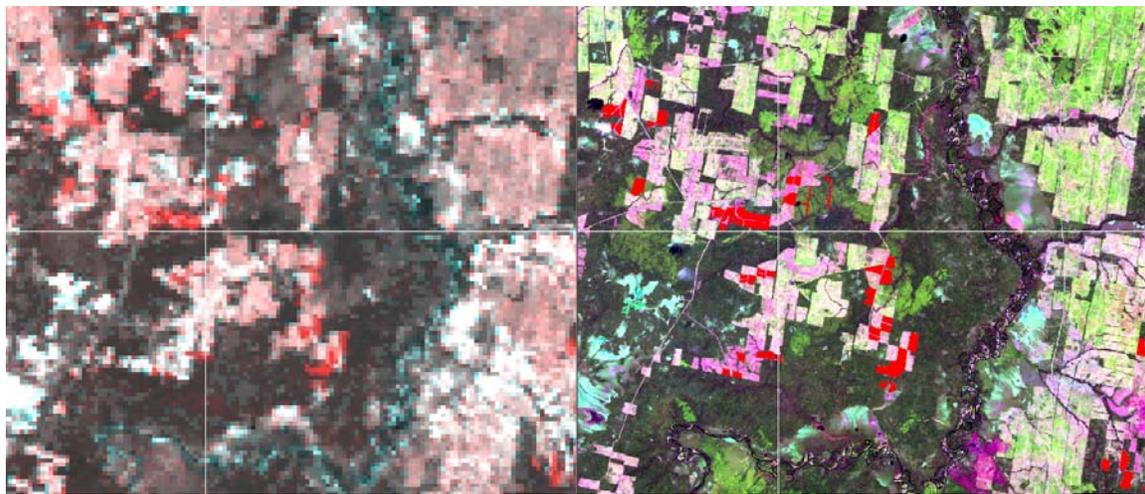


**Feasibility study on the use of medium resolution satellite data for the
detection of forest cover change caused by clear cutting of coniferous forests
in the northwest of Russia**

Report



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in the northwest of Russia**

Report

prepared by

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Abstract

This feasibility study examines possibilities of identifying and mapping of clear cuts in the boreal coniferous forests of north western Russia based on satellite imagery of medium spatial resolution (MRSR).

Different image products obtained from the MODIS and MERIS sensors were visually examined in order to assess their suitability for clear cut detection. MODIS images of 250 m spatial resolution from the years 2001 and 2002 were ultimately selected as the main data source for change analysis. The study compares different detection and mapping approaches, including (i) visual interpretation using principal components, (ii) unsupervised digital classification and (iii) a combination of image differencing and textural analysis, defining statistical thresholds for the identification of clear cuts.

The results show that the detection of clear cut locations is feasible by each approach, provided that the size of the clear cut is larger than about 15 ha.

For mapping and area estimation the digital approaches are considered more efficient. The best mapping result was achieved based on the combination of image differencing and textural analysis. However, the mapping accuracy is affected by omission and commission errors, mainly caused by the limited spatial resolution of the imagery and by slight geometrical location shifts between different acquisitions. Also atmospheric and seasonal effects can influence the reliability of change indications. Based on a set of reference clear cut areas, delineated from Landsat TM imagery, the best mapping accuracy achieved was at about 65 %.

Abbreviations

AQUA	EOS-PM satellite (pm = afternoon pass)
CV	Coefficient of Variation
ENVISAT	Environmental Satellite (ESA)
EOS	Earth Observation System (NASA Satellites)
ERDAS	Image Processing Software, registered trademarks of ERDAS, Inc., US.
ESA	European Space Agency
ETM	Enhanced Thematic Mapper (sensor on LANDSAT 7 satellite)
FLEGT	Forest Law Enforcement, Governance and Trade
ha	Hectare (s)
HRSD	High Resolution Satellite Data (10 - 30 m spatial resolution)
IUCN	International Union for Conservation and Nature
LANDSAT	Series of NASA earth observation satellites
MD	Mahalanobis Distance
MERIS	Medium Resolution Imaging Spectrometer (sensor on ENVISAT)
MIR	Middle Infrared Band
MODIS	Moderate Resolution Imaging Spectroradiometer (sensor on EOS satellites)
MRSD	Medium Resolution Satellite Data (150 m - 500 m spatial resolution)
NAP	Northern Dimension Action Plan
NASA	National Aeronautics and Space Administration
NIR	Near Infrared Band
NDVI	Normalized Difference Vegetation Index
PC(A)	Principal Component (Analysis)
SD	Standard Deviation
TERRA	EOS-AM satellite (am = morning pass)
TM	Thematic Mapper (sensor on LANDSAT 4-5 satellites)

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1 BACKGROUND AND OBJECTIVES

The study has been conducted in the context of JRC's activities on monitoring and assessing ecosystem sustainability (ISA 222), more specifically under the GVM action on 'Terrestrial ecosystem monitoring in EU development-assistance priority regions' (TEM 2221).

The objective of the study is to examine the feasibility of identifying and monitoring of forest clear cuts in the boreal forests of north western Russia, based on satellite imagery of medium spatial resolution (MRSD). MRSD combines the advantages of daily acquisition and large area coverage, with low cost and a spatial resolution (250 m - 500 m) deemed to be sufficient for detecting forest cover changes caused by clear cutting. MRSD could therefore help to cope with the issue of monitoring the huge extent of boreal forests in Eurasia.

With about 850 million ha Russia has the largest forested area of the world. Forest cover is reported to have increased between 1990 and 2000 [1]. The forest cover (stocked area) was estimated in 2000 at about 722 million ha. With about 550 million m³ of timber the official annual cut of the year 2000 reached only about 27 % of the (sustainable) allowable cut [2]. Large parts of Russian forests are so called 'reserve inaccessible forests', where exploitation is limited also for economical reasons. The exploitable growing stock is mainly located in the northern European and the Asian part of Russia [3]. In the European part of Russia forests occupy about 169 million ha, with about 65 % of coniferous forests and about 35 % of broadleaved forests [4]. The intensive logging of valuable old-growth coniferous forests in these accessible areas has raised concerns about the long-term sustainability and intactness of the boreal forest ecosystem in specific regions [5, 6]. But also illegally logged and traded timber has become an issue, causing environmental as well as economic damage. The share of illegally logged wood in Russia is estimated to amount at least to 20 % [7]. For north western Russia the share of illegal wood might be even higher than 30 % [8]. Regular monitoring of the huge forested areas of Russia is therefore of vital interest and considered a key requirement for achieving the nation's goals of sustainable development and for providing transparency to the different actors in the forestry sector [9].

The sustainable management and protection of these forests is also of European interest. The forests in the northwest of Russia comprise about 44 % of Europe's forests, they are an important reserve of carbon and contain still a large portion of undisturbed forests [4]. The EU is encouraging the sustainable development of the forest resources in the huge neighbouring country, recognizing the forest's role for biodiversity, for timber production and as a stabilizing factor in the context of global climate change. This co-operation is reflected in the Northern Dimension Action Plan [10]. Russia is further considered a 'key region' in the scope of the FLEGT Action Plan [11], aiming to combat illegal logging. The northwest of Russia is the largest supplier of round-wood to the EU.

The main issues addressed in this study are

1. can clear cuts be sufficiently identified and mapped from MRSD?
2. can one obtain useful estimates for the total clear cut area?
3. which type of imagery, spectral bands and processing can be recommended?
4. are sufficient cloud-free images available?
5. can MRSD contribute to an operational forest monitoring system?

2 GEOGRAPHICAL AREA, FOREST TYPES, FOREST MANAGEMENT

The study concentrates on the coniferous forests of the Taiga in the European part of Russia, which are partly still classified as intact forest landscape. Coniferous forests represent the natural para-climax forest ecosystem of the region, they also make a big contribution to the EU round wood imports from Russia (e.g. [8]).

The test region covers parts of the Arkhangel'sk and Komi Oblast (province), including parts of the districts Pinezhskiy, Udorskiy, Vinogradovskiy, Verkhnetoyemskiy, Krasnoborskiy and Lenskiy; most of the forests in these provinces are production forests (Fig. 1, Tab. 1). In spite of its large size, the test area corresponds only to a limited portion of an original full path MRSD acquisition (Fig. 2). The choice of a larger area was restricted by the frequent cloud cover and by the requirement of concentrating to the path centre in order to avoid large viewing angles (see chapter 5.1.3).

The study further focuses on forest cover change caused by clear cutting and therefore on mature (coniferous) forest stands. Clear cutting is the common forest harvesting practice in the coniferous forests of north-western Russia, leaving most of the land for natural regrowth of forests. The monitoring of selective logging is not the scope of this study.

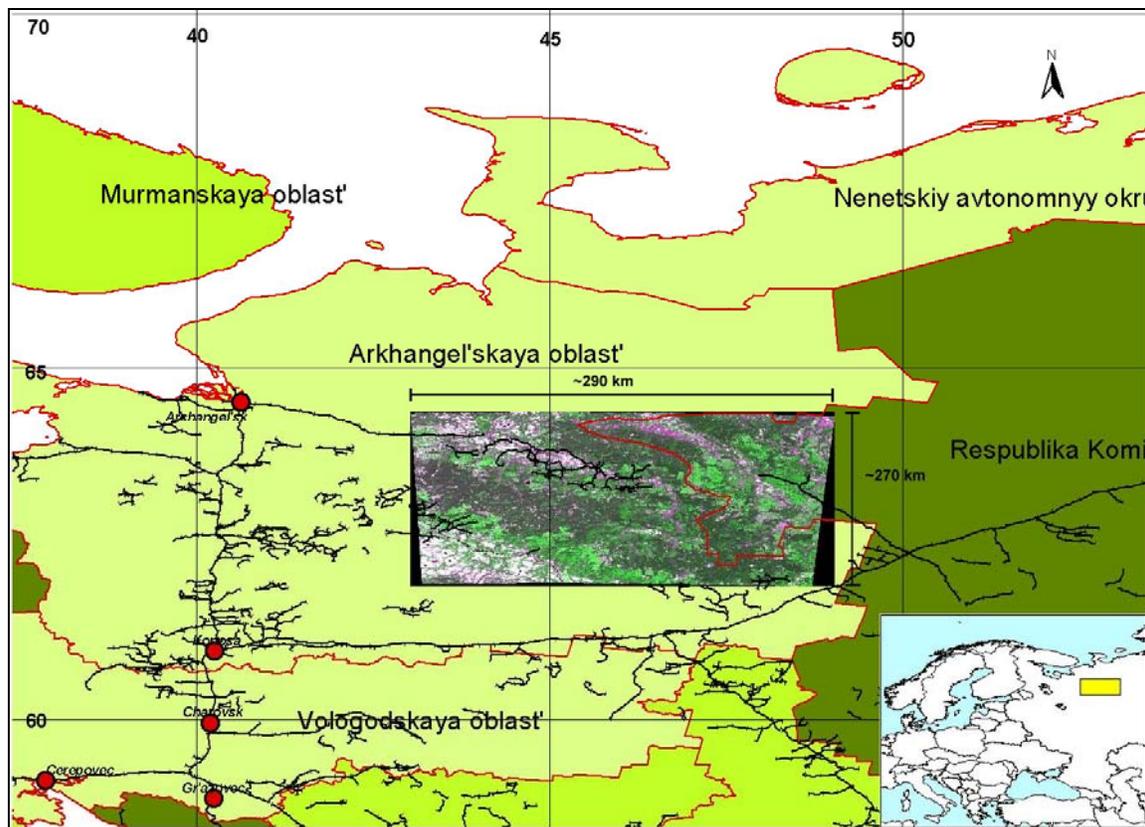


Figure 1. Location of test region: MODIS image overlaid on administrative map (lat/long; Mercator Projection).

Table 1. Test region characteristics

Area extent	about 290 km x 270 km, ~ 79000 km ²
Coordinates	43°01'04"E - 48°42'59"E; 61°53'13"N - 64°21'47"N (UTM, Zone 38, x : 404793 m - 695293 m; y : 6867189 m - 7138939 m)
Forests characteristics	<ul style="list-style-type: none"> • spruce dominated coniferous forests • classified as production forest • stem wood volume: 101 m³/ha -150 m³/ha [6] • mean site productivity 1 m³/ha - 2 m³/ha • classified as intact forest landscape [6]

3 SATELLITE IMAGERY

Table 2 gives an overview on the satellite imagery used for this study.

The medium resolution satellite data (MRSD) was almost exclusively acquired from the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor on the TERRA (EOS AM) satellite, launched by the US in 1999. A first image could also be obtained from the new European MERIS sensor on the ENVISAT satellite, launched in 2002. However, because of haze we could only perform a first visual comparison to the MODIS data. The main characteristics of the two MRSD sensors are given in the tables 3 and 4. Table 5 provides more detail on the different MODIS products used in the study. An example for the full area coverage of the original MODIS swath product is displayed in Fig. 2.

The Landsat TM / ETM images of the years 2001 and 2002 were used as reference data sets.

Table 2. Satellite imagery used

Sensor	Date	Spatial resolution	Orbit / Tile
MODIS (TERRA satellite)	11. 07. 2001	250 m & 500 m	MOD02: Swath product
	12. 06. 2002	250 m & 500 m	MOD09: V02 / H20
	14. 05. 2003	250 m	
	04. 08. 2004	250 m	
	28. 04. 2001	250 m	
	06. 05. 2004	250 m	
MERIS (ENVISAT)	02. 07. 2003	300 m	Path: 6989, Track 422
TM / ETM (Landsat 5&7)	11. 07. 2001	30 m (15 m B & W)	Path: 174 Row:16
	12. 06. 2002		

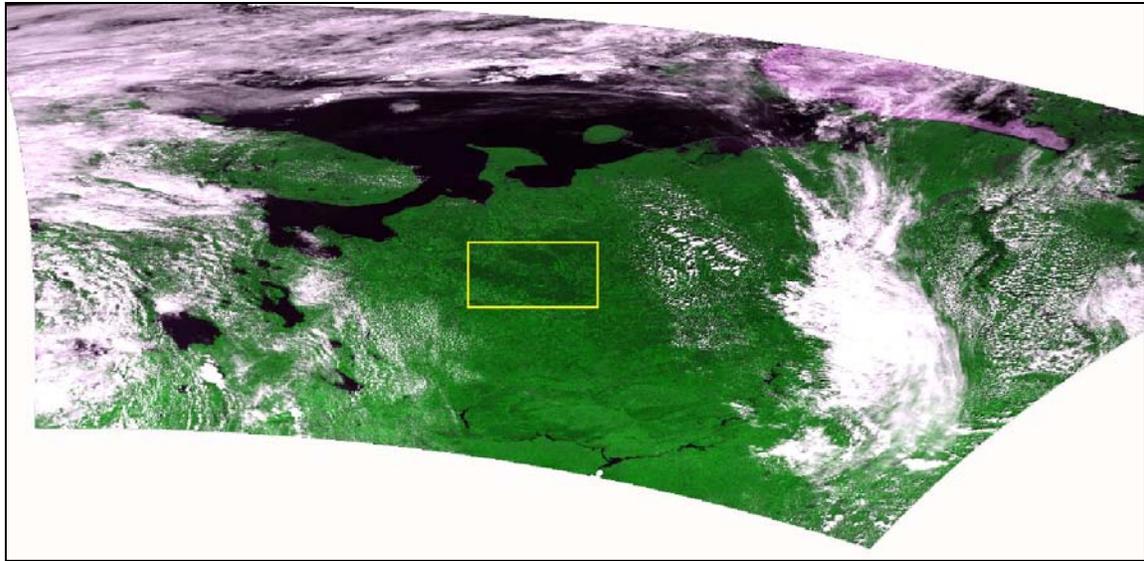


Figure 2. MODIS MOD02QKM full single path product, 11 July 2001, geographical projection (test region = yellow rectangle).

Table 3. Characteristics of MODIS sensor (EOS) [12]

Orbit:	705 km, Terra-satellite descending node 10:30 am; (Aqua satellite ascending node 1:30 pm), full coverage of earth every 1-2 days, sun-synchronous, near-polar, circular
Swath width:	2330 km (cross track)
Quantization:	12 bits
Spatial resolution:	250 m (bands 1 - 2), 500 m (bands 3 - 7), 1000 m (bands 8 - 36)

Spectral Bands:					
Band	Bandwidth (nm)	Band	Bandwidth (nm)	Band	Bandwidth (nm)
1	620 - 670	13	662 - 672	25	4482 - 4549
2	841 - 876	14	673 - 683	26	1360 - 1390
3	459 - 479	15	743 - 753	27	6535 - 6895
4	545 - 565	16	862 - 877	28	7175 - 7475
5	1230 - 1250	17	890 - 920	29	8400 - 8700
6	1628 - 1652	18	931 - 941	30	9580 - 9880
7	2105 - 2155	19	915 - 965	31	10780 - 11280
8	405 - 420	20	3660 - 3840	32	11770 - 12270
9	438 - 448	21	3929 - 3989	33	13185 - 13485
10	483 - 493	22	3929 - 3989	34	13485 - 13785
11	526 - 536	23	4020 - 4080	35	13785 - 14085
12	546 - 556	24	4433 - 4498	36	14085 - 14385

Table 4. Characteristics of MERIS sensor (ENVISAT) [13]

Orbit:	800 km, local time at the descending node: 10:00 am, sun-synchronous, near circular, near-polar (98.5 inclination); 14 orbits / day, repeat period 35 days		
Swath width:	1150 km (cross track)		
Spatial resolution:	300 m (at nadir)		
Spectral Bands:			
Band	Band centre (nm)	Band width (nm)	Potential Application
1	412.5	10	Yellow substance and detrital pigments
2	442.5	10	Chlorophyll absorption maximum
3	490	10	Chlorophyll and other pigments
4	510	10	Suspended sediment, red tides
5	560	10	Chlorophyll absorption minimum
6	620	10	Suspended sediment
7	665	10	Chlorophyll absorption, chlorophyll fluorescence reference
8	681.25	7.5	Chlorophyll fluorescence peak
9	705	10	Chlorophyll fluorescence reference, atmosphere corrections
10	753.75	7.5	Vegetation, cloud
11	760	2.5	O ₂ R- branch absorption band
12	765	5	O ₂ P- branch absorption band
13	775	12.5	Atmosphere corrections
14	865	10	Atmosphere corrections
15	890	10	Vegetation, water vapour reference
16	900	10	Water vapour, land

Table 5. Characteristics of MODIS products used in the feasibility study [12]

Product	Product description
MOD02QKM MODIS/Terra Calibrated Radiances 5-Min L1B Swath 250 m	MOD02QKM data set contains calibrated and geo-located at-aperture radiances generated from MODIS Level 1A scans of raw radiance (MOD 01). The radiance units are in $W \cdot m^{-2} \cdot \mu m^{-1} \cdot sr^{-1}$. This is the 250 m resolution product for bands 1 and 2.
MOD02HKM MODIS/Terra Calibrated Radiances 5-Min L1B Swath 500 m	MOD02HKM contains calibrated and geo-located at-aperture radiances generated from MODIS Level 1A scans of raw radiance (MOD 01). The radiance units are in $W \cdot m^{-2} \cdot \mu m^{-1} \cdot sr^{-1}$. This is the 500 m resolution product for bands 3 to 7.
MOD03 MODIS/Terra Geo-location Fields 5-Min L1A Swath 1km	The geo-location product (MOD03) contains the results of geo-location processing which are used by higher-level MODIS processes.
MOD09GQK MODIS/Terra Surface Reflectance Daily L2G Global 250 m SIN Grid	MOD09GQK is computed from the MODIS Level 1B land bands 1 and 2. The product is an estimate of the surface spectral reflectance for each band as it would be measured at ground level if there were no atmospheric scattering or absorption. A correction scheme reducing the effects of atmospheric gases, aerosols, and thin cirrus clouds is applied to all pixels passing Level 1B quality control.
MOD09Q1 MODIS/Terra Surface Reflectance 8-Day L3 Global 250 m SIN Grid	MOD09Q1 is a composite of the previous 8 daily products (MOD09GQK), which maintain the native 250 m resolution in bands 1 and 2. The best observations during an 8-day period, as determined by overall pixel quality, observational coverage, and minimum 500 m Band 3 value, are matched geographically according to corresponding 250 m.

4 METHODOLOGY

All available MRSD satellite image products of the years 2001 to 2004 were screened ‘on-line’ in order to select good quality imagery and to address questions of image suitability, seasonality, geometry and image availability.

From the large number of change detection approaches described in literature (e.g. [14]) we selected the following for testing the potential of MRSD for the assessment of forest change within the time period 2001- 2002:

- (i) visual interpretation of changes,
 - (ii) straightforward unsupervised digital classification,
 - (iii) image differencing and definition of statistical change thresholds, combining change vector and textural change analysis.
- (ad i) From an operational point of view the visual interpretation of MRSD might offer a simple possibility for a rapid identification of clear cut patterns over large geographical areas. Such an approach might be of interest as an ‘early warning’ component in the context of an advanced forest monitoring system.
- (ad ii) The straightforward unsupervised classification was chosen as an easy approach of digital classification and area assessment, providing an indicative estimate on the total clear cut area.
- (ad iii) Change detection by image differencing and combining of change vector and textural change analysis was considered a more demanding option in terms of time and data processing. However, the mapping accuracy is expected to be higher than for the simple unsupervised classification approach.

Due to the limited availability of MERIS imagery all testing was done for MODIS data only.

4.1 Preparation of data set and image pre-processing steps

All MODIS data were freely available and downloaded from the MODIS server [15]. The study is mainly based on single-path MOD02 imagery of the years 2001 and 2002; a data set of 2004 was used as an additional reference. MOD02 images require additional processing and re-projection, which was performed by using the corresponding MOD03 geo-location products and the ‘MRT-Swath tool’ provided by USGS [16].

In order to avoid spectral effects from differing viewing angle (θ), we selected MOD02 images of identical orbits and geometrical properties. The image area used was further restricted to the central part of the swath in order to avoid large viewing angles (θ in the range of -16° and 2°).

The images were re-projected to an UTM projection (zone 38, WGS84 ellipsoid) for the test region.

A standard haze removal procedure (*ERDAS De-haze*) was applied to the MOD02 images in order to reduce the impact of haze apparent in some image parts. The algorithm is based on a tasselled-cap transformation and removes the spectral component that correlates with haze.

Due to the high spectral similarity of Landsat TM and MODIS bands, we used the transformation coefficients established from Landsat TM bands [17]. The procedure of de-hazing included (i) the creation of a six-band stack from the re-projected MOD02HKM (500 m) and MOD02QKM (250 m) products, containing the bands Blue₅₀₀, Green₅₀₀, Red₂₅₀, NIR₂₅₀, MIR1₅₀₀ and MIR2₅₀₀ as input to the *Dehaze* module, and (ii) the re-extraction of the de-hazed Red₂₅₀ and NIR₂₅₀ bands from the stack. An additional haze mask (mask_haze) was created manually for areas where the impact of haze could not be completely removed. These zones, located at the edges of the test region, were excluded for final area calculations.

The Landsat TM/ETM images of 2001 and 2002, obtained of the same date than the MODIS imagery, were accordingly re-projected to UTM parameters.

A ‘clear cut reference data set’ for the time period 2001-2002 was established by visual identification and delineation of clear cuts from the Landsat imagery within the MODIS overlap area. The reference data set was used for (i) the calculation of the statistical values and thresholds for change detection and for (ii) testing the accuracy of the different methods.

The principal components (PC1 and PC2) were calculated for the MODIS images of 2001 and 2002 using a standard utility (*ERDAS*).

4.2 Visual interpretation of principal component

The visual interpretation of the MODIS imagery was based on a principal component analysis (PCA). We calculated for the MOD02 data sets of 2001 and 2002 the principal components (PCs), using for the year 2002 the ‘de-hazed’ data set. The first principal components of each data set were extracted and combined to one single data set ‘PC1₂₀₀₁₋₂₀₀₂’. Clear cuts were then visually interpreted and compared to the reference clear cuts: when a reference clear cut was visually ‘recognized’ it was considered a successful identification.

4.3 Unsupervised digital classification

The PC1₂₀₀₁₋₂₀₀₂ data set was also used for the standard unsupervised classification approach (*ERDAS, Isodata*).

Forest mask for the year 2001

A forest₂₀₀₁ mask was generated by digital unsupervised classification (60 initial clusters) of the original MOD02 2001 image. The mask was established by extracting those clusters representing mature forest cover classes: (i) Coniferous forest cover, closed canopy, (ii) Coniferous forest cover, open or disturbed canopy, or with a deciduous component, (iii) Deciduous forest with a coniferous component. Clumps of up to two pixels were eliminated by spatial filtering (*ERDAS Clump & Eliminate*).

Exclusion of clouds and cloud-shadows

As none of the images was completely cloud-free over the test region, clouds and cloud-shadows were excluded by two simple masks, established from the ancillary bands 3 and 4 (Uncertainty Indices) of the MOD02 imagery. The cloud mask (mask_cloud) was generated from MOD02 band 3, identifying dense cloud cover by selecting the digital values 0, 1 and 2 (out of 15). A spatial buffer of 2 pixels was added in order to include adjacent pixels. The cloud-shadow mask (mask_cloud-shadow) was generated from MOD02 band 4, where strong cloud shadows could be extracted by selecting the digital values 3 to 7 (out of 15).

Digital Classification

The unsupervised classification of the PC1₂₀₀₁₋₂₀₀₂ data set was then performed with 60 initial spectral clusters, which were assigned and regrouped by comparing to the Landsat TM imagery to the following three classes:

- (i) Clear cut
- (ii) Potential clear cut (spectral change not only due to clear cuts)
- (iii) Other (no change & non-forest)

Single pixels and isolated pixel pairs were removed by a standard spatial filtering process (*ERDAS Clump & Eliminate*).

Based on a 3 x 3 kernel contiguous groups of pixels were identified, taking all eight neighbours of a pixel into account. Then single pixels and pixel pairs were assigned to the adjacent larger contiguous pixel group, based on a focal majority filter.

Further analysis concentrated only on those areas included in the mask forest₂₀₀₁, i.e. those areas considered forest in 2001. The classification result was compared to the reference clear cut layer (polygons) and to the Landsat TM image. A polygon was labelled 'identified' if a portion of the reference area was classified as 'clear cut' on the MODIS data set. Estimates on the mapping accuracy were obtained as described below (see Chapter 4.5). An estimate for the total clear cut area in the test region was derived.

4.4 Image differencing, change vector and textural change analysis

From the range of techniques available [14] we choose a combination of change vector analysis in the red-NIR feature space and textural change detection, following partly a methodology already tested for MODIS imagery [18].

The 'de-hazed' and 'histogram-matched' MOD02 images from 2001 and 2002 served as input for calculating the 'Difference Images₂₀₀₂₋₂₀₀₁' used for further analysis.

In the process of change vector analysis two different forest masks (= pixel selections) were used:

Forest Mask_{MD}

The forest mask included all pixels considered forest in 2001 as well as in 2002. The mask served only for calculating from the target image (Difference Image) the statistical parameters needed to establish the thresholds of change from forest to non-forest.

In order to perform this 'forest' pixel selection (masking) means and standard deviations were calculated from the pixel values of the clear cut reference areas in the original image of 2001 (i.e.

forest in 2001). Then all pixels were included if meeting the criteria ‘mean₂₀₀₁ ± 2 sd₂₀₀₁’ for the spectral bands red₂₀₀₁, red₂₀₀₂ and NDVI₂₀₀₁.

Forest Mask_{final}

This forest mask was established in order to select from the target image (Difference Image) those pixels to be used for change mapping. The mask included all pixels which were forest in 2001 and forest or clear cut in 2002. It served mainly for avoiding false forest change indications caused for example by remaining clouds in 2002 or shadows in 2001.

This forest and clear cut pixel selection (masking) was again performed using the statistical parameters (means and standard deviation) derived from the clear cut reference areas from the initial red, NIR and NDVI bands of both years and of the ‘Difference Image₂₀₀₂₋₂₀₀₁’. To be considered for the change assessment, pixel values in the initial bands had to be in the range of ‘mean ± 3 sd’ in all bands. (If ‘mean ± 3 sd’ exceeded the minimum or maximum value calculated from reference plots, then these values were used instead of the ±3 sd threshold.)

The criteria (values) used to define the two forest masks are given in Annex 1.

a) Change vector analysis

The ‘multivariate’ change vector analysis is based on the origin, magnitude and direction of the change vector, defined by the pixel values at time T₁ and T₂ in the two dimensional feature-space of the two MODIS bands.

From the MODIS images of the year 2001 and 2002 the ‘Difference Image₂₀₀₂₋₂₀₀₁’ was calculated, subtracting the corresponding red and infrared bands, respectively.

All pixels included in the Forest_Mask_{MD} were selected in order to calculate the vector of means and the covariance matrix. Based on these statistical parameters we calculated the Mahalanobis distance (MD) for each pixel of the ‘Difference Image’. We used the MD for expressing the magnitude of change because it accounts for the variability and correlation structure of the input bands (contrary to the ‘Euclidian distance’ or the ‘normalized distance’).

The MD thresholds for change can be defined based on the χ^2 distribution at the critical values of $\chi^2_{0.68, 2}$ and $\chi^2_{0.95, 2}$. A change is assumed significant for MD > $\chi^2_{0.68, 2}$, and highly significant for MD > $\chi^2_{0.95, 2}$.

In order to select the change vectors with directions corresponding to changes from forest to clear cut, we calculated the direction θ of the space change vectors from the reflectance values of the red and NIR bands at T₁ and T₂, applying the equations given in literature [18, 19]:

$$\theta = \begin{array}{ll} \theta_0 & \text{If } \Delta\rho_{Red} \geq 0 \text{ and } \Delta\rho_{NIR} > 0; \\ 90^\circ & \text{If } \Delta\rho_{Red} > 0 \text{ and } \Delta\rho_{NIR} = 0; \\ 180^\circ - \theta_0 & \text{If } \Delta\rho_{Red} > 0 \text{ and } \Delta\rho_{NIR} < 0; \\ 180^\circ + \theta_0 & \text{If } \Delta\rho_{Red} \leq 0 \text{ and } \Delta\rho_{NIR} < 0; \\ 270^\circ & \text{If } \Delta\rho_{Red} < 0 \text{ and } \Delta\rho_{NIR} = 0; \\ 360^\circ - \theta_0 & \text{If } \Delta\rho_{Red} < 0 \text{ and } \Delta\rho_{NIR} > 0; \end{array}$$

where

$$\theta_0 = \arctan(\Delta\rho_{Red} / \Delta\rho_{NIR})$$

$$\Delta\rho_{Red} = \rho_{Red}^{time2} - \rho_{Red}^{time1}$$

$$\Delta\rho_{NIR} = \rho_{NIR}^{time2} - \rho_{NIR}^{time1}$$

and

ρ_{Red}^{time1} , ρ_{NIR}^{time1} , ρ_{Red}^{time2} , and ρ_{NIR}^{time2} are the surface reflectance values of the red and the NIR MODIS bands for the images of the years 2001 and 2002, respectively.

The range for θ (vector directions) corresponding to changes from forest to non-forest was established from the values obtained for the reference clear cut areas. The change criteria obtained for MD and θ were ultimately applied to all pixels of the ‘Difference Image’, included in the Forest_Mask_{final}.

We performed the change vector analysis also with an additional image (2001-2004), intending to confirm the first result (2001-2002). In an optimal case the date of the additional data set would have been close to the date of the 2002 image, however, a subsequent image of good quality and suitable geometry parameters was only available for 2004.

b) Textural change detection analyses

In order to add a spatial component to the pure spectral approach we tested also textural change detection.

We applied the coefficient of variation (CV) as a textural measure for change, calculated from the NDVI for T₁ and T₂ within a 3 by 3 kernel [18, 19]:

$$CV = \frac{SD}{Mean}$$

Calculating the difference of coefficients of variation for two dates as $CV_{diff} = |CV_{T2} - CV_{T1}|$, we defined the threshold value for change from the pixel values of our reference clear cut areas.

The textural change analysis was tested for the MODIS image data sets 2001-2002 and 2001-2004.

c) Combination of change vector analysis and textural change detection

The results obtained from the change vector and textural analysis for 2001 - 2002 and from the change vector analysis for 2001 - 2004 were then combined, keeping - as a ‘conservative’ approach - a change indication only if confirmed by all three data sets.

The thresholds for change defined in each individual approach were not chosen too tight in order to avoid the omission of change pixels. These thresholds would therefore not keep the commission errors at the minimum. The reduction of commission errors was aimed for in the subsequent process of combining the results of the individual approaches.

Single pixels and isolated pixel pairs were removed by a standard spatial filtering process (*ERDAS Clump & Eliminate*).

Estimates on the mapping accuracy were obtained as described below (see Chapter 4.5). An estimate for the total clear cut area in the test region was derived.

4.5 Validation of the results and area estimates

We used the clear cut reference layer for estimating the omission error and we compared visually the clear cut mapping result to the Landsat TM / ETM data set in order to estimate the potential commission error.

For the clear cut reference plots the area not correctly classified as ‘change’ was determined and the omission error estimated as:

$$e_{om(\%)} = \frac{\text{pixels not identified as clear cuts} * 100}{\text{total number of pixels}}$$

Within the MODIS / Landsat TM overlap area ‘false’ change indications were identified and the commission error was estimated as:

$$e_{com(\%)} = \frac{\text{pixels erroneously classified as clear cuts} * 100}{\text{total number of pixels classified as clear cuts}}$$

We estimated the overall mapping accuracy (MA), omission error ($e_{all_{om}}$) and commission error ($e_{all_{com}}$) by re-scaling the independently calculated omission and commission errors as follows:

$$e_{all_{om}(\%)} = \frac{e_{om(\%)} * 100}{100 + (e_{com(\%)} * (100 - e_{om(\%)})) / (100 - e_{com(\%)})}$$

$$e_{all_{com}(\%)} = \frac{e_{com(\%)} * 100}{100 + (e_{om(\%)} * (100 - e_{com(\%)})) / (100 - e_{om(\%)})}$$

The mapping accuracy (MA) was estimated as follows:

$$MA (\%) = 100 - e_{all_{om}(\%)} - e_{all_{com}(\%)}$$

The total clear cut area for the test region refers to those areas not affected by remaining haze (mask_haze).

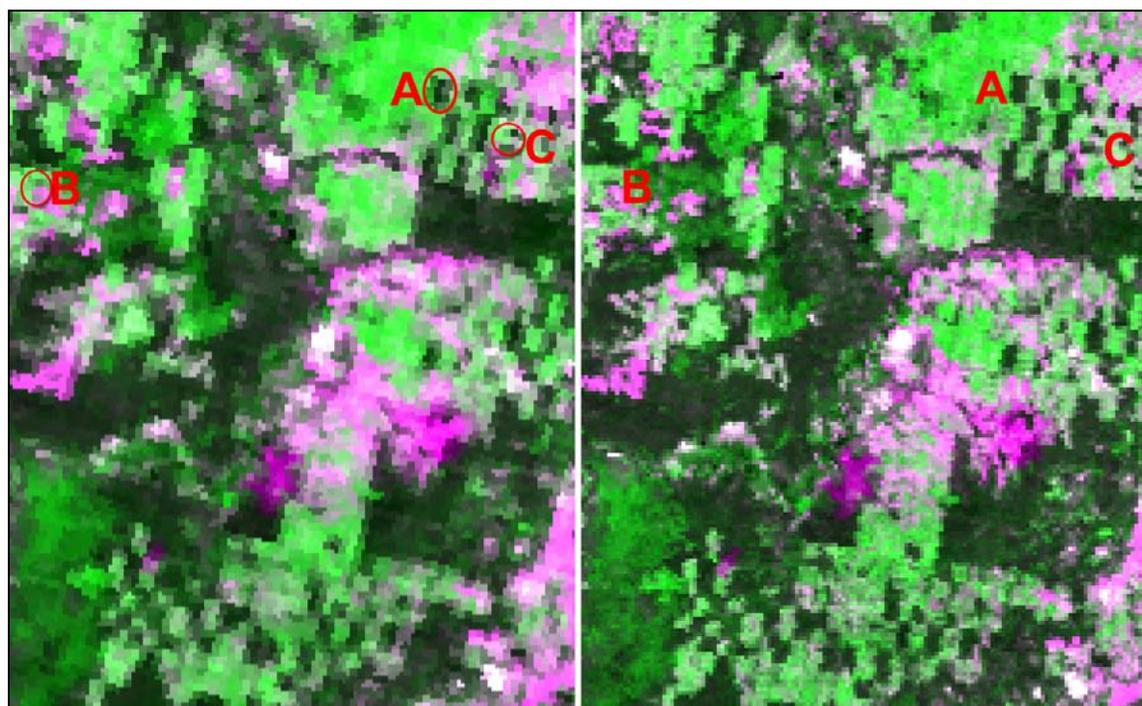
5 RESULTS

5.1 Aspects of image selection: comparison of MRSD products

5.1.1 MODIS: 500 m versus 250 m products

The MODIS sensor provides imagery at 500 meter spatial resolution and at 250 m resolution (two bands). Whilst the general forest / non-forest pattern is reflected in both, the higher spatial resolution provides a significant improvement for the detection of forest lots or clear cuts of typical size (Fig. 3).

Referring to the 500 m spatial resolution (Fig. 3, left), there is a notable impact of edge pixels (blurring) also for large forest lots or clear cuts (~200 ha size), i.e. units much bigger than the usual and legally allowed clear cut size in the northwest of Russia (Fig. 3, A). Small and linear forest patterns of about 20 ha get almost completely lost (Fig. 3, B). But also clear cuts and forest stands sized between 20 ha and 50 ha (= maximum allowable size of clear cuts) cannot be reliably recognized (Fig. 3, C). The 250 m spatial resolution (Fig. 3, right) delivers much more reliable spatial information for clear cut mapping in the region. Due to the distinct contrast between coniferous forest stands and clear cuts, the two available red and infrared spectral bands were found to provide sufficient spectral information for clear cut detection.



----- ~ 38 km -----
Figure 3. Comparison of MODIS satellite data of 500 m (left) and 250 m (right) spatial resolution (forest lots: A ~ 150 - 200 ha; B ~ 20 - 30, C ~ 30 - 50 ha)

5.1.2 MODIS versus MERIS

An in-depth comparison of MODIS and MERIS imagery could not be performed because of the few cloud-free MERIS images available for the test region. Looking for comparable viewing angle conditions, only a small sub-window of one MERIS image was found suitable for a visual comparison.

This visual comparison of the MODIS 250 m and MERIS 300 m product indicates that in terms of spatial resolution one could expect an almost comparable performance of the MERIS imagery (Fig. 4). With 16 spectral bands MERIS might offer some advantage for the spectral analysis, however, we did not further examine spectral bands because of the remaining impact of clouds and haze in the available sub-window. Furthermore, also for MODIS imagery there is the option of integrating additional spectral bands from the 500 m resolution product.

Cost may become a significant factor for operational monitoring. In fact, one may need a large number of images for obtaining a complete cloud free view over NW Eurasia. MODIS images are presently freely available (internet download) whilst MERIS images need to be purchased.

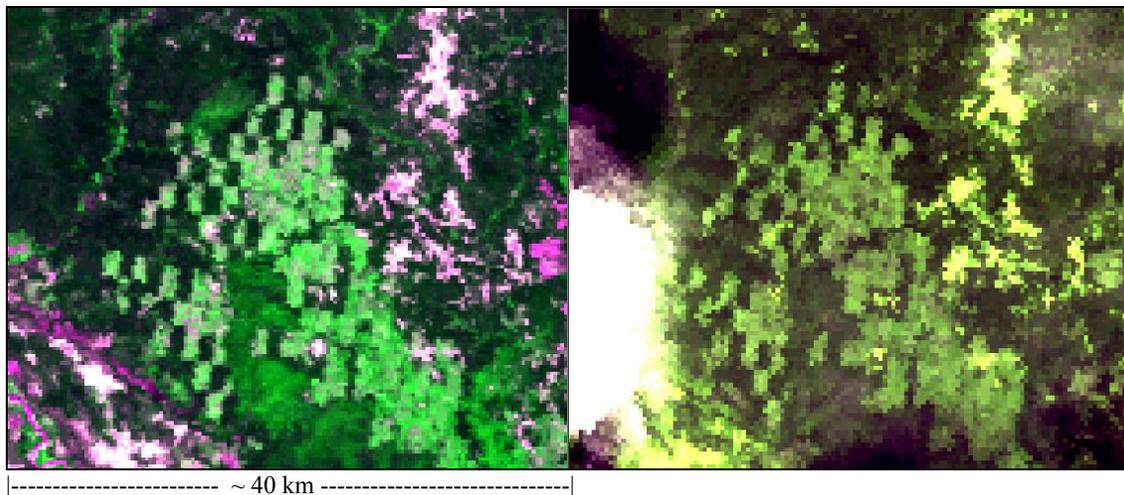


Figure 4. MODIS data (left: date 11. 07. 2001) and MERIS data (right: date 2. 07. 2003), both taken at almost nadir conditions over a small sub-window within the test region (forest = dark or dark green; non-forest = light tones)

5.1.3 MODIS standard 8-day composites, MOD09 and MOD02 single day products

The operationally provided MODIS standard 8-day composites could have been an attractive alternative to single day imagery, if the compositing procedure reduced clouds, haze and shadows. However, the standard 8-day MODIS products were found inferior to good single day MOD09 products, due to presence of pixel gaps and compositing artefacts and due to a loss of spatial detail (Fig. 5).

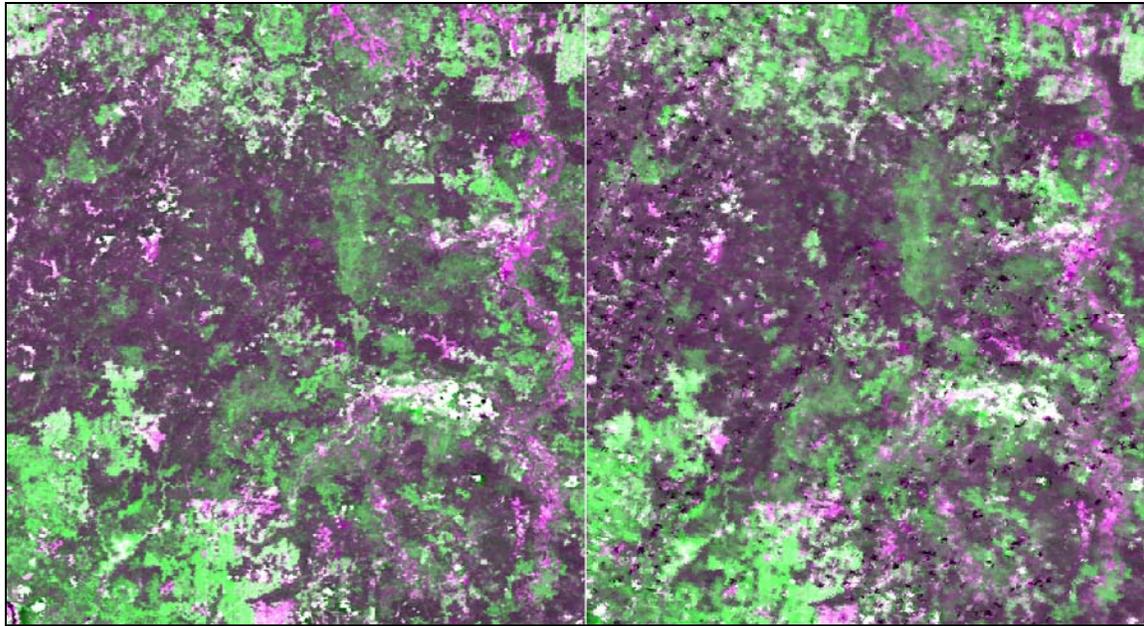


Figure 5. MOD09 single day image (left) from 11 June 2001 and MOD09 8-day composite (right) from 4 -11 June 2001 (coniferous forest cover = dark magenta).

Further compositing of MODIS 8-day products to monthly mosaics did not lead to an improvement (we tested a pixel selection by the minimum value in the near infrared, excluding pixels of high values in the blue band > 1000 and of low values in the near IR band < 500). The compositing over larger time periods is constrained at these latitudes by the impact of seasonality.

Also the single-day MOD09 images proved to be of limited value for the detection of clear cut patterns. Although corrected for atmospheric parameters, these images consist of two to three image tiles, taken from the different orbits of one day. The boundaries of the individual tiles are clearly marked, caused by differing angle conditions of the adjacent pixels from different orbits and resulting in a variation of spatial resolution and of spectral response (Fig. 6, left).

Figure 7 displays the viewing angles for the MOD09 and MOD02 products. For the MOD09 image the transition between tiles is characterized by a change of zenith observation angle from nadir to almost edge conditions (= large viewing angle). It further appears that only the forward looking portion of each orbit is kept: the backward-looking close-to-nadir zones are dropped, in spite of favourable angular conditions (= small viewing angle).

Provided good image acquisition conditions and a concentration to central image parts, the original single path MOD02 products were therefore considered to be the better choice (Fig. 6, right), although some additional processing is required.

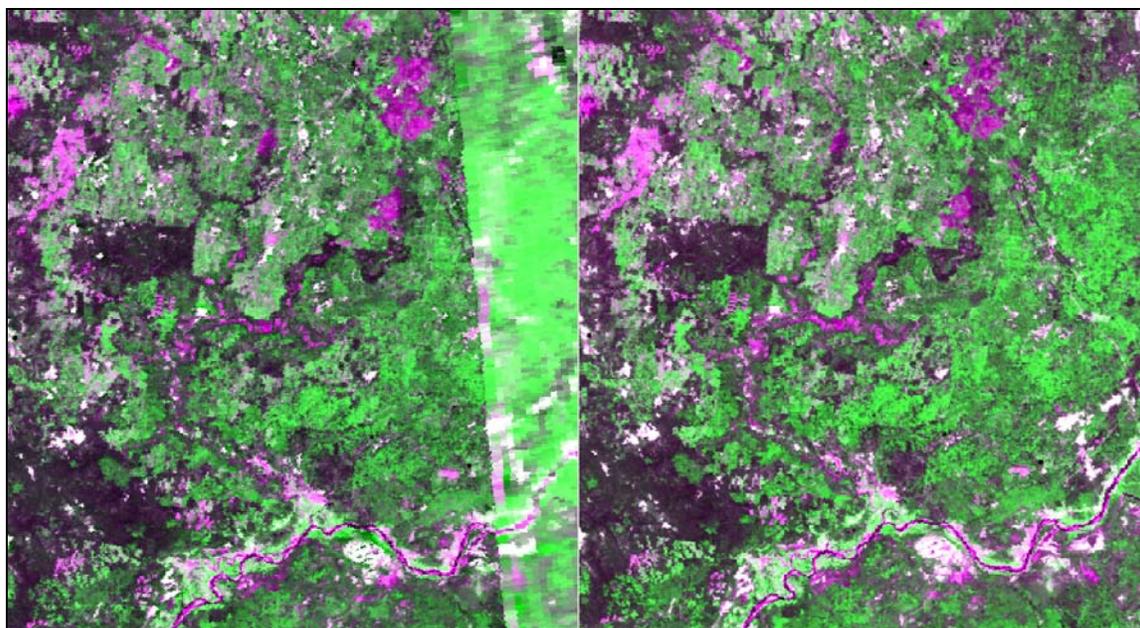


Figure 6. Daily MODIS 09 image (left) and orbit based MOD02 swath image (right) from 1.07. 2001. (coniferous forests = black & dark magenta).

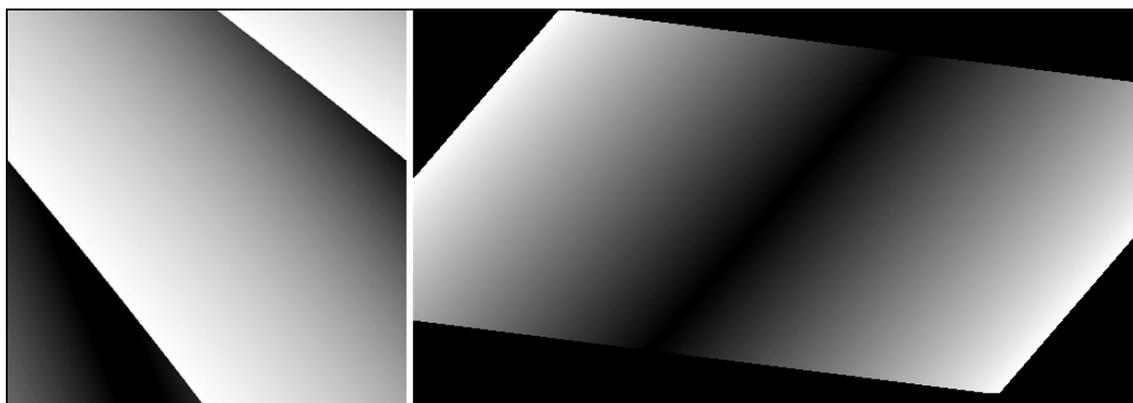


Figure 7. Viewing zenith angles displayed in a MOD09 (left) and in the single path MOD02 image (right); black = close to nadir ($\theta \sim 0^\circ$); bright = off nadir ($\theta_{\max} \sim 65^\circ$).

5.1.4 Seasonality: Winter imagery

At high geographical latitudes vegetation seasonality plays a significant role for the spectral response of vegetation and limits the possibilities of using imagery from different seasons for change detection.

Based on the screening of the MODIS imagery of the years 2000 to 2004, the months from June to September were considered the most suitable season for image selection, because (i) the tree foliage is stable, i.e. potential deciduous vegetation components do not introduce

additional seasonal variations, (ii) daylight illumination and contrasts are good, and (iii) the chances for low cloud cover are higher than for the rest of the year.

However, also winter images (end of April & beginning of May) allow the visual detection of clear cuts in evergreen coniferous forests (*Pinus*, *Picea*), particularly if the forest canopies are free of snow and the non-forest surfaces are still snow covered (Fig. 8). However, for digital change assessment, snow cover proved to be a disturbing factor if only partial and heterogeneously distributed in the image pair used. We therefore recommend imagery of the summer season.



Figure 8. MODIS ‘winter’ image from 6 May 2004 (coniferous forest = dark green & black).

5.1.5 Aspects of image availability, usable image area, viewing angle

By screening through four years of MODIS imagery (2000 - 2004) it became obvious that cloud cover over the northwest of Eurasia may lead to significant restrictions in terms of image availability.

For an annual monitoring of a predefined area, only a few cloud free image pairs of comparable phenological conditions could be found. Opting further for image pairs of comparable geometry (identical orbit) in order to avoid an impact of differing viewing angles (bi-directional effect, resolution), one may find only one or two image pairs for a given location and a specific year.

As image parts acquired at large viewing angles suffer from a notable decrease of spatial resolution and from bi-directional effects (see Fig. 6), it is necessary to focus on the image centres only (e.g. $\theta = 0 \pm 30^\circ$), which leads to a further reduction of the ‘usable area’.

As a consequence, screening for suitable imagery may become a time consuming task. For monitoring of large areas one may need to extract and join sub-windows, taken from different image pairs, each suitable only for a specific area. In fact, for the selected test region only one image pair from the period 2001 to 2002 could be identified which fulfilled all requirements reasonably well, some small image parts still had to be masked because of a remaining cloud and haze impact.

5.2 Visual identification of clear cuts (based on principal component composites)

A visual interpretation of MODIS imagery could offer a quick and simple approach for screening large areas for major clear cuts and could serve as a basic component of an operational monitoring system.

Given the sufficient co-registration of the images of the two dates (≤ 1 pixel) one could perform visual screening based on the simultaneously displayed original images. However, a more efficient approach proved to be the use of a combined data set, such as generated from the first principal components of the two dates. In fact, the band combination R/G/B = PC1₂₀₀₂/PC1₂₀₀₁/PC1₂₀₀₁ was found to highlight quite well the removal of coniferous forest cover and could be used as a basis for the identification of clear cuts (Fig. 9).

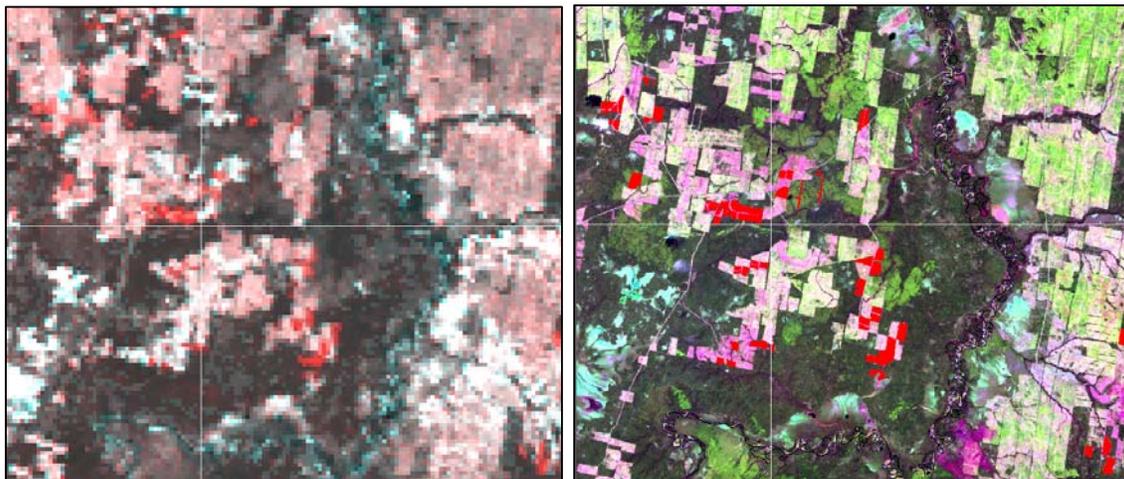


Figure 9. Left: Clear cuts (in red) as displayed in the PC1₂₀₀₂₋₂₀₀₁ composite (R/G/B = PC1₂₀₀₂/ PC1₂₀₀₁/ PC1₂₀₀₁). Right: Reference clear cut polygons (in red) overlaid on the Landsat TM imagery. Coniferous forests = black & dark grey.

Coniferous forest clear cuts of several pixels size could be well identified in all image parts not contaminated by haze.

‘False’ change indications were obtained (see Figs. 10 & 11):

- at edges of forest blocks, where a slight difference of geometry (variation of sensor positions, re-sampling process) could produce false change indications.
- for all areas still affected by remaining clouds and haze in the more recent imagery (in spite of applying a de-hazing processing).

- in some cases for single pixels or small groups of pixels, where change indications were obviously caused by annual variations of vegetation phenology, small clouds or local haze.

Small clear cuts of only one or two pixel size could not be detected consistently (see Fig. 11).



Figure 10. 'False clear cut' indication caused by slight shift of pixel location and forest pattern as a result of slightly differing acquisition parameters and re-sampling.
 UL: MODIS 2001; UR: MODIS 2002, LL: TM 2001, LR: ETM 2002.

Depending on whether after clear cutting all vegetation is removed and the soil unveiled, whether soils are dry or wet, or whether a layer of small trees, shrubs, grass and slash remains, the spectral appearance of clear cuts may vary. This could cause difficulties for the consistent mapping of clear cuts, particularly if occurring in deciduous forest cover. Some problems could also occur if the previous crown cover was already very open or disturbed, or if there was a significant component of deciduous trees. However, for the spruce dominated forests of the test region, we did not experience major problems related to a different spectral appearance of clear cuts.

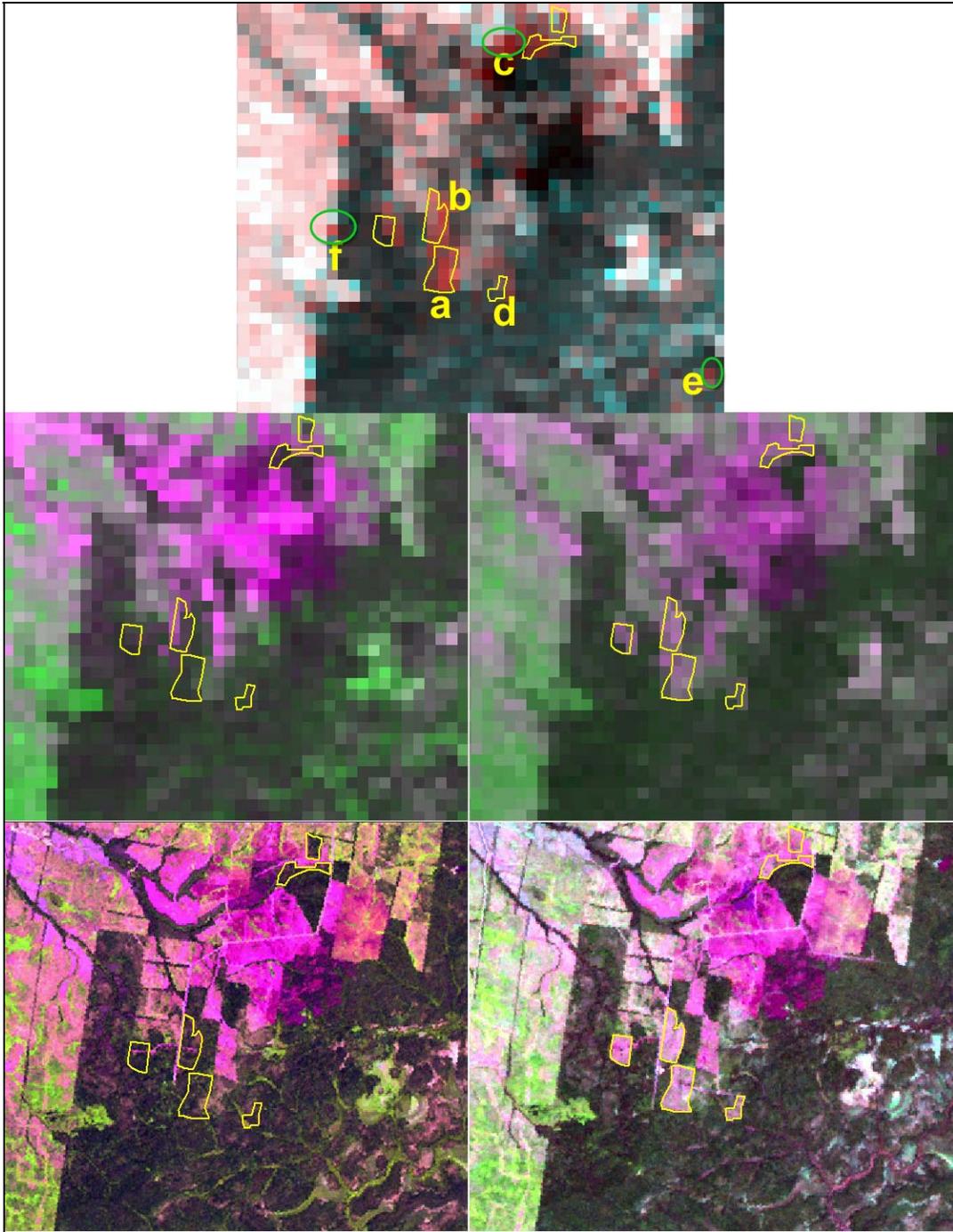


Figure 11. Comparison of $PC1_{2001-2002}$ composite (top) with original MODIS images from 2001 (middle left) and 2002 (middle right) and the Landsat TM imagery from 2001 (bottom left) and 2002 (bottom right). Clear cut indications on the $PC1_{2001-2002}$ composite appear in dark red. The boundaries of the digitized reference clear cuts are overlaid as yellow lines.

Examples:

- a) clear cut (~ 54 ha)
- b) clear cut, canopy disturbance present before clear cut (~ 43 ha)
- c) most probably removal of already disturbed tree cover (green circle)
- d) small clear cut (~ 13 ha), affected by pixel shift
- e) single pixel, false change indication caused e.g. by seasonality (difficult to assess)
- f) single edge pixel, false change indication due to edge effects (green circle)

We examined for each reference clear cut site, whether it would have been visually identified from the PC1₂₀₀₁₋₂₀₀₂ composite, assigning the following labels:

- not identified = 1,
- identified with difficulties = 2,
- identified = 3.

A clear cut was considered as ‘identified’ if the major part of the clear cut area showed a clear spectral indication for change. If the spectral contrast was less distinct or only a small part of the reference polygon was covered, we considered the clear cut as ‘identified with difficulties’. Although the approach is based on a subjective interpretation, it provides an indication on the feasibility of identifying clear cuts.

The results of this visual classification (Fig. 12, Table 6) show the following:

- almost all larger ‘coniferous’ clear cuts (> 15 ha) were recognized;
- problems occur for small ‘coniferous’ clear cuts (< 15 ha) where about one third was not ‘identified’ at all, mainly because of slightly differing image geometry or already existing canopy disturbances;
- problems may occur for coniferous canopies with a component of deciduous trees (mixed);
- clear cuts of deciduous forest stands (red labels), even if large, were not recognized based on the principal component combination used.

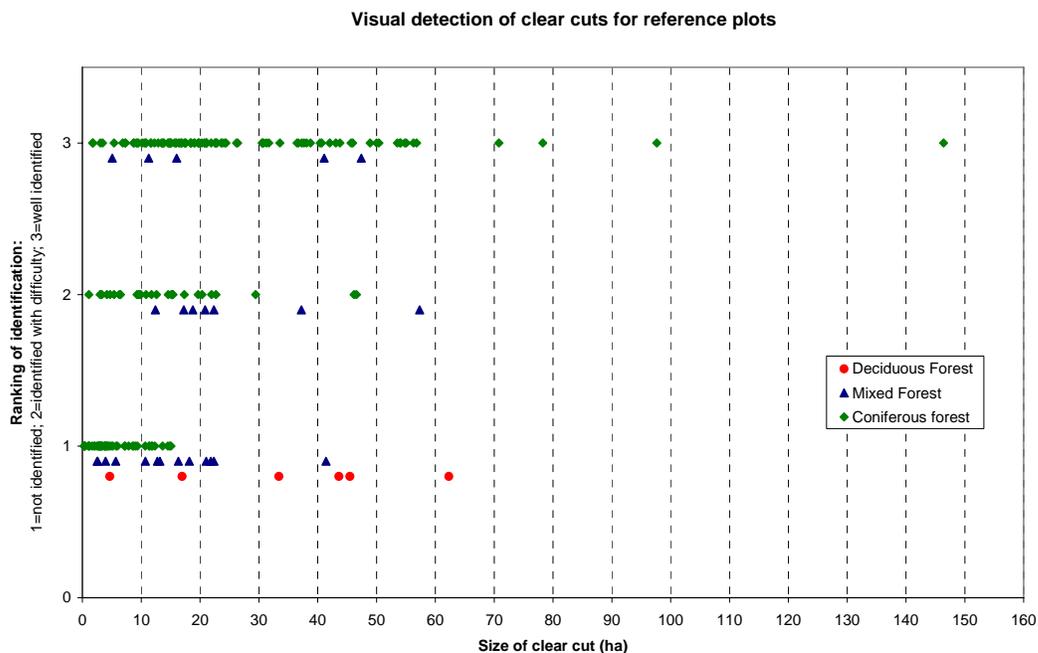


Figure 12. Identification of clear cuts, classified in three categories:
1 = not identified, 2 = identified with difficulties, 3 = identified

In fact, looking at coniferous forest stands larger than 15 ha, almost 90% of the clear cuts were detected (Table 6).

Table 6. Percentage of recognized clear cuts of coniferous forest stands

	Coniferous stands pure	Coniferous stands pure > 15 ha	Mixed stands or disturbed canopies
No of clear cuts:	177	56	25
Identification ranking :			
1 = not identified	28 %	0 %	52 %
2 = identified with difficulties	16 %	11 %	28 %
3 = identified	56 %	89 %	20 %

Table 6 does not reflect potential ‘false’ indications of clear cuts outside of the clear cut reference areas (commission error). When screening across the MODIS PC1 composite, it became obvious that from the spectral point of view a number of signatures might have been interpreted as ‘clear cuts’, although they could not be confirmed as such on the TM imagery. Such ‘false’ clear cut indications often occurred at edges of forest blocks (usually of one pixel width), in still haze affected image parts or were caused for example by small clouds (detectable as accompanied by a corresponding shadow pattern).

In order to avoid such commission errors, change indications visually obtained from the PC1 composite need to be interpreted in the context of the overall forest pattern visible, neglecting clear cut indications (i) of only one or two pixel size (particularly at forest edges), (ii) in non-forest areas, and (iii) in not accessible forest areas. A cross-check to the original image bands helps to reduce interpretation errors.

Taking these precautions into account, the PC1 composite proved to be suitable for identifying clear cut patterns in the coniferous forest of north western Russia.

Detecting clear cuts based on the simultaneously displayed original images was found feasible but less efficient.

We also examined the combination of the two second principal components (PC2_{2001,2002}), which performs for example in the case of clear cuts in deciduous forest stands better than the PC1 composite. However, given the focus on coniferous forest cover, the PC2 composite was considered less suitable, as it indicated similarly changes caused by (i) deforestation, (ii) re-growth or afforestation, (iii) effects of clouds, haze or shadows and (iv) changes within non-forest vegetation.

5.3 Mapping of clear cuts by unsupervised digital classification

The forest mask for the year 2001, generated from the original data by unsupervised digital classification, served for focusing on forested areas of interest only. The forest classification displays the distribution of coniferous forests in the test region, depicting the main clear cut patterns (Fig. 13). About 61 % of the test region is covered by mature coniferous and mixed forests (Tab. 7), neglecting young forest regrowth and other forest land.

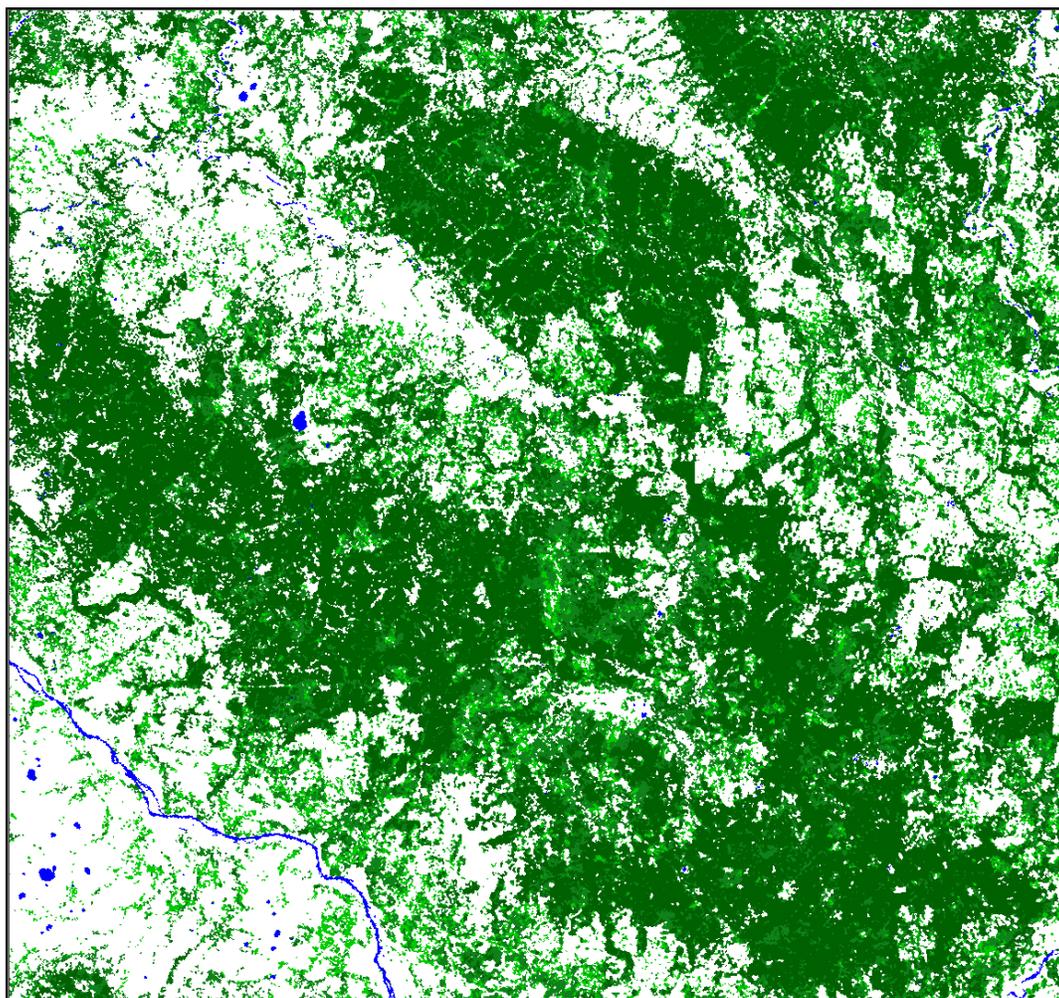


Figure 13: Forest cover of test region (very dark green = coniferous forests, closed canopy; dark green = coniferous forests, open/disturbed canopy or with deciduous component; bright green = deciduous forest with coniferous component; blue = water, burnt areas; white = non-forest)

Table 7: Forest cover area in the test region

Forest / Land cover class	Pixels (Count)	Area (ha)	Area (%)
Coniferous forests, mature, closed canopy	467774	2923588	37
Coniferous forests, mature, open or disturbed canopy or admix of deciduous component	211488	1321800	17
Deciduous forest, mature, with coniferous component	89389	558681	7
Water, Burnt areas	5290	33062	0
Non-Forest, including forest regrowth	491403	3071269	39
Total	1265344	7908400	100

Digital classification of combined principal component data set

We first performed a test with independent unsupervised classifications of the original MODIS images of 2001 and 2002, mapping forest change as the difference of the classified forest areas. However, this change map displayed a large number of small and spatially dispersed ‘false’ clear cuts indications, obviously the result from the independent processes of clustering, classification and subsequent regrouping of the spectral clusters, combining the errors of each process.

We therefore favoured a classification of a combined data set of the years 2001 and 2002. Instead of the (4) original bands we used the two first principal components ($PC1_{2001}$, $PC1_{2002}$) also for unsupervised digital classification. Starting from 60 spectral clusters the following classes were established by regrouping: (i) ‘Clear cut’ (derived from 2 spectral clusters), (ii) ‘Potential clear cuts’ (derived from 3 spectral clusters), and (iii) ‘Other’, including all remaining land cover.

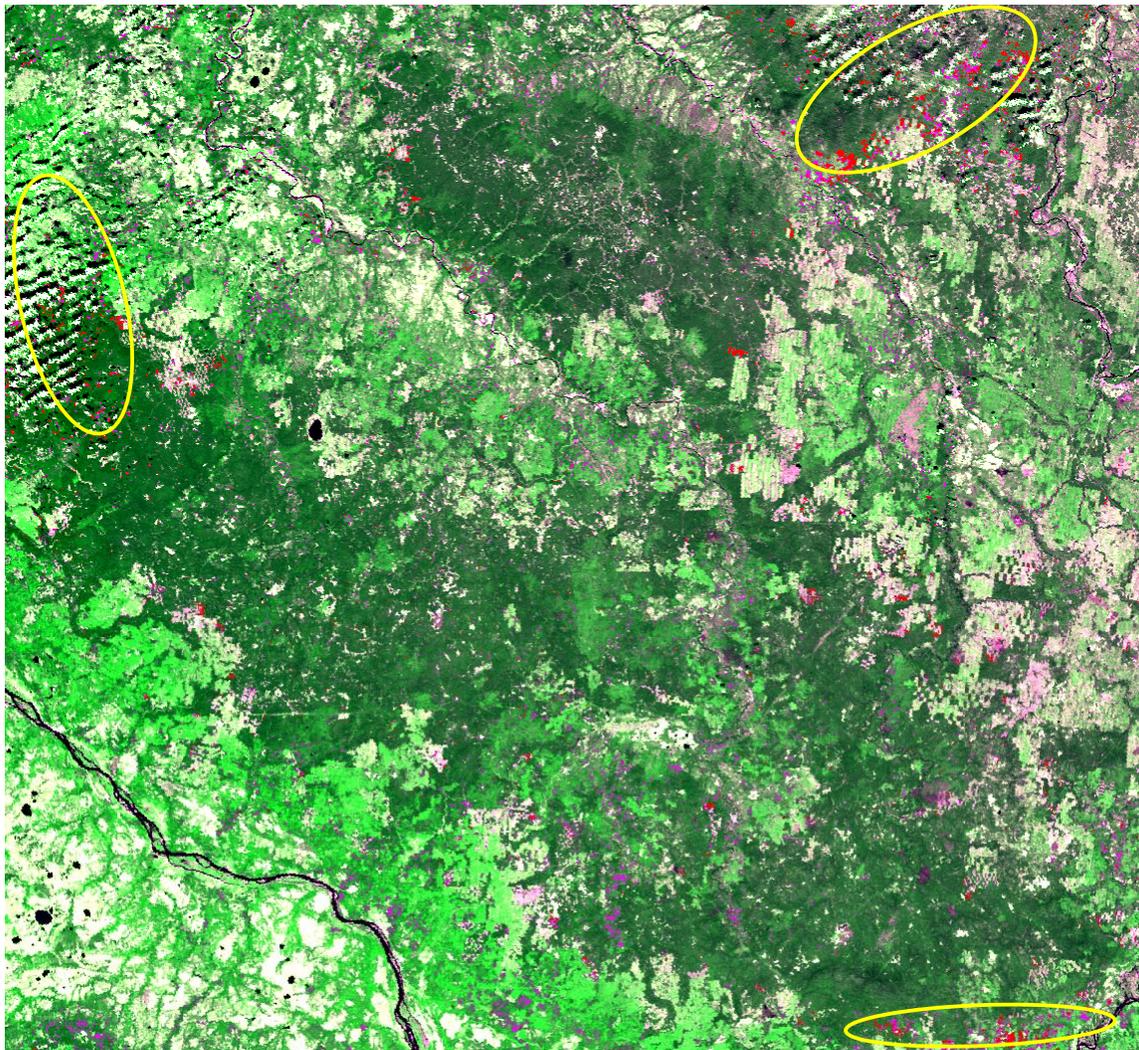


Figure 14. Result of digital change classification, overlaid on original MODIS image from the year 2002: red = clear cut; magenta = potential clear cut.

The class ‘Clear cut’ (= red) corresponded well to clear cut patterns visible in the test region (Fig. 14). The vast majority of the pixels of the class ‘Potential clear cuts’ (= magenta) did not correspond to change on the reference data and the class was not included in the further evaluation.

Within the class ‘Clear cut’ some misclassifications were noted:

- for small areas of one or two pixels size and at the edges of forest blocks, often caused by slight differences in image geometry and by the resampling process,
- for small areas displaying local disturbances, caused e.g. by remaining clouds, cloud shadow, atmospheric and seasonal effects, and by canopy disturbance,
- in haze influenced areas even after ‘de-hazing’ (at the edges of the test region = yellow circles in Fig. 14).

The spatial filtering applied removed the misclassifications of very small size, i.e. single pixels and isolated pixel pairs. The still haze contaminated areas at the edges of the test region were excluded by applying the manually defined haze mask (mask_haze).

Figure 15 shows an example of ‘classified’ clear cuts (see also descriptions of Fig.11).

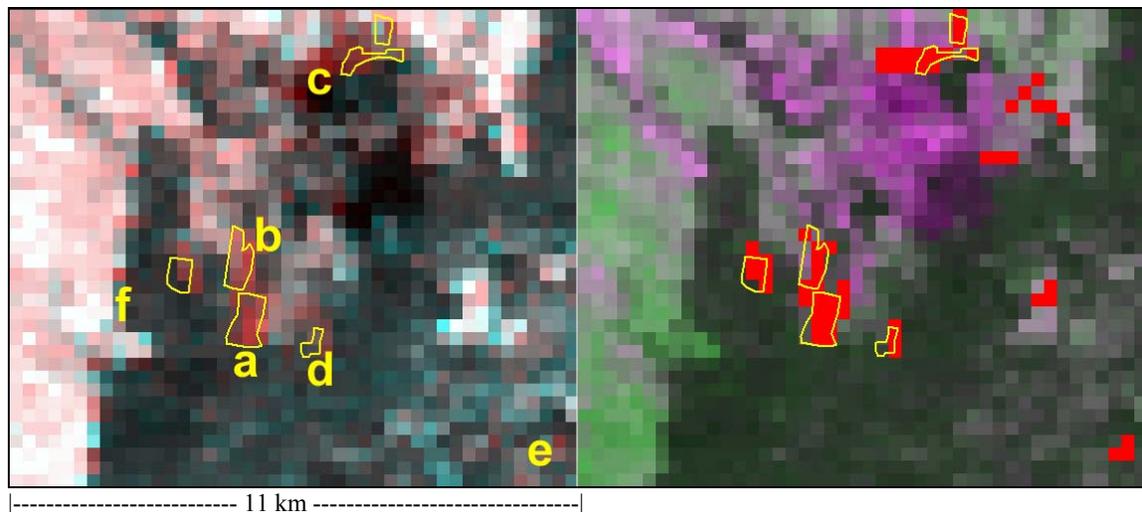


Figure 15. Detail of mapping result: Left: clear cuts as visible from combined PC1 data, overlaid with boundaries of reference areas. Right: Clear cuts (red) as mapped from unsupervised classification, overlaid with boundaries of reference areas (clear cut sizes: a ~ 54 ha; b ~ 43 ha; d ~12 ha).

Identification and mapping of the reference clear cuts

We assessed the potential for *clear cut identification* by comparing to the reference clear cut polygons, considering them as ‘identified’ if a major portion was classified as ‘Clear cut’. As a result, the digital classification would detect about 56 % of the 179 coniferous reference areas, which include pure and disturbed coniferous canopies (Tab. 8). This percentage would rise to about 59 % and 86% when referring to pure stands and pure stands larger than 20 ha, respectively.

Table 8. Percentage of clear cut areas identified by digital classification

	Coniferous stands all	Coniferous stands pure all	Coniferous stands pure ≥ 20 ha	Coniferous stands pure ≥ 50 ha
No of reference clear cuts	179	159	58	12
Identified clear cuts ¹	100 (56 %)	94 (59 %)	50 (86 %)	12 (100 %)

¹ after removal of single, isolated pixels and pixel pairs by spatial filtering

Figure 16 shows graphically that only a few ‘not-identified’ reference clear cuts (= negative values, red bars) are larger than ~15 ha. For the remaining clear cuts, the discrepancy between the classified area (= blue bars) and the reference area (red bars) would reflect the omission error. However, it should be noted that some ‘correctly’ classified clear cut portions are neglected if located outside the reference polygons due to a slight geometrical mismatch.

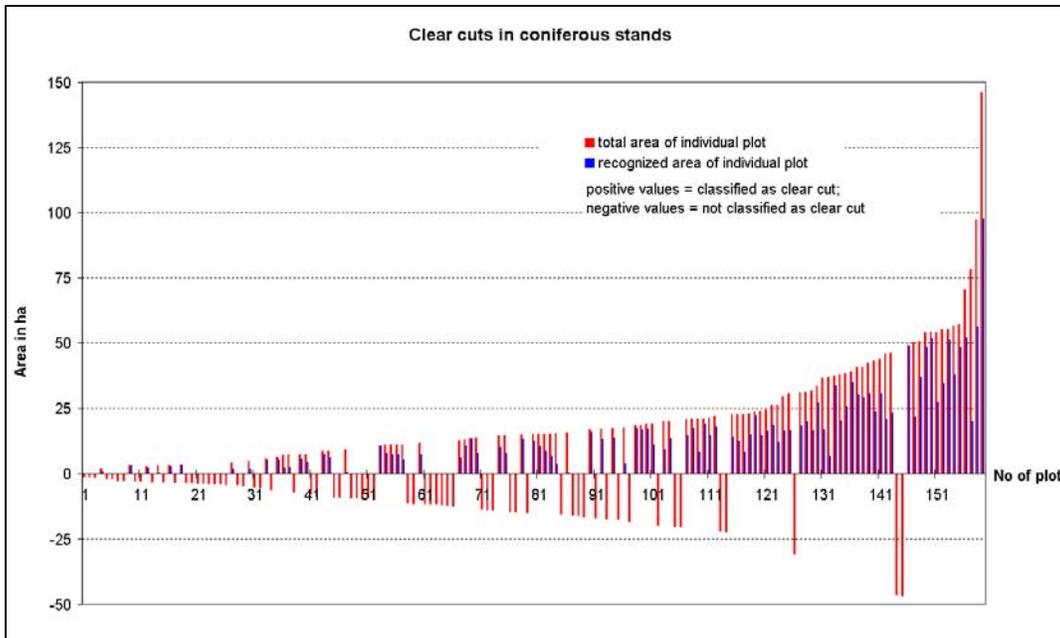


Figure 16. Areas of reference clear cuts (red bars: positive values=identified, negative values=not identified) and of correctly classified portions (blue)

Referring to *clear cut area mapping*, the correctly classified portion ranges between 46 % and 68 % of the total reference area, depending on the category of clear cut size considered (Tab. 9). The total omission error would be about 54 %, and about 45 % if considering only clear cuts larger than 15 ha. The omission error might decrease when accounting for the slight geometrical shift occurring between the classified clear cuts and some of the reference polygons.

However, these figures do not yet reflect commission errors.

Table 9. Classified clear cut area within the reference plots

	Reference clear cut area		Area classified as clear cut ¹	
	no	ha	ha	% of reference
Coniferous stands, all	179	3662	1692	46
Pure coniferous stands	159	3226	1636	51
Pure coniferous stands >15 ha	68	2707	1498	55
Pure coniferous stands >20 ha	58	2251	1316	58
Pure coniferous stands >50 ha	12	828	560	68

¹ after removal of single, isolated pixels and pixel pairs by spatial filtering

Estimating the potential commission error by checking each as ‘clear cut’ classified pixel on the Landsat TM image within the MODIS overlap area, about 32 % of the classified clear cut pixels could not be confirmed (Tab. 10).

Table 10. Agreement and commission errors within the Landsat TM overlap area

	2 pixel removal %
Confirmed change: Forest to clear cut	68.0
Commission error 1: Forest to forest	29.1
Commission error 2: Clear cut to clear cut	2.9

Considering the estimates for omission and commission as representative and integrating them by rescaling, the final mapping accuracy would be estimated at about only 37 % (Tab. 11).

Table 11. Mapping accuracy, commission and omission errors

	2 pixel removal %
Accuracy	37.1
Omission error	45.4
Commission error	17.5

A calculation of the **total clear cut area** - after exclusion of single pixels, isolated pixel pairs and the haze contaminated areas (mask_haze) - would come up with about 9700 ha of clear cut in the coniferous forests of the test region (Tab. 12).

Table 12. Forest and clear cut area figures for test region, excluding deciduous forest stands

	Test region Ha
Total area - not haze influenced	6344700
Forest cover ₂₀₀₁ (mature stands)	3890700
Coniferous forest ₂₀₀₁ (mature stands)	3390800
Classified as clear cut (> 2 pixel)	9700

However, due to the expected omission and commission errors (Tab. 11) the reliability of the clear cut mapping remains moderate. Taking the errors into account the actual annual clear cut area could amount to about 14650 ha. This figure would mainly relate to the coniferous forests and indicate an annual cutting rate in coniferous forests of about 0.4 %.

5.4 Image differencing, change vector and textural change analysis

With multivariate image differencing and setting of statistical change thresholds we aimed at an approach independent from pre-defined forest masks. The thresholds for forest change as well as for any pixel selection would be derived from the statistics obtained from the pixels of the reference clear cut areas only.

We had tested univariate image differencing based on individual spectral bands and linear combinations of the latter. The best results for mapping the clear cut reference areas were obtained by using the original red or the normalized PC1 bands (see Annex 2). The results were influenced not only by the choice of the spectral bands, but also by the choice of the masks applied to derive the statistical parameters Mean and SD. Based on a visual assessment of preliminary mapping results the multivariate approaches appeared to perform better and we did not further evaluate univariate image differencing.

a) Change vector analyses in the red-NIR feature space

Based on the χ^2 distribution of the Mahalanobis distances the significance threshold value for change was set at a value of 2.279: all pixels of the ‘Difference Image’ with a Mahalanobis distance to the vector of means (calculated within $Forest_Mask_{MD}$) equal or bigger than this value were classified as ‘change’ pixels.

Analysing for the Differential Image₂₀₀₂₋₂₀₀₁ the directions of the change vectors obtained from the reference clear cut plots, the range of angles indicating forest change could be defined for the 2001 - 2002 data set as: $\theta < 100^\circ$.

Table 13 displays the change criteria, also for the additional data set of the years 2001 - 2004.

Table 13. Change criteria for change vector analysis

Change Criteria 2001-2002: ‘forest’ to ‘clear cut’	MD > 2.279 ‘AND’ $\theta < 100^\circ$
Change Criteria 2001-2004: ‘forest’ to ‘clear cut’	MD > 2.279 ‘AND’ $\theta < 50^\circ$

Applying these criteria to the data set, the reference clear cut areas were mapped correctly at 84 % for the time interval 2001 - 2002 and 85 % for the time interval 2001 - 2004 (Tab. 14). The ‘omission error’ proved to be significantly lower than noted for the unsupervised classification. (This was expected since the threshold criteria were calculated from the reference clear cut areas.)

Table 14. Results of change mapping obtained for the clear cut reference dataset*

Change	Change (%) 2001- 2002	Change (%) 2001 - 2004
Change (very significant)	79.0	76.0
Change (significant)	5.1	9.0
No change (Omission)	15.9	15.0
<i>Number of pixels</i>	<i>566</i>	<i>566</i>

* based on dehazed & histogram-matched bands and applying $Forest_Mask_{MD}$

Based on a single change vector analysis only, the commission error for the whole test region would have remained quite high. For example, examining the changes within the forest area previously mapped by unsupervised classification (Fig. 13) the commission error was estimated at about 70 %. A change vector analysis as 'stand alone' approach would require the definition of tighter change thresholds, however, increasing at the same time the omission error.

b) Textural change detection analyses based on the coefficient of variation (CV)

The CV_{diff} values were calculated based on the NDVI bands, subtracting the CV values at time1 and time2: $CV_{diff} = |CV_{T2} - CV_{T1}|$.

Figure 17 displays the histograms of the CV_{diff} values for the data sets 2001 - 2002 (left) and 2001 - 2004 (right) for the pixels of the reference clear cut areas. Low values would indicate no (significant) change, high values would indicate change.

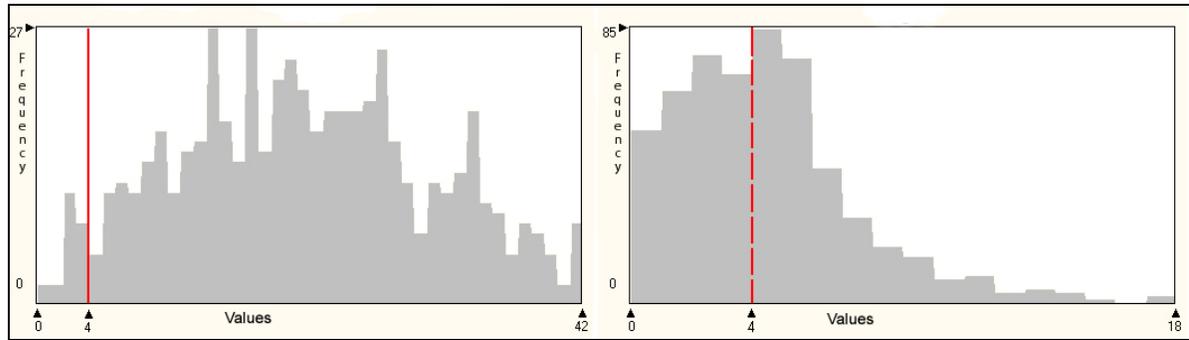


Figure 17. Histograms of CV_{diff} values from clear cut reference sites: red line = threshold value 4
 Left: data set 2001 - 2002: mean = 20.0 ; $s_x = 9.8$; Min = 0; Max = 46;
 Right: data set 2001 - 2004: mean = 4.1; $s_x = 3.1$; Min = 0; Max = 17;

Examining the values obtained from the reference clear cut areas, the threshold of $CV_{diff} \geq 4$ could be confirmed as appropriate for detecting change from forest to non-forest for the time period 2001 - 2002 (Fig.17, left). As expected, the reference clear cut areas were mapped with high accuracy (96 %) and a low omission error (4.1 %) (Tab. 15).

For the 2001 - 2004 data-set the method was found not suitable. Applying a threshold of $CV_{diff} \geq 4$, a huge number of the reference 'change' pixels would still be considered as 'no change' (Fig.17 (right); Tab. 15). However, further lowering the threshold would include almost all pixels of the test region as change. The weak performance could be due to the sensitivity of the NDVI to the regrowth of vegetation within the three years after clear cutting.

Table 15. Results of change obtained for the clear cut reference plots for $CV_{diff} \geq 4$

	2001 - 2002	2001 - 2004
	%	%
Change	95.9	47.3
No change (Omission)	4.1	52.7
<i>Number of pixels</i>	566	566

From a visual assessment of the textural change detection result the commission error would be expected as high as reported for the 'stand alone' change vector analysis.

**c) Combination of change vector and textural change analysis 2001 - 2002,
Integration of results from the additional change vector analysis 2001 - 2004**

In a next step we combined the individual approaches, aiming at decreasing the commission error ('false' clear cut indications) obtained from the individual steps.

The amount of 'false' clear cut indications decreased already notably when accepting a change indication only if confirmed by both, the change vector and the textural change analysis 2001 - 2002.

However, a satisfying improvement of the mapping result and a strong reduction of the commission error were achieved when further integrating the results obtained from the change vector analysis of the second data set (2001 - 2004). The additional data set obviously confirms 'real' change, whilst not identically repeating the 'noise' pattern (geometry shifts, phenology, shadows or haze) of the 2001 - 2002 image pair.

'False' clear cut indications were therefore largely removed if 'change' was only accepted when confirmed (i) by the change vector analysis 2001 - 2002, (ii) by the textural change analysis 2001 - 2002 and (iii) by the change vector analysis of an additional data set (in our case 2001 - 2004).

As with the unsupervised classification, we removed single pixels and clumps of two pixels by spatial filtering. Most of these 'false' small change indications occurred at edges of clouds, of shadows and of forest patterns.

Identification of clear cut areas

Using this combined approach 74 % (118) of the 159 reference clear cuts in coniferous stands were *identified* (Fig. 18), compared to 59 % (94) detected by unsupervised classification of the PC1 composite. Almost all reference clear cuts in (pure) coniferous stands > 15 ha size were identified. Contrary to the unsupervised classification of the PC1 composite, the combined approach also performed well for change of deciduous forest cover with a mix of coniferous trees.

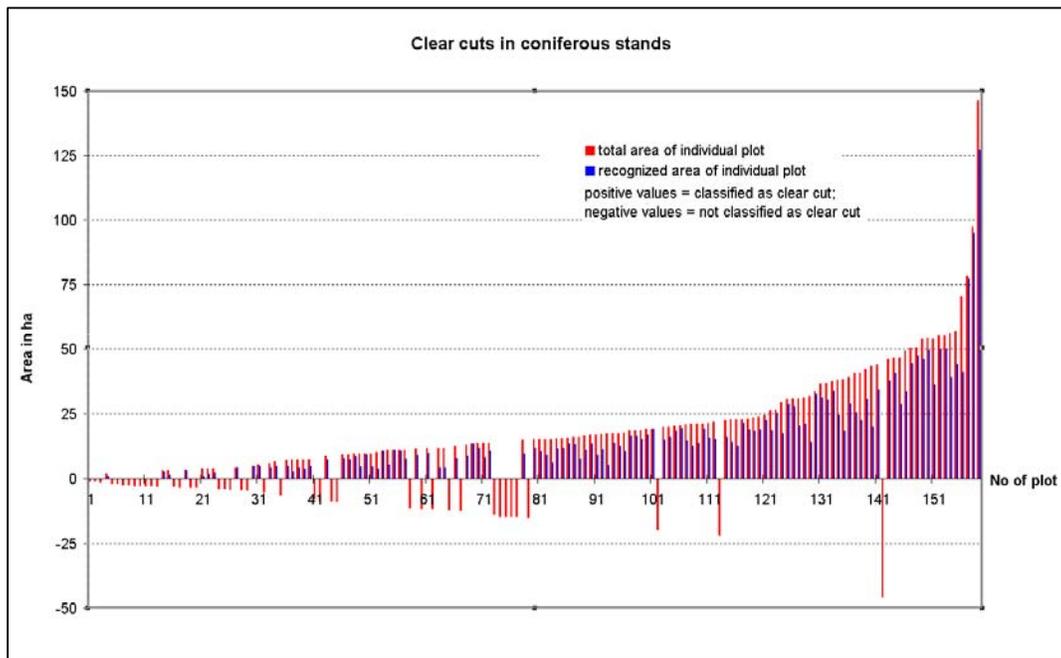


Figure 18. Areas of reference clear cuts (red bars: positive values=identified, negative values=not identified) and of correctly classified portions (blue bars)

Mapping of clear cut areas

Referring to *clear cut area mapping* the omission error is notably lower than reported for the unsupervised classification approach of the PC1 composite (see difference of red and blue bars in Fig. 18 compared to Fig. 16). For the reference clear cut plots 68 % of the area was correctly classified, leading to an omission error of about 32 % (Tab. 16). The omission error had slightly increased from 29 % to 32 % due to the removal of single pixels and also isolated pixel pairs, respectively.

Table 16. Results of change mapping obtained for the clear cut reference plots

	No pixel removal %	1 pixel removal %	2 pixel removal %
Change	71.0	70.1	68.0
No change (Omission)	29.0	29.9	32.0
<i>Number of pixels</i>	<i>566</i>	<i>566</i>	<i>566</i>

At the same time, the commission error, estimated within the Landsat TM overlap area by verifying the change for each pixel on the high resolution satellite data (after the removal of single pixels and isolated pixel pairs) would amount to only 7.4% (Tab. 17).

Table 17. Agreement and commission errors within the Landsat TM overlap area

	1 pixel removal %	2 pixel removal %
Confirmed change: Forest to clear cut	79.3	92.6
Commission error 1: Forest to forest	7.5	3.2
Commission error 2: Clear cut to clear cut	13.2	4.2
<i>Number of 'change' pixels</i>	<i>1023</i>	<i>838</i>

Rescaling and combining the two errors, the final mapping accuracy would be estimated at about 65 % (Tab. 18) and is notably higher than reported for the unsupervised classification approach tested (see Tab. 11).

Table 18. Mapping accuracy, commission and omission

	%
Accuracy	64.5
Omission error	30.3
Commission error	5.2

Total clear cut area estimate

The total clear cut area for the test region - excluding the still haze affected image parts in 2002 by applying the haze mask (mask_haze) - is estimated at about 12 500 ha (Tab. 19). This figure is higher than the one obtained from the unsupervised classification approach (see Tab. 12), mainly because (i) it also contains some change of forest stands dominated by deciduous species and (ii) it captures changes at forest edges which were excluded in the unsupervised classification approach by the forest mask. A few false clear cut indications in non-forest areas are also contained. Accounting for omission and commission errors (Tab. 18), the clear cut area of the whole test region would be estimated at 17010 ha.

For comparison, if limited to the forest area (mask forest₂₀₀₁) used for the unsupervised classification approach, the clear cut area in coniferous forests would be estimated at 9544 ha (Tab. 19). Accounting for omission and commission errors (Tab. 18) this estimate would rise to 12980 ha, indicating also an annual cutting rate in the order of 0.4 %.

Table 19. Forest and clear cut area figures for test region

	Test region ha	Classified as clear cut (> 2 pixel) ha
Total area - not haze influenced	6344700	
Forest cover ₂₀₀₁ (mature stands)	3890700*	12 506
Coniferous forests ₂₀₀₁ (mat, stands)	3390800*	9544

* figures taken from forest₂₀₀₁ mask of chapter 5.3

In view of the mapping accuracy, the ‘combined image differencing’ approach can be considered as more reliable, for mapping as well as for estimating the total clear cut area. Figure 19 displays the final clear cut map obtained from this approach for the test region.

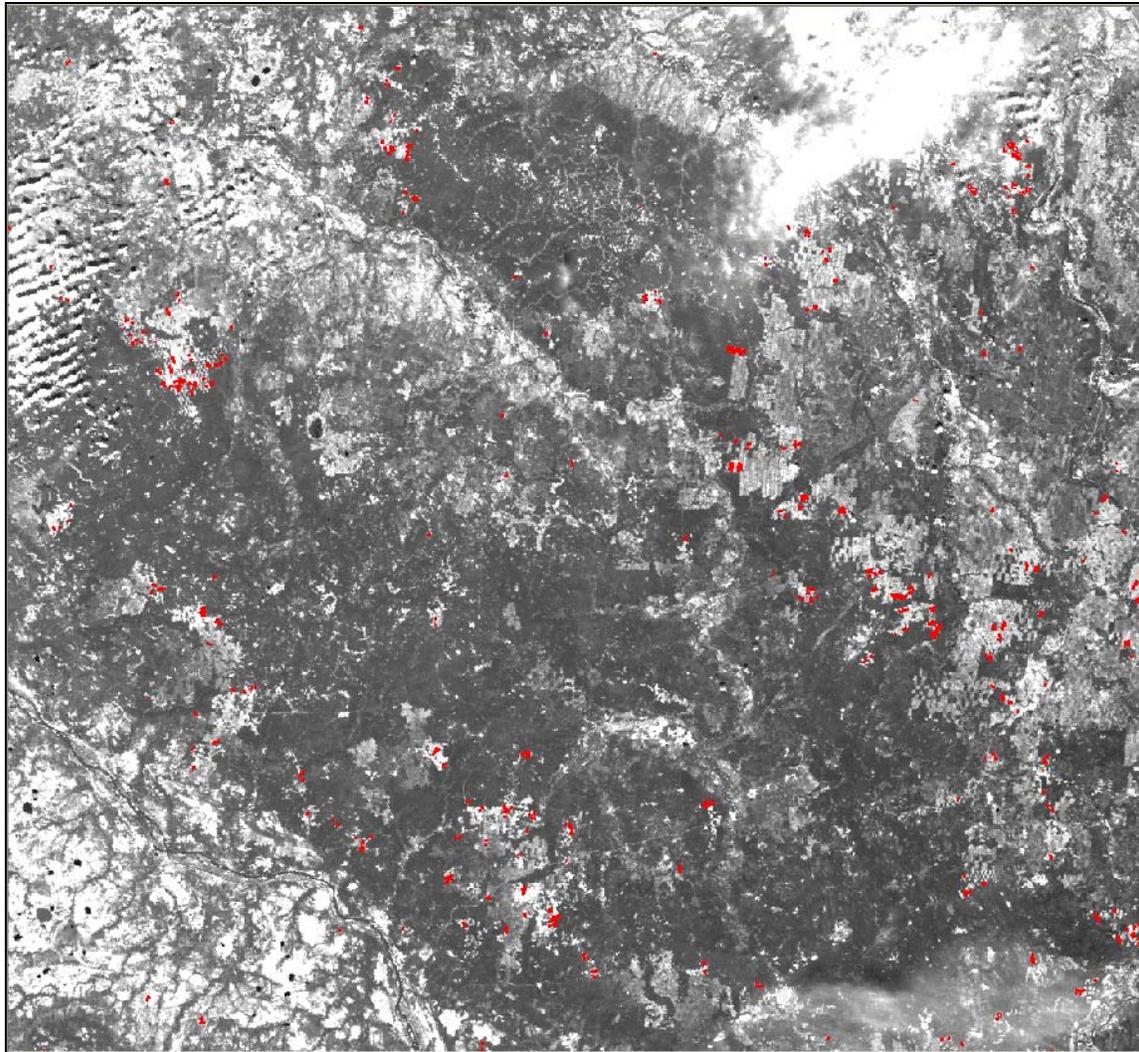


Figure 19. Classified clear cuts (red) for the time period 2001 to 2002. Background: original B&W MODIS image (red band) from 2002.

A zoom into a sub-window (Fig. 20) confirms the correct identification of the main clear cut pattern. Most of the larger individual clear cuts were mapped, however, some smaller clear cuts were also omitted.

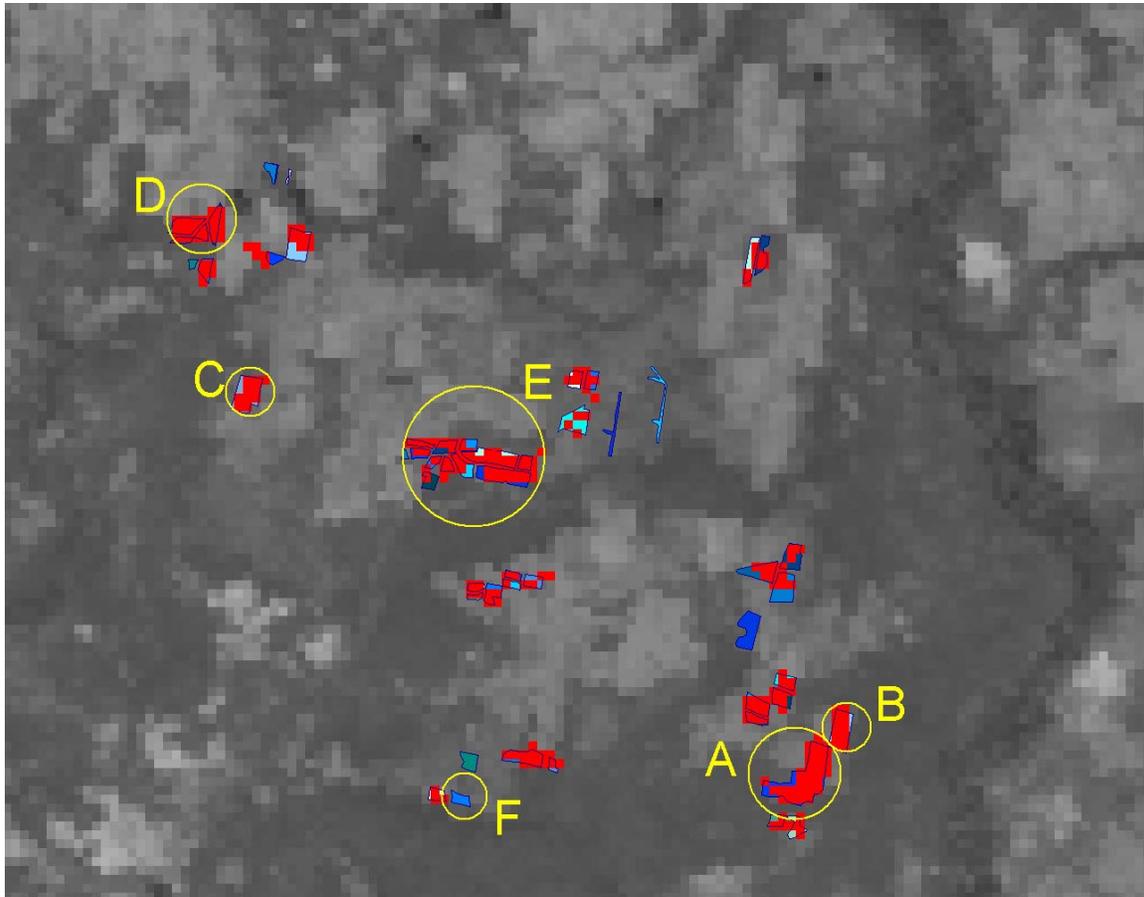


Figure 20. Clear cuts mapped (red), reference clear cuts (blue areas & outlines), background MODIS B & W image (examples: A: ~ 154 ha, B & C: ~ 54 - 64 ha, D & E: conglomeration of clear cuts, not dissolved as single lots at the 250 m spatial resolution, F: ~ 15 ha).

6 CONCLUSIONS

Sensors and image products

- A spatial resolution in the range of 250 m to 300 m is a minimum requirement for a reasonable identification and mapping of clear cuts in the northwest of Russia.
- MODIS (250 m) and MERIS (300 m) imagery are expected to provide comparable information on clear cuts in coniferous forests of the northwest of Russia. In this study MERIS images could not be analyzed in depth due to limitations in data availability.
- The swath-based daily MOD02 product proved to be superior to other MODIS products in terms of image geometry and spectral properties.

A spatial resolution in the range of 250 m to 300 m is a minimum requirement for a reasonable identification and mapping of clear cuts in the northwest of Russia. Many of them are of a size between 10 ha and 50 ha and cannot be reliably identified at a spatial resolution of 500 m.

From a visual comparison of MERIS 300 m and MODIS 250 m products one can expect a similar performance for the identification of clear cuts in the boreal forests. For area mapping the performance of MERIS might be slightly lower due to the slight decrease of the spatial resolution. Conclusions on the geometrical quality of MERIS data cannot be drawn at this stage and an in-depth comparison of the two products was not possible due to limited availability of MERIS images for the test region at the time of the study.

Referring to the MODIS imagery, the original, swath-based daily MOD02 product proved to be superior to the daily MOD09 or the standard MODIS 8-day products, which combine tiles from different orbits and pixels from different viewing angles. Comparable viewing angles are important for the reliable detection of clear cuts. Image pairs should therefore be of identical orbits, only the central parts of the images should be used (e.g. $\theta = 0^\circ \pm 30^\circ$) in order to avoid an impact of bi-directional effects or decreasing spatial resolution. Provided a proper selection of the image pairs and of the image parts to be used, the geometric quality of the MODIS imagery was considered satisfying. The two spectral bands available for the MODIS 250 m product were found sufficient for the detection of clear cuts in coniferous forests.

Seasonality, clouds and haze, image availability and cost

- Summer images (June-August) were found superior to late winter images (April-May), although the latter can be useful for the visual identification of clear cuts in coniferous forests.
- Haze can become a major obstacle for digital classification approaches, visual interpretation can cope with haze up to a certain extent.
- The high repetition rate and the large area coverage are striking advantages of MRSDD. However, it should be noted, that within a one-year time interval and for a given location in the northwest of Eurasia one may obtain only one or two cloud and haze free image pairs of the same orbit (= identical geometry).
- The cost-free distribution and the online accessibility are arguments for MODIS imagery.

At high geographical latitudes, vegetation phenology is an important factor and should be comparable for the pair of images used for change detection. Summer images (June-August) were found superior to late winter images. The latter often display a heterogeneous snow cover distribution which complicates digital change assessment. Winter images (April-May) can serve, however, for the visual identification of clear cuts in coniferous forests.

‘Haze’ proved to be a major obstacle for the digital change analysis and can result in ‘false’ clear cut indications. If indicated, a radiometric improvement (de-hazing) of the images should be foreseen, although strong haze impact cannot be sufficiently removed. Remaining haze may need to be excluded by manual masking. Visual approaches can cope with the influence of haze up to a certain degree.

Online-screening [21] of all MODIS imagery of the time period from 2001 to 2004 showed, that for north western Russia one may find for a specific location within a time interval of one year only one or two cloud and haze free image pairs of identical geometry (same orbit). Taking into account that the edges of the swath need to be excluded (large viewing angles) and that remaining haze-affected areas may have to be masked, image availability may become an issue.

The daily repetition rate (for the test region), the large area coverage and the low cost remain major advantages of MRSD, even if one may need to combine sub-windows of different image pairs in order to achieve large area coverage. For comparison, in order to completely cover the selected test region about six Landsat ETM scenes or 25 SPOT HRV images would have been required, causing cost in the order of 4000 Euro and 45 000 Euro, respectively. Furthermore, the problem of cloud cover exists also for these images and the repetition cycle of the satellites is much lower.

Arguments for using MODIS imagery are their cost-free distribution and the online accessibility.

Visual identification of clear cuts

- The visual identification of clear cuts in coniferous forests is considered feasible starting from clear cut sizes of about 15 ha.
- Visual screening of MRSD could serve for a rapid detection of major change patterns.

The visual identification of clear cuts in coniferous forests is considered feasible starting from clear cut sizes of 15 ha (and larger). The visual interpretation of MRSD could therefore be a basis for a rapid screening for changes in forest cover over large geographical areas.

The PC1 composite proved to be an efficient approach for a relative quick screening and identification of clear cuts in coniferous forest cover. However, a careful interpretation of the forest pattern is required, in order to exclude ‘false’ clear cut indications at forest edges or caused by remaining clouds, haze or shadow. The PC1 composite did not perform well for the monitoring of clear cuts in deciduous forest cover.

Digital detection and mapping of clear cuts

- The digital mapping of forest change due to clear cutting based on pairs of MODIS imagery (2001, 2002) provided satisfying results if combining different change detection methods and if integrating an additional image from a different acquisition date.
- One can then expect to identify the vast majority of clear cuts larger than about 15 ha.
- Digital mapping provided a satisfying spatial overview of the main clear cut patterns in a larger geographical context. The best area accuracy achieved was estimated at about 65 %. The mapping result provides also a ‘first estimate’ of the total clear cut area within a specific region.
- MRSD is, however, not the appropriate choice when detailed and accurate clear cut maps or area figures are required.

The identification and mapping of the majority of clear cut patterns in the boreal coniferous forests of north western Russia from MRSD by digital classification is considered feasible, provided that the main emphasis is on the generation of overview data rather than on obtaining accurate local maps and area estimates.

The digital mapping of changes depends heavily on the selection of cloud and haze free images or image parts, remaining haze may cause commission errors and unreliable results.

Change indications of only one or two pixel size were found unreliable and should be excluded as ‘noise’, in spite of increasing the potential omission error.

Choosing a proper digital classification approach, one can expect to identify and map the vast majority of clear cuts larger than about 15 ha. Clear cuts of smaller size are often omitted.

The mapping accuracy was estimated for the best approach of being in the order of 65 %, the total clear cut area could be underestimated by about one third. Reasons for the underestimation were the omission of small clear cuts (< 15 ha) due to the spatial resolution of MRSD, but also the spatial filtering of single and pixels pairs. However, not removing single pixels and isolated pixel pairs would have led to the inclusion of a large number of ‘false’ clear cut indications and an overestimation of the total clear cut area.

Classification and mapping approaches:

The simple unsupervised classification of the combined first principal components from 2001 and 2002 proved to be useful for the identification of clear cuts. However, the mapping accuracy and the clear cut area estimate suffered from high omission and commission errors in the range of 45 % and 18 %, respectively, reducing the final mapping accuracy (area) to about 37 %. It was further necessary to pre-define a forest mask in order to exclude change indications outside of the forest area. This mask may screen out potential clear cuts at the edges of forest blocks.

The combination of image differencing techniques with definition of statistical change thresholds (change vector analysis and textural change) and the integration of an additional image (optimally as close as possible to the second date, in our case due to limitations in image availability only from 2004) provided a more satisfactory result. Most of the reference clear cut areas (~ 95 %) larger than 15 ha were detected. The mapping accuracy achieved was estimated at 65 %, the omission and commission errors at about 30 % and 5 %, respectively. The approach benefits from its independence from a pre-defined forest

mask and from the fact that all needed parameters can be established from a set of reference clear cut areas.

However, the methodology is more time consuming. It should be noted that the specific combination of digital change detection techniques presented here is one out of other possible options, which may lead to similar results.

For our test region, digital mapping would lead to a total clear cut area of about 12500 ha. Taking omission and commission errors into account, the total clear cut area would be in the order of 17000 ha. Referring to the total forest area of about 3.9 million ha (excluding hazy areas), the annual cutting rate would be of the order of 0.4%. However, if more detailed clear cut maps and more accurate clear cut area figures are required, e.g. for local forest planning, MRSD is not the appropriate choice.

Conclusions on legality, forest area sustainability, harvested volume, operational use

- Based on the information obtainable from MRSD, conclusions on legality and sustainability may be drawn only at a very general and indicative level.
- Large clear cuts (> 7 pixels) could indicate a violation of the regulations on the maximum clear cut size (50 ha); clear cuts located in protected areas may point to illegal operations.
- Indications on the ‘sustainability’ of forest management would mainly refer to the sustainability of ‘forest area’ in the context of larger geographical units. A multi-annual image series would help to come to more profound conclusions.
- MRSD could serve as a basic component of an operational large-scale monitoring system for the boreal coniferous forests in the northwest of Eurasia.

The extent and regularity of the clear cut patterns in the test region suggest that they result in principle from planned logging operations. Indications on potential violations of existing rules may be derived from the size of individual clear cut lots, or when combining with existing information on forest protection:

- Clear cuts larger than 50 ha (e.g. Fig. 20: example A ~ 150 ha) might indicate a violation of the regulations on the maximum clear cut size. However, one would have to verify whether local exceptions apply or whether due to the spatial resolution a number of adjacent smaller clear cuts were classified as one lot (example C and E): in reality they might be separated for example by stripes of trees, meeting therefore the formal ‘legal’ requirements, even if possibly neglecting those of sustainability or production stability.
- Clear cuts indications could be examined in terms of their location in or vicinity to protected areas or protection zones (international or national protected areas, slope restrictions, distance restrictions, intactness). One would have to verify the applicable legal regulations and to which extent the protection status would permit forest operations.

Indications on the ‘sustainability’ of forest management would mainly refer to the sustainability of ‘forest area’ in the context of larger geographical units. The large size of some clear cut patterns and their spatial concentration raises questions on the sustainability. However, based on a single annual change assessment from MRSD of the whole test region, and assuming that (i) only forest area has to be considered, (ii) all forests are production

forests, (iii) natural regeneration of coniferous forests is successful, and (iv) the regrowth period for mature coniferous forest stands is about 200 years, an annual cutting rate of about 0.4 % would not yet provide an indication of unsustainable forest management. A multi annual series of satellite observations and additional information on the success of natural regeneration, on growth parameters and on the long-term forest and protected area policy for the region would be required to come to further conclusions.

Given the indicative character of the clear cut area estimates from MRSD, any estimate of the annually harvested volume can also be only indicative and depends further on accurate timber stocking information. Taking the estimated 17000 ha of annual clear cut and the range of stocking stem-wood of 100 m³ to 150 m³ [6], the total timber harvested in the test region for the period June 2001 to July 2002 could be of an order of 1.7 million m³ to 2.5 million m³.

The results of this report refer mainly to the spruce dominated boreal coniferous forest type present in the test region and will be complemented by results from other test sites.

Considering satellite image availability, accessibility and cost, and referring to the results obtained so far, we consider MRSD a potential component for an operational large-scale monitoring system for boreal forest cover. The identification of major clear cut activities proved to be feasible already by visual interpretation. A careful selection and combination of digital mapping approaches would further deliver overview maps and indicative figures on the potential clear cut area of a region. Such information could help to focus further monitoring efforts and guide subsequent detailed analysis of satellite imagery of high spatial resolution and field survey.

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Annex 1

Criteria for pixel selection (masks) used in the context of change vector analysis (i) for the calculation of statistical parameters and (ii) for focusing at forest and clear cut areas.

Data set 2001 - 2002:

Criteria for pixel selection, used as basis of calculation of Mahalanobis distance (MD): (<u>Forest_Mask_{MD}</u>)	$(0.73 < NDVI^{T1} < 0.87)$ 'AND' $(222 < \rho_{Re\ d}^{T1} < 655)$ 'AND' $(222 < \rho_{Re\ d}^{T2} < 655)$
Criteria for 'forest' and 'clear cut' pixel selection: <u>Forest_Mask_{final}</u>	$(0.70 < NDVI^{T1} < 0.87)$ 'AND' $0.23 < NDVI^{T2} < 0.89)$ 'AND' $(222 < \rho_{Re\ d}^{T1} < 664)$ 'AND' $223 < \rho_{Re\ d}^{T2} < 3675)$ 'AND' $(2991 < \rho_{NIR}^{T1} < 6068)$ 'AND' $3348 < \rho_{NIR}^{T2} < 6846)$ 'AND' $(-975 < (\rho_{Re\ d}^{T1} - \rho_{Re\ d}^{T2}) < 60)$

Data set 2001 - 2004:

Criteria for pixel selection, used as basis of calculation of Mahalanobis distance (MD): (<u>Forest_Mask_{MD}</u>)	$0.73 < NDVI^{T1} < 0.87)$ 'AND' $222 < \rho_{Re\ d}^{T1} < 655)$ 'AND' $222 < \rho_{Re\ d}^{T2} < 655)$
Criteria for 'forest' and 'clear cut' pixel selection: <u>Forest_Mask_{final}</u>	$0.70 < NDVI^{T1} < 0.87)$ 'AND' $0.23 < NDVI^{T2} < 0.89)$ & $301 < \rho_{Re\ d}^{T1} < 762)$ 'AND' $326 < \rho_{Re\ d}^{T2} < 1768)$ & $2991 < \rho_{NIR}^{T1} < 6068)$ 'AND' $3926 < \rho_{NIR}^{T2} < 7811)$

Annex 2

Results from univariate image differencing

The ‘Difference Images’ were generated subtracting the pixel values of the 2001 and 2002 data for the following spectral bands and linear combinations: RED, NIR, PC1 (= principal component 1), PC2, NDVI and NSC (= New Synthetic Channel), analogue to the methodology described in [20].

The NSC was calculated as a linear combination of original bands as:

$$\text{NCS} = A_1 * X_1 + A_2 * X_2, \text{ where}$$

where

X_i = reflectance values of MODIS bands

transformation coefficients are calculated as $A_i = b_i / B$

and

$$b_i = (X_{\text{clearcut}} - X_{\text{forest}})_i \quad i = 1, 2 \text{ (Red and NIR band of MODIS)}$$

- normalization of vector $b = |b_1, b_2|$:

$$B = \left(\sum_{i=1}^2 b_i^2 \right)^{1/2}$$

Based on the clear cut reference areas the mean and standard deviation (SD) were calculated from the pixels of the reference clear cut areas, in order to define the significance thresholds for ‘change’. Potential clouds and cloud-shadow pixels had been excluded using the cloud (mask_cloud) and cloud-shadow masks (mask_cloud-shadow). Furthermore, the forest mask forest₂₀₀₁ had been applied, in order to exclude potential non-forest pixels which could originate from inaccurate delineation at the ‘relative coarse’ spatial resolution..

Change was assumed for all pixels with values in the interval ‘mean \pm >1SD’. The change results refer to the clear cut reference areas only. Table 1 displays the percentages of pixels determined as change pixels by image differencing (>1SD = ‘significant’, >2 SD = ‘very significant’). The pixels classified as ‘non-significant’ would need to be considered as ‘omission error’.

The best result from the original band was obtained for the red band (Tab. 1), followed in decreasing order by the bands PC₂, NSC, NIR, PC₁, and NDVI.

Table 1. Impact of using different bands for change detection (at 68 % and 95 % significance levels).

Significance level	Bands	Δ RED %	Δ NIR %	Δ PC1 %	Δ PC2 %	Δ NDVI %	Δ NSC %
1 Very significant change ($\geq +95$ %)		24.0	7.8	4.1	0.0	0.0	12.6
2 Significant change ($\geq +68$ %)		52.7	58.0	51.0	0.0	0.0	55.8
3 Not significant change		23.0	28.6	39.2	2.8	3.4	27.7
4 Not significant change		0.3	4.9	5.2	29.2	54.3	3.5
5 Significant change (≤ -68 %)		0.0	0.5	0.5	50.0	39.1	0.4
6 Very significant change (≤ -95 %)		0.0	0.2	0.0	18.0	3.2	0.0
Tot. no. of pixels included		566	566	563	566	565	566

Image normalisation improved the results for the PCs and for NSC (Tab. 2). This is obviously due to the comparable value ranges and variances of the red and NIR bands after normalising. For the normalised PC₁, NSC and the red bands similar accuracies were obtained (at 68 % significance level). The PC₁ performed best with an agreement of ~ 80 %, the ranking for the remaining bands was - in decreasing order - NSC, Red, and NIR. The NDVI had not been further investigated.

Table 2. Impact of normalization of different bands on univariate change detection

Bands	Δ RED normalized %	Δ NIR normalized %	Δ PC1 normalized %	Δ PC2 normalized %	Δ NSC Normalized %
Significance level					
1 Very significant change ($\geq +95$ %)	25.1	4.6	29.9	0.0	30.2
2 Significant change ($\geq +68$ %)	49.6	51.4	49.3	0.0	47.4
3 Not significant change	24.4	37.5	19.8	8.3	21.9
4 Not significant change	0.9	6.0	1.0	61.0	0.5
5 Significant change (≤ -68 %)	0.0	0.3	0.0	28.6	0.0
6 Very significant change (≤ -95 %)	0.0	0.2	0.0	2.1	0.0
Tot. no. of pixels included	566	566	566	566	566

Applying a forest mask (mask2 & mask3) for the definition of the change thresholds increases the percentage of pixels corresponding to a significant change (due to decreased variances) (Tab. 3). However, applying stricter masks, one may lose at the same time ‘change’ pixels, that should have been included (~ 11 % and ~ 17 % for mask2 and mask3, respectively).

Table 3. Impact of different masks on the accuracy of change, using the difference (Δ) images obtained from the normalized PC bands of 2001 and 2002

Significance level	Masks:	Mask 1*		Mask 2*		Mask 3*	
		Δ PC ₁	Δ PC ₂	Δ PC ₁	Δ PC ₂	Δ PC ₁	Δ PC ₂
1 Very significant change ($\geq +95$ %)		4.1	0.0	12.5	0.0	12.0	0.0
2 Significant change ($\geq +68$ %)		51.0	0.0	49.2	0.0	48.1	0.0
3 Not significant change		39.2	2.8	30.1	4.0	33.5	4.0
4 Not significant change		5.2	29.2	7.8	21.8	5.8	25.4
5 Significant change (≤ -68 %)		0.5	50.0	0.4	40.1	0.6	43.5
6 Very significant change (≤ -95 %)		0.0	18.0	0.0	34.1	0.0	27.1
Number of pixels included		563	566	502	504	468	469

* Mask 1 - all pixels, except clouds and shadows excluded
 Mask 2 - only pixels classified as forest (coniferous + broadleaves) included
 Mask 3 - only pixels classified as coniferous forest included

In view of these results and for reasons of simplicity, the original red band appears to be most suitable for an univariate approach.

However, it should be noted that the tables above do not indicate the potential error of commission. The straight forward univariate differencing did however display a large number of ‘false’ clear cut indications. Additional ‘forest’ masks and other post-verification procedures will be required in order to reduce these commission errors

European Commission

EUR 21579 EN - Feasibility study on the use of medium resolution satellite data for the detection of forest cover change caused by clear cutting of coniferous forests in the northwest of Russia

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Abstract

The study examines possibilities of identifying and mapping of clear cuts in the boreal coniferous forests of north western Russia based on satellite imagery of medium spatial resolution (MRSR). MODIS imagery of 250 m spatial resolution served as the main data source for the change analysis. The study compares different detection and mapping approaches, including (i) the visual interpretation of principal components, (ii) an unsupervised digital classification and (iii) a combination of image differencing, change vector and textural analysis, defining statistical thresholds for the identification of clear cuts.

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