterns of regrowth for different ecosystems. Post-disturbance regrowth patterns are more distinct in the coniferous communities than in broadleaf and mixed stands thus potentially leading to greater mapping errors in the southern part of the region.

7. Conclusions

Russian boreal forests are a tremendous pool of organic carbon. The limited information regarding forest extent, structure, successional stage, and disturbance history adds to the disagreements in the scientific literature regarding carbon stocks and fluxes within this largest forested area in the world. These uncertainties contribute strongly to the uncertainties in the global carbon budget and climate modeling efforts. This study presents a viable method for reducing this uncertainty by reconstructing the disturbance history from the present distribution of land cover across the boreal region using publicly available data sources.

This project is designed to test the opportunities offered by combining the spatially limited long-term Landsat data and the wall-to-wall mapping capabilities as well as spectral and temporal advantages offered by the MODIS data sources to hind-cast disturbance regimes over the RFE — a region of high biological importance (Olsson et al., 2001). Our results show that the presented method provides a reliable identification of previously disturbed forests in general within forest-dominated landscapes over the 30-year period prior to MODIS data acquisition. Burned areas are in general more easily identifiable than logged areas. Disturbances that occurred within 20-years of MODIS data acquisition are mapped better than those that occurred more than 20 years prior. Successful identification of individual categories was also related to the number of pixels in the training sample. Misclassification of various disturbances is partially explained by the ecosystem specifics of the RFE, differences in burn impacts of the area, and regrowth trajectories of disturbed forest stands.

We expect that this method can be applied to reconstruct past disturbance records across the full extent of Russian boreal forests due to the low rates of forest regrowth under the influence of low temperature and a limited growing season in this region. The presented method was tested in the south-eastern part of Russia at the boundary between boreal and temperate forests where the trees grow faster than in many northern and central regions of Russia. Therefore, it is likely that disturbances older than those that occurred in within the 30 years prior to the time of mapping can be identified in other regions of Northern Eurasia using this methodology. In addition, this approach provides an avenue for developing new methods aimed at hindcasting disturbance record in boreal forests even further in time using AVHRR data. Developing a consistent and unbiased long-term record of forest disturbances across Russian boreal forest will improve our understanding of global carbon stocks and fluxes and will provide a climatologically significant record of climate-driven disturbances (e.g. fire) in remote areas of Northern Eurasia.

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