TREE COVER LOSS ESTIMATIONS IN THE BOREAL FORESTS USING MODIS TIME-SERIES DATA SETS

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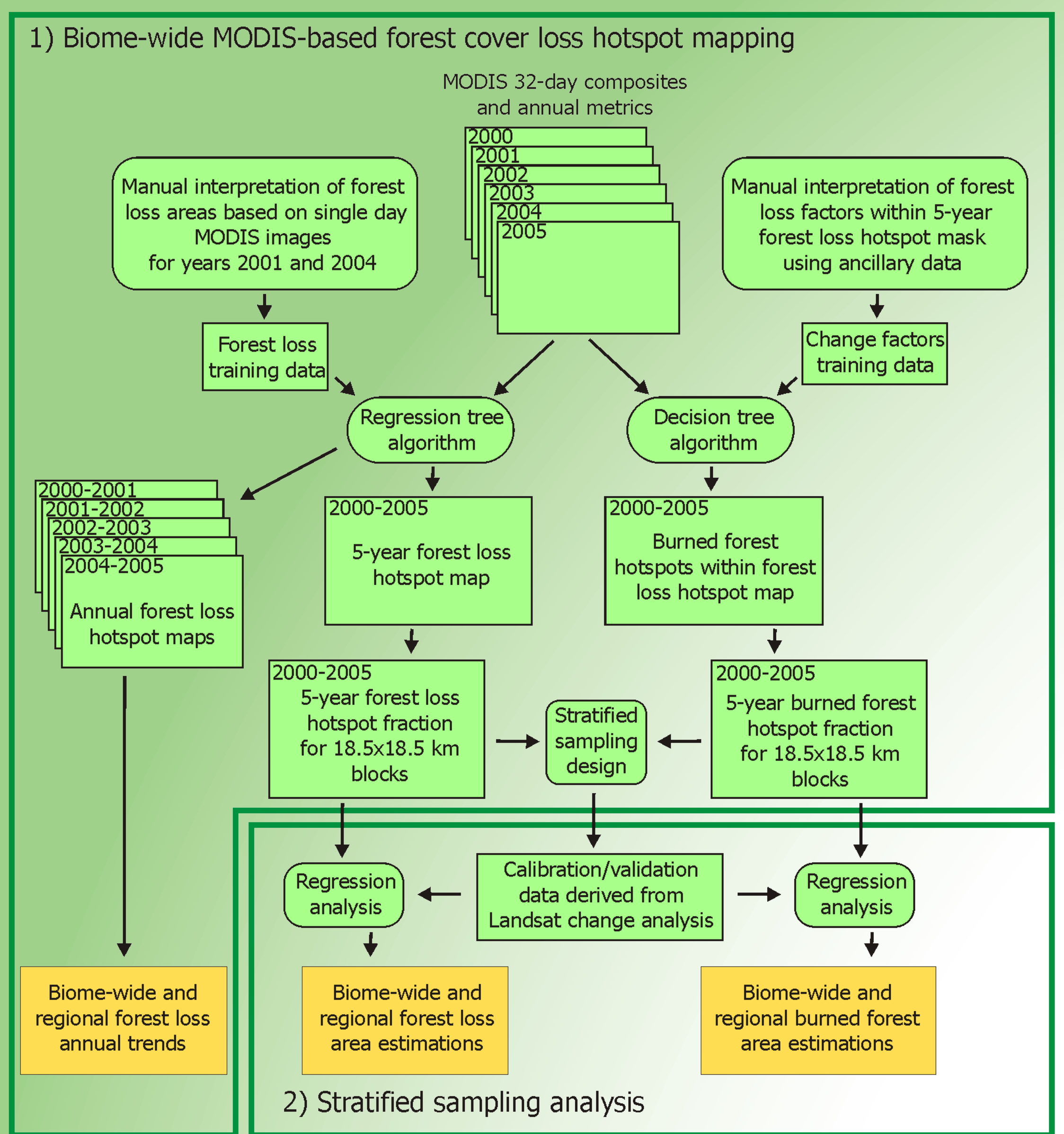
Estimation of forest cover change is important for boreal forests, one of the most extensive forested biomes, due to its unique role in global timber stock, carbon sequestration and deposition, and high vulnerability to the effects of global climate change. We used MODIS time-series data to produce annual forest cover loss hotspot maps. These maps were used to partition the boreal biome into strata of high, medium and low likelihood of forest cover loss using 18.5x18.5 km sample blocks. A stratified random sample of 118 blocks was interpreted for forest cover and forest cover loss using Landsat imagery from 2000 and 2005.

Area of forest cover gross loss from 2000 to 2005 within the boreal biome is estimated to be 1.63% (standard error 0.10%) of the total biome area. This translates to an estimated forest loss area of 35.1 Mha (s.e. +/-2.2 Mha) and represents a 4.02% reduction in year 2000 forest area. The proportion of identified forest cover loss relative to regional forest area is much higher in North America than in Eurasia (5.63% to 3.00%). Of the total forest cover loss identified, 58.9% is attributable to wildfires. The MODIS pan-boreal change hotspot estimates reveal significant increases in forest cover loss due to wildfires in 2002 and 2003, with 2003 being the peak year of loss within the 5-year study period.

Overall, the precision of the aggregate forest cover loss estimates derived from the Landsat data and the value of the MODIS-derived map displaying the spatial and temporal patterns of forest loss demonstrate the efficacy of this protocol for operational, cost-effective, and timely biome-wide monitoring of gross forest cover loss.

Data and Methods

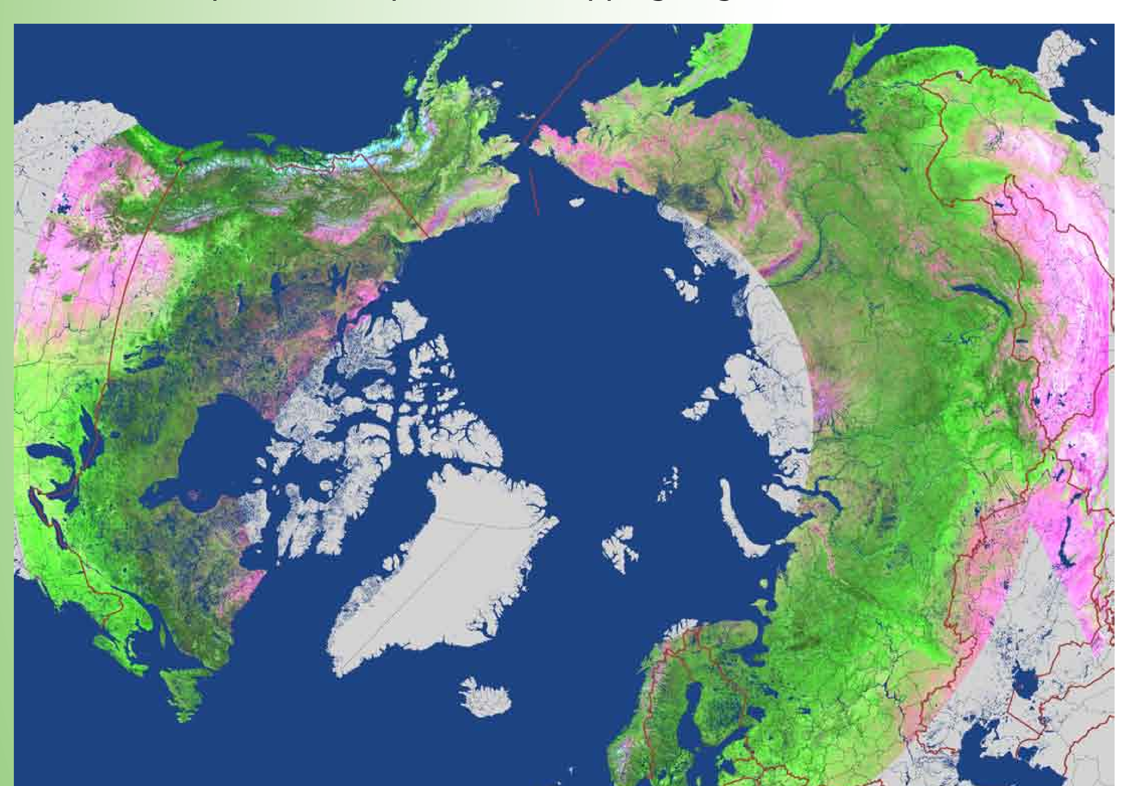
The biome-based forest cover loss analysis workflow included two main parts: (1) biome-wide MODIS-based forest cover loss hotspot mapping, (2) stratified sampling and analysis of Landsat imagery to estimate forest loss area.



1) MODIS-based forest cover loss mapping

A. MODIS imagery

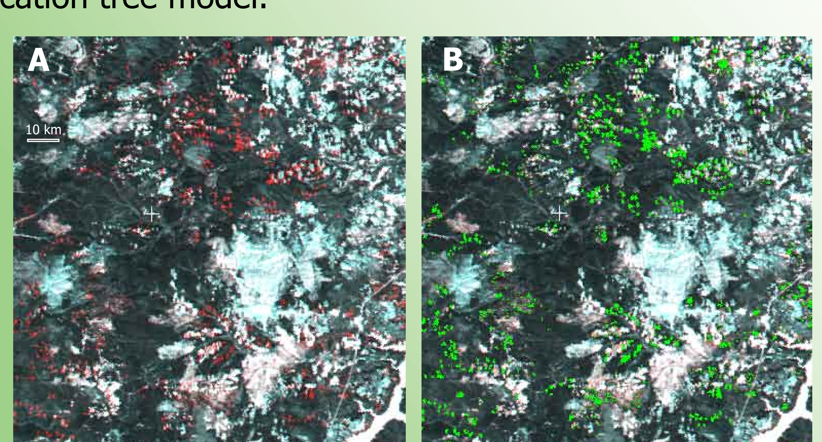
The MODIS/Terra visible and infrared bands (1-7) surface reflectance 8-Day L3 global 500m (MOD09A1) composites along with Land Surface Temperature/Emissivity 8-Day L3 global 1km product for years 2000-2005 were used as the primary inputs to our analysis. The initial 8-day composites were combined into 32-day composites that were subsequently transformed to multi-temporal annual metrics that capture the salient points of phenological variation by calculating means, maxima, minima and amplitudes of spectral information. Metrics have been shown to perform as well or better than time-sequential composites in mapping large areas.



Color composite made using mean value of 3 monthly composites corresponding to 3 highest NDVI values for band 1 (Red), 2 (NIR), and 7 (SWIR). This composite illustrates the ability of annual metrics to produce cloud-free, internally consistent image inputs that facilitate regional-scale mapping.

B. MODIS data analysis

The primary goal of the MODIS-scale analysis was to create a wall-to-wall biome-wide forest cover loss hotspot map to enable the stratification of the area for sampling. This was achieved using a regression tree approach. Regression tree models derived using training data from 2000 to 2004 were applied to all interannual intervals. To create training data, pairs of single date MODIS images for March, years 2001 and 2005, were classified using a supervised classification tree model.

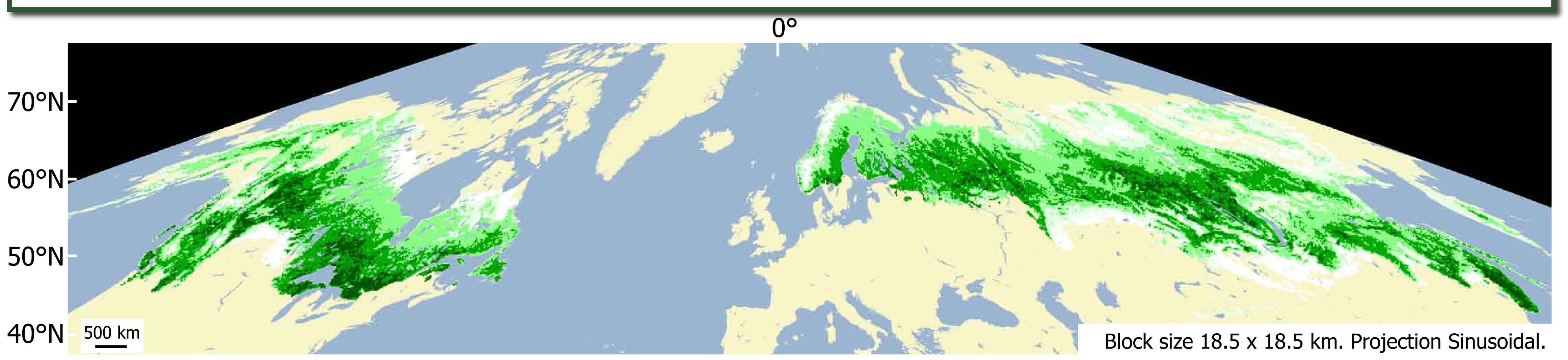


Example of a MODIS training site (Angara River, Russia).

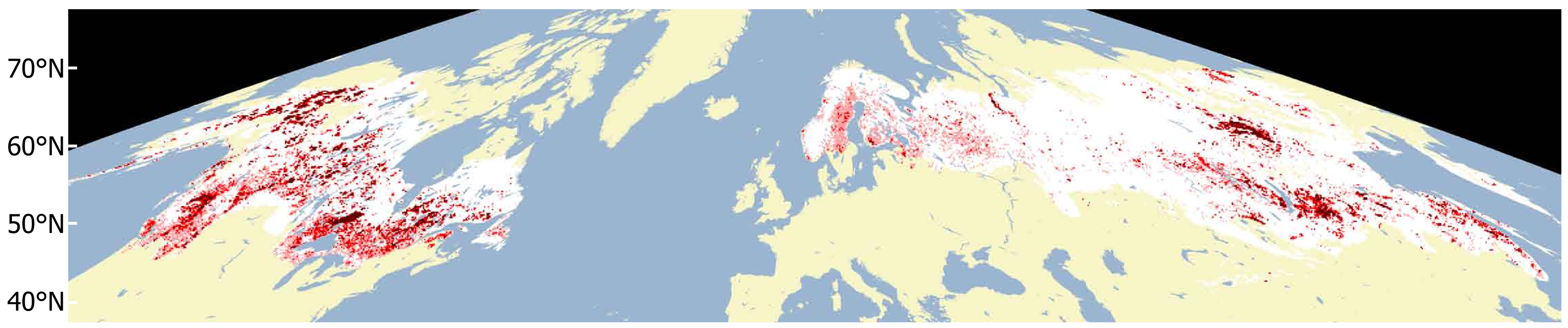
A. Multi-temporal MODIS image (NIR bands) for 2001 and 2005 years (red color reveals logging areas);

B. Change detection results (green mask) over MODIS image.

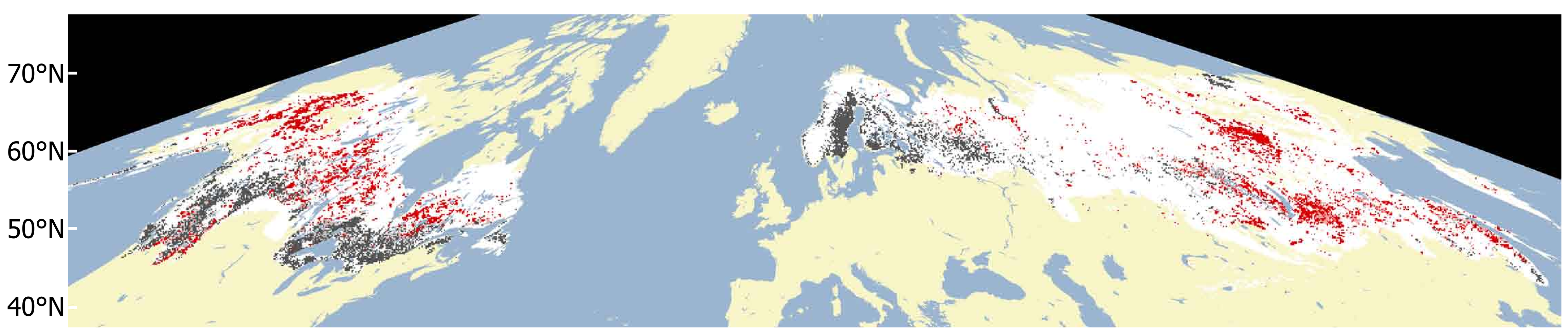
The final interannual forest loss detection results for the 2000-2005 interval were thresholded to produce the forest cover loss hotspot map, while annual results were used for subsequent biome-wide interannual change trend analysis. The forest loss hotspot map was used to calculate a MODIS-indicated percent forest loss value for each 18.5x18.5 km block within the biome. These data were input to the stratified sampling design. Additionally, MODIS hotspots were classified into forest cover loss due to wildfire and due to other forest loss factors. The analysis of change factors employed a decision tree classification based on an extensive training set that was manually created from available ancillary information.



Year 2000 forest cover percent per block: <10% | 10-25% | 25-50% | 50-75% | >75%



Forest cover loss 2000-2005 percent per block: <1.5% | 1.5-5.0% | 5.0-10.0% | >10.0%



Burned forest percent of forest cover loss area per block: <25% | 25-50% | 50-70% | >75%
(only within blocks with forest cover loss above 1.5%)

2) Stratification and Landsat data analysis

A stratified sampling design was implemented as a precision enhancing feature, directing the sample allocation to areas likely to exhibit change (Tab. 1). A stratified random sample of 118 blocks 18.5 km per side was interpreted for forest cover, forest cover loss and forest change type using high spatial resolution Landsat imagery from 2000 and 2005. A separate regression estimator employing MODIS change hotspot fraction was used to estimate Landsat-derived forest area loss for the high and medium change strata (Strata 3 and 4).

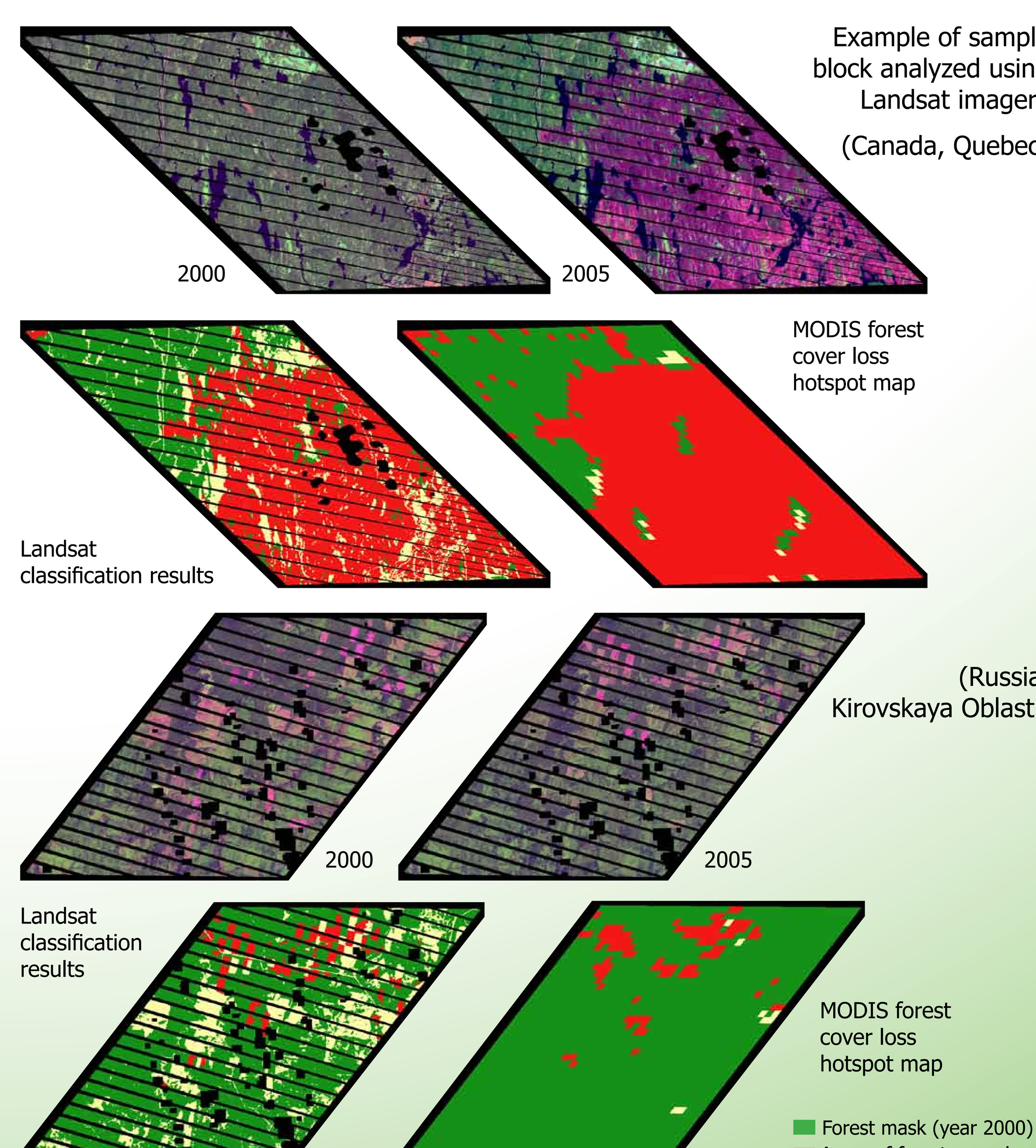
Table 1. Stratified sampling design

Stratum	MODIS-derived forest canopy loss	Standard deviation of forest canopy loss, %	Number of blocks within biome	Number of blocks sampled
1	0 - 0.25%	0.0655	43,968	25
2	0.25 - 1%	0.210	7,357	25
3	1 - 6%	1.345	7,886	25
4	> 6%	11.415	3,414	43
Total			62,625	118

Within the original strata 1 and 2, post-stratification was implemented to partition blocks into 8 post-strata representing areas of near zero change and areas of some change. The post-stratification employed road density and VCF tree cover data. The sample means were calculated to estimate change per each post-stratum.

3) Interannual trends

To analyze temporal trends, we disaggregated the change depicted by the 5-year forest loss hotspot map by identifying the year of maximum forest cover loss within the set of 5 annual intervals. Taking into account the fact that the most important inputs for change detection within the regression tree models were for the growing season (June-August), our results reflect annual intervals from August of the preceding year to August of the following year.



Results

1. Forest cover and forest cover loss area estimate

The extent of the boreal biome used for the change analysis was 2,150.9 million hectares (Mha). Boreal forest extent was estimated to be 872.3 Mha for year 2000. Based on the Landsat sample blocks, the area of forest cover loss from 2000 to 2005 within the boreal biome is estimated to be 1.63% (standard error 0.10%) of the total biome area. This translates to an estimated forest loss area of 35.1 Mha (s.e. +/-2.2 Mha) and represents a 4.02% reduction in year 2000 forest area. Of the total area of forest cover loss, 77.4% occurs in the region consisting of strata 3 and 4, which constitutes only 18.0% of the biome area. This illustrates the presence of forest cover loss hotspots associated with intensive industrial logging and wildfires.

Forest cover loss is distributed unevenly within the biome (see central figure). The largest forest loss areas occurred within regions of intensive logging operations (southern parts of Ontario, Québec and British Columbia) and of large-scale wildfires (Northern Canada, Alaska and Eastern Siberia). Our results emphasize the difference in forest cover loss between North America and Eurasia (Tab. 2). While North America and Eurasia contribute approximately equally to the total area of forest loss in the biome, the forest area lost expressed as a percent of the biome area in North America is nearly twice that of Eurasia. For the largest countries within the boreal biome, the area of forest loss expressed as a percent of the biome area in Canada is twice that of Russia. The higher forest loss in North American boreal regions could be explained by extensive wildfires and high intensity logging operations in the southern part of the boreal forest biome in Canada.

Table 2. Forest cover loss area 2001-2005 for the continents and selected countries within the boreal biome.

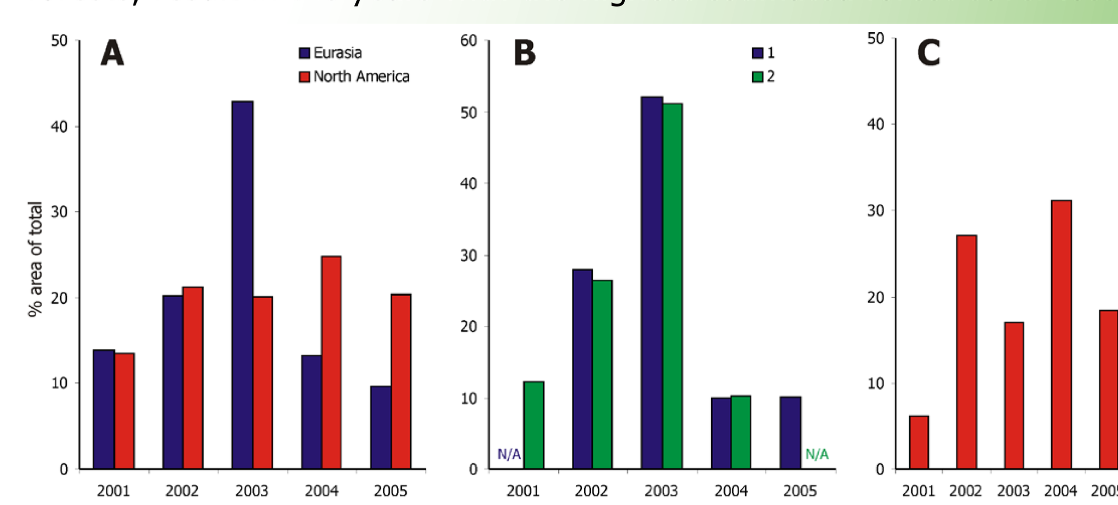
Region	Within-region forest cover loss as percent of land area (s.e.)	Within-region forest cover loss as percent of year 2000 forest area	Percent contribution of region to forest cover loss in the biome	Percent forest cover loss within the region attributed to fire	Number of blocks sampled
North America	2.44 (0.12)	5.63	54.5	57.9	62
Eurasia	1.17 (0.12)	3.00	45.5	60.0	56
Canada	2.34 (0.15)	5.28	43.7	54.7	50
Russia	1.18 (0.19)	2.91	39.0	65.2	47

2. Burned forest area estimate

Based on sample block analysis, the area of forest cover loss due to wildfires is estimated to be 0.96% (standard error of 0.093%) of the total biome area, or 20.6 Mha (s.e. +/-2.0 Mha). Of the total forest cover loss area, 58.9% was attributed to wildfires and the rest, 41.1%, to other disturbances, including logging, wind and snow damage, and insect outbreaks. Fire plays an equal role in forest loss in North America and Eurasia, but the proportional contribution of fire to forest loss is higher in Russia compared to Canada.

3. Interannual trend of forest cover loss

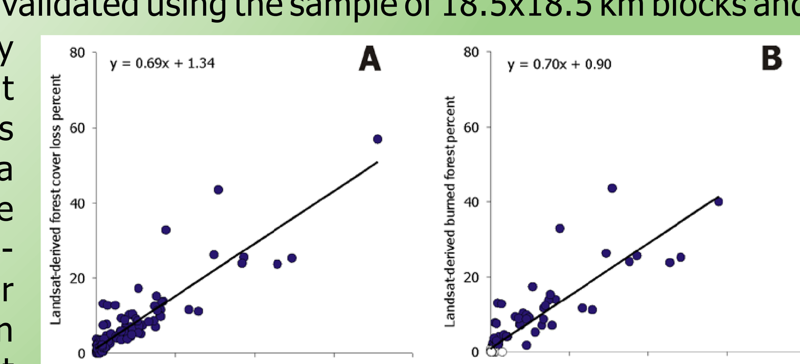
The pan-boreal interannual distribution of MODIS forest cover loss showed a significant increase of forest loss for 2002 and 2003, with a subsequent decrease. Our results illustrate interannual differences in forest cover loss for North America and Eurasia. The comparison of our results with existing data on interannual burned areas revealed that fire is the most important forest loss driver in the boreal biome. For Eurasia, we used the compilation of official data for 2001-2004 and annual aggregation of the MODIS active fire detection product (Achard et al. 2007) for comparison. Both our and external datasets illustrate a significant increase of forest loss due to wildfires in East Siberia for 2002 and 2003, followed by a subsequent decrease in forest loss. A comparison of interannual forest loss hotspot trends for North America was made with the annual forest area burned dataset for Canada (National Forestry Database Program, 2007). In North America, the fire seasons of 2002 in central Canada and Québec, and of 2004 in the Alaska-Yukon boreal forests, result in the years with the highest estimated forest cover loss.



A. Annual distribution of total 5-year forest cover loss hotspots area within boreal biome (separately for Eurasia and North America). **B**. Annual distribution of total burned forest area in Russia: 1 – Total area of fire-affected pixels from MODIS active fire product, 2002-2005 (Achard et al., 2007); 2 – Official forest burned area data compilation, 2001-2004 (Achard et al., 2007). **C**. Annual distribution of total forest area burned in Canada, 2001-2005 (NFDP).

4. MODIS product validation results

The unadjusted MODIS-derived forest cover loss hotspots and burned forest fraction were validated using the sample of 18.5x18.5 km blocks and the independently derived Landsat values of forest loss and burned area fraction as reference data. The MODIS-based forest cover loss hotspot fraction has an estimated root mean square error (RMSE) of 2.53%, the mean absolute error (MAE) of 1.08% and an R^2 of 0.75. For the MODIS-derived burned forest area fraction, the comparison to the Landsat values resulted in an estimated RMSE of 2.24%, MAE of 0.54% and an R^2 of 0.75.



Plot of Landsat-derived versus MODIS-derived forest cover loss (**A**) and burned forest (**B**) percent per sample block (n=118 sample blocks)

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