Assessment of Driving Factors Affecting Radiance Changes in Regenerating Mixed Forest Clearcuts Using Landsat Winter Imagery

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Abstract

This paper describes an approach for estimating the effect of stand variables on radiance of forest patches that were regenerating after the disturbance of clearcut felling. Analysis was performed on a difference image of a two-date Landsat Thematic Mapper (TM) image pair. Landsat TM images from late winter made in plain snow cover conditions – a non-traditional season for forest mapping – were used in the study. Seasonal snow cover in winter in boreal and hemi-boreal latitudes presents specific conditions with high target (stems and branches of shrubs and trees) to background radiance contrast and is therefore a well-timed season for the detection of subtle changes in shrub and tree cover in patch areas regenerating after disturbance.

The results of the study show that, in all spectral bands studied (TM1–TM4), there is a significant effect of patch age (i.e.) time passed since disturbance of clearcut logging, on the radiance difference of regenerating patches on a difference image. Radiance change in none of the Landsat TM bands 1–4 was found more sensitive than others to patch variables. The marginal effect of Spruce index, a binary variable denoting whether the patch was managed as a young spruce stand or a deciduous stand, means that the chance for discrimination of young spruce-dominated stands from deciduous-dominated stands in winter images is low in most cases. No significant effect of stand variables on patch-wise differences was found between the patch areas classified from difference image to that represented in the forestry database. There was a significant effect of the type of neighbours – either bright or dark – on the estimation of the patch area on a difference image.

Key words: forest change detection, Landsat TM winter images, clearcut regeneration

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Introduction

Repeatable and consistent measurements make satellite remote sensing well suited for change detection; the field is rich in case studies in forested areas. Images acquired at different dates are compared to find radiance differences caused by land cover changes (Coppin and Bauer 1996, Mas 1999, Coppin et al. 2004, Lu et al. 2004). The dramatic changes in patch radiance occurring after forest removal render successful deforestation mapping. However, the mapping of regenerating forest succession after disturbance remains a challenge due to the subtle reflectance changes associated with forest succession in optical imagery (Song et al. 2007). The relationship between stand age and patch radiance can be highly variable especially in young stands (Horler and Ahern 1986). Causes for this variability include differences in site quality, site preparation, planting practices and species composition (Schroeder et al. 2006). Additionally, forest age is not as directly remotely detectable as are forest structure and composition; both are related to and change within forest succession (Cohen et al. 1995).

Remote sensing studies predicting forest successional stage have used single date measurements (Fiorella and Ripple 1993, Peterson and Nilson 1993, Jakubauskas 1996). Generally, a few broad successional classes have been derived from single-date images. An alternative use of remotely sensed images for characterizing forest succession is examination of multi-temporal images as two-date image pairs or multi-date image series (Joyce and Olsson 2000, Kennedy et al. 2007, Schroeder et al. 2007, Liu et al. 2008).

However, few researchers have assessed the influence of driving factors on subtle radiance change in forested patches of northern temperate forests following clearcutting. Therefore it is necessary to continue to test the influence of patch attributes such as time since gap generation, site conditions, and applied silvicultural treatments on image classification results.

Landsat Thematic Mapper images from late winter, made in March in plain snow cover conditions – a non-traditional season for forest mapping – were used (A forest map of Estonia 2003, Peterson et al. 2005, Peterson et al. 2008).

The reflectance of snow is high in the visible and near-infrared part of the spectrum (Кринов 1947), where the Landsat TM spectral bands TM1–TM4 are located. Snow reflectance increases up to the depth of approximately 15 cm; further depth increase of snow cover does not cause significant reflectance changes (Robinson and Kukla 1985). The differences in spectral reflectance between different snow cover types of different granular size are relatively small in the visible spectral region (TM1–TM3 in this study), but are large in the mid-infrared spectral region (Xiao et al. 2002). Seasonal snow cover presents specific conditions with high target (stems and branches of shrubs and trees) to background radiance contrast. Late winter is considered the best season for forest mapping in forest to non-forest boundary delineation (Peterson et al. 2004) and for the detection of subtle changes in shrub and tree cover in regeneration following disturbance of patch areas.

The retrospective data provided by remote sensing scanners particularly by the long time series of Landsat images have provided a means to characterize forest successional stage across large spatial areas. Data by optical sensors have been used to predict stand age with varying degrees of accuracy. The accuracy is usually limited, because stand age is not directly observable by remote sensing methods. Also, after an initial rapid reflectance change during the first 15 to 20 years of stand development, the correlation of reflected radiance with stand age in northern temperate forests becomes weak. This study is aimed to contribute to the forest stand age estimates from medium spatial resolution satellite images.

There exists a chance that age estimates could be extended beyond the time interval covered by more than 25-year archive of Landsat TM images. When the age of stands older than 20–25 years in northern temperate forests cannot be estimated with acceptable accuracy from single images, the results could be improved by using the early images in the Landsat TM archive (from 1985 to 1987) together with images made a couple of years later. From these difference images the changing patches in forests could be isolated (see Figure 1) and the age of then young stands with rapidly changing reflectance could be estimated. Better estimates could be extended up to the stand age of 35 to 40 years.

Figure 1. Subsamples of the Landsat TM winter images taken in March 1996 and in March 2005 respectively. Dark patches in the difference image are regenerating after disturbance clearcuts, bright patches are recently cut clearcuts

The aim of the study was to analyse the possible driving factors derived from the forestry database that could affect radiance changes in regenerating after the disturbance of clearcutting forest patches. Radiance differences were derived from a difference image of a two-date Landsat Thematic Mapper (TM) image pair made in late winter in March 1996 and in March 2005 respectively.

Our tasks were as follows: 1. To find which variables in the forestry database have statistically significant effect on radiance changes during early secondary succession on a difference image made in seasonal snow cover conditions, and 2. To determine which factors are causing patch-wise areal differences between the patch areas classified from difference image to that represented in the forestry database. The comparison is made in conditions where the total areas of all patches are kept equal.

Materials and methods

Study area and data

The study area is located in Central Estonia and falls within the World Reference System of satellite images path/row 187/19. The area represents a typical northern temperate forest of mixed stands dominated by Birch (*Betula pendula* and *Betula pubescens*), Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*) and European aspen (*Populus tremula*). A sub-scene covering 40 km by 40 km on the ground centered at 58°30’ N and 26°20’ E was selected for this study (see Figure 2). We chose the area due to its high forest coverage, flat terrain and dominance of state-owned forests managed for timber production. Forests cover 53% of the study area (Forest Map of Estonia 2003).

Two Landsat Thematic Mapper near anniversary late winter satellite images acquired on 10 March 1996

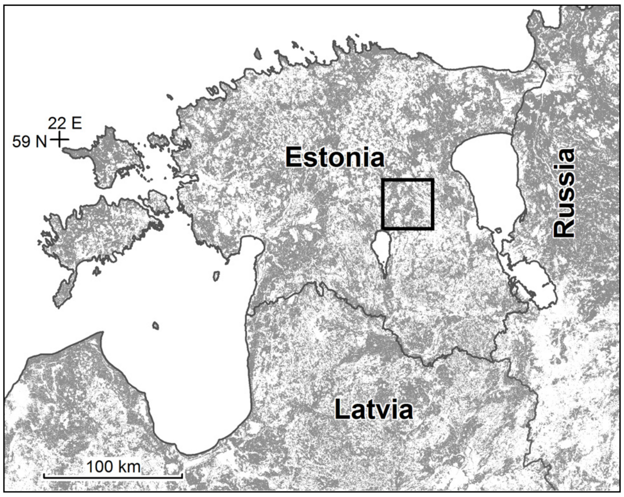

Figure 2. Location of the study area with a black quadrangle. A forest map compiled using Landsat TM winter images is on the background

and on 03 March 2005, respectively, were used in this study. The snow cover had remained at a thickness of about 13 to 30 cm for 2 weeks preceding satellite overpass on both dates. Total precipitation as snow in the 10 days preceding Landsat overpass was less than 3 mm with daily mean temperatures remaining below zero. Atmospheric transparency at the time of the satellite overpass, calculated from incoming direct solar radiation, was 0.82–0.83 on both dates. The long-term average transparency on clear days in March is 0.77 (Russak 2003). The atmospheric haze level was low; horizontal visibility was 20 km. Weather information was obtained from the Estonian Meteorological and Hydrological Institute weather station at Tõravere, located within 20 km of the study area. Noise effects due to differences in illumination geometry and surface conditions were minimized given the similarity in both conditions.

A vector format forest stand layer together with the forest inventory database provided by the Estonian State Forest Management Centre was used to extract regenerating forest stand polygons, together with the data on site type, year of clear-cut logging and post-logging treatments. Clearcut felling was implemented as a common commercial forest management operation; most clearcuts are predominantly elongated rectangular in shape. In total 436 regenerating clearcuts were selected. Almost half (45%) of regenerating clearcuts were fresh boreo-nemoral forests, 33% were rich paludified forests, 15% were drained peatland forest; fresh boreal forest, dry boreal forests, minerotrophic bog forests and ombrotrophic bog forests comprised altogether 7%.

The area of regenerating clearcuts varied between 0.8 and 11.2 hectares, with an average of 2.96 hectares. The average area and perimeter ratio – shape was 1.21, with minimum value of 0.96 and maximum 1.76. The age of the regenerating clearcuts varied from 8 to 17 years. Each year was represented with the number of objects varying from 22 to 93. Most intensive pre-commercial thinning was done within three years preceding the second image date – years 2002–2004 (36 to 49 patches were thinned). The mean volume of retention trees on regenerating clearcuts was 0.53 m^3 ha^{-1}.

The year of felling, a crucial parameter noted in the database, verifiable from other sources, was confirmed by visual on-screen inspection using a vector overlay of patch boundaries together with Landsat TM summer images from 1988–96. Patch boundaries in the vector overlay were compared also to digital orthophoto quads (DOQ), an independent source of imagery obtained from the National Land Board. DOQs for the years 1995 and 2003 were, on order of magnitude, finer spatial resolution than Landsat imagery with a nominal spatial grain less than 1 m. Boundaries of the regenerating patches were visually inspected and were corrected if necessary.

The studied regenerating clearcuts were logged up to 8 years before the date of the first image acquisition, i.e. the year of logging was between 1988–96. Data from Landsat TM visible and near infrared bands (TM1–TM4) (visible blue to near infrared spectral regions) were used in the study. Data from bands TM5 and TM7 were not used in the analysis, because these two channels are spectrally centered close to the water absorption bands and have very low dynamic range in low illumination conditions with snow-covered ground in winter (Püssa et al. 2005).

Image processing

The Landsat TM images were geometrically corrected using a first-order linear transformation and resampled to a 25 m pixel size. The satellite images were rectified to the national grid using ground control points collected from national Basic Map Digital Orthophoto Quads. The total root mean square errors in image rectification remained below 0.4 pixels using 50 or more GCPs per image. Nearest-neighbour resampling was used.

Factors affecting change detection in a two-date Landsat dataset were evaluated. A common change detection method, a two-date image differencing was tested. In the image differencing method, a linear regression model is produced between the two images to normalize the image radiance differences caused by factors not related to real land cover change (Coppin et al. 2004). The normalizing of two-date images corrects for the differences in radiance of the same area caused by differences in atmospheric conditions and illumination geometry.

In this study, we adopted the radiometric normalization method among the many where radiance responses of pseudo-invariant features match between the two dates of the images.

Then the image acquired on a later date will be subtracted by the predicted image and a difference image will be obtained. As the next step in change detection, a threshold is determined according to statistical procedures and subsequent thresholding the difference image into change/no change areas. We have used percentile values while trying to normalize the two images of the two dates to similar conditions. About half of the sub-image area is covered by bright snow and the other half contains conifer-dominated dark forests that are commonly used for image radiometric rectification.

Image normalization of the two satellite images to a common radiance scale was performed with values of pseudo-invariant-features of dark targets that were represented by 2nd, 5th, and 10th percentile values in the bimodal frequency distribution of pixel brightness of Landsat TM bands and bright targets of 90th, 95th and 98th percentile values representing bright targets of dry snow. (For frequency distribution of late winter images see e.g. Peterson et al. 2004, Liira et al. 2006). We used Landsat TM “digital numbers” (DN) when calculating the difference image. Conversion of the Landsat TM recorded radiance data to ground reflectances was not considered necessary in this study as the difference image represented relative changes from no-change to “significant change” on the normalized-to-common scale seasonally snow-covered images. Regenerating clearcuts in the area are relatively small patches on medium resolution satellite images and are represented by a small number of pixels. The regenerating patch polygons were buffered one pixel wide array inward from the perimeter to reduce possible edge effects. Mean radiance values of patches were calculated for non-boundary (core) areas and were used in the analysis.

In the analysis of possible factors causing errors in area estimates of regenerating patches, the difference image was classified into two classes of changed and non-changed pixels by thresholding. The threshold was determined iteratively to match the total area of classified patches from the difference image to the total area of the same patches fixed in the forestry database. A mask of one-pixel-wide neighbourhood around the database-patches was allowed for pixels representing the regenerating patches classified from the difference image.

The thresholds for identifying changed pixels from non-changed background were determined separately for difference images of the four spectral bands used in the study. After the threshold was determined the change/no change map was generated.

The possible effect of neighbouring patches to studied patches was acknowledged in the area estimations. The neighbours could represent bright neighbours, dark neighbours or no change areas on the difference image. In this study, the thresholds for identifying radiance increase for bright neighbours and for dark neighbours were defined separately. The non-changed pixels were between the two threshold values. The threshold for bright neighbours showing radiance increase was found as the threshold appropriate for classification of clearcut patches from the difference image. The threshold for dark neighbours was the same as that used for classifying regenerating patches from the difference image. The thresholds were identified separately for each spectral band and were applied as global thresholds over the whole subscene area. Both bright neighbours and dark neighbours were defined in the one-pixel-wide buffer zone outside the studied patches.

Statistical treatment

The relationship of radiance differences of regenerating forest clearcuts on patch variables was tested for four Landsat TM bands in the visible and near infrared region separately (TM1, TM2, TM3 and TM4). The General Linear Modeling incorporating regression and variance analysis was applied with PROC GLM of SAS software Version 9.1 which is appropriate to analyse unbalanced designs (Cody and Smith 2006). The following patch variables as linear model predictors were considered:

AGE – time passed since clearcut logging (year);

THIN – binary variable, indicating pre-commercial thinning in young stands within the three years preceding the second image date (years 2002 to 2004) as value 1, otherwise 0;

SI – site index class by M. Orlov (Vaus 2005) of previous stand with integer values 0–6;

SITE – site type group by J. Paal (1997). In this study seven site groups were used: 1) fresh boreal forests; 2) dry boreal forests; 3) minerotrophic bog forest; 4) fresh boreo-nemoral forests; 5) ombrotrophic bog forests; 6) rich paludified forests; 7) drained peatland forests;

SPRUCE – binary variable indicating spruce as dominating species in young stand composition as value 1, otherwise 0;

VOLRET – volume of retention trees (m^3 ha^{-1}), including stem volume of seed and remnant trees left after clear-felling for seed production or for biodiversity considerations.

Variables AGE and SI can be analysed as the continuous variable for detecting trend or as categorical variable for detecting nonlinear relationship. In the case of evident nonlinear relationship of continuous variables, the quadratic term was added into the linear model.

In the second analysis of factors influencing patch-wise area, both absolute and relative area differences were used as dependent variables:

$$P_{absolute} = P_{database} - P_{classified} \qquad P_{relative} = \frac{(P_{database} - P_{classified})}{P_{database}}$$

where

$P_{absolute}$ is the absolute area difference;

$P_{relative}$ is the relative area difference;

$P_{database}$ is the area of a regenerating patch represented in the forestry database in hectares; $P_{classified}$ is the area of a regenerating patch classified from the difference image in hectares.

In the patch-wise area analysis, in addition to variables the AGE, THIN, SI, SITE, SPRUCE and VOLRET, the following factors were analyzed:

SHAPE is the area-to-perimeter ratio, calculated from the subsequent records in the forestry database:

$$SHAPE = \frac{0.25 * U}{\sqrt{S}}$$

where U is the perimeter and S is the area of the patch (Jagomägi *et al.* 1988).

DARK_NBR (dark neighbours' ratio) is the relative boundary length of a regenerating patch shared with neighbours that also belonged to the "regenerating" class on the difference image;

BRIGHT_NBR (bright neighbours' ratio) is the relative boundary length of a regenerating patch shared with neighbours that have been classified as "clearcut" on the difference image;

AREA is the area of the patch from the forestry database.

Results

Relationships between the radiance differences of regenerating forest clearcuts and patch variables were examined for four Landsat TM bands in the visible and near infrared region (TM1, TM2, TM3, TM4) separately. Our analysis revealed the radiance change in regenerating forests that had been felled 0 to 8 years before the first image was taken.

Factor AGE had the biggest effect on radiance in all analysed Landsat TM bands in the difference image (according to the Table 1). The change in radiance of regenerating forest patches on a difference image with time passed since clearcut felling is shown in Figure 3. Similar trends were observed for the three visible and near infrared spectral bands of Landsat TM. In the studied Landsat TM bands the trend was linear, decreasing with regeneration time (factor AGE) which showed greater negative mean values for patches in the difference image that were cut in earlier years. Although factor AGE as a categorical variable with ANOVA showed higher R^2 value than factor AGE as continuous variable (Table 1), residuals from the linear trend did not reveal evident nonlinear regularity with factor AGE in the years 8 to 17 following disturbance (Figure 4A).

Table 1. Adjusted coefficients of determination R^2 for single factor models of the average pixel values of regenerating patches on Landsat TM difference image by bands TM1–TM4

Variable	Type	TM1	TM2	TM3	TM4
AGE (Time past since clearcut)	*Continuous*	**0.109**	**0.108**	**0.124**	**0.078**
	Categorical	**0.139**	**0.141**	**0.158**	**0.132**
THIN (Pre-commercial thinning)	*Binary*	**0.031**	**0.040**	**0.031**	**0.054**
SI (Site index class by Orlov)	*Continuous*	0.000	0.000	0.001	0.000
	Categorical	**0.030**	**0.028**	**0.024**	**0.040**
SITE (Site group)	*Categorical*	**0.044**	**0.053**	**0.044**	**0.056**
SPRUCE (Spruce indicator)	*Binary*	**0.007**	0.004	**0.009**	0.000
VOLRET (Volume of retention trees)	*Continuous*	0.000	0.000	0.000	0.000

Note: significant p-values ($p<0.05$) are shown in bold

Depending on the spectral band, 18–20% of the radiance change variance was described by the variables of the forestry database (Table 2). In addition to factor AGE, the categorical factor of thinning (THIN) had significant effect in all the studied Landsat TM bands (Table 2). The effect of pre-commercial thinning on radiance in young stands was significant if the treatment was performed within three years before the second image was taken in 2005 (see Figure 4D). Pre-commercial thinning was subsequently accounted for in the model as a binary variable having value "1" if the thinning was performed within years 2002 to 2004, otherwise the value was "0". The "recently" thinned stands showed relatively more positive mean values for patches in the difference image (Figure 4D) which corresponds to the significant positive estimate of regression coefficient for THIN in Table 3.

A curvilinear relationship between radiance change and Orlov site index class (factor SI, see Figure 4C). However, simple regression did not reveal the significant effect when the site index was treated as a continuous variable (Table 1). The significant relation-

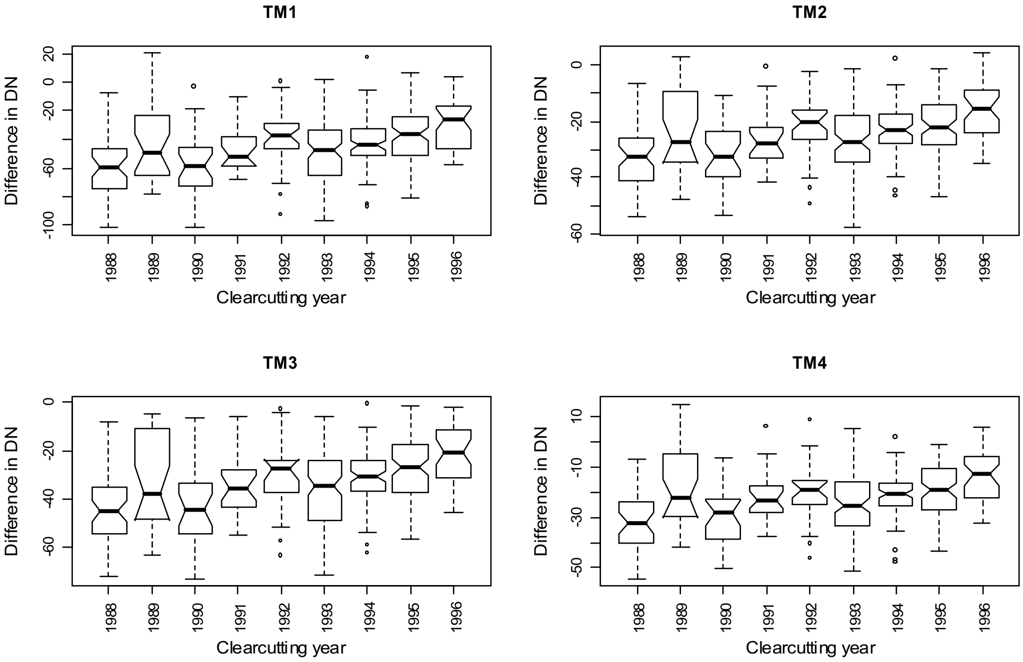

Figure 3. Boxplots of mean radiance change of regenerating patches on the difference image in the visible and near-infrared bands Landsat TM1–TM4 by clearcut year

ship between radiance change and Orlov site index class became evident using one-way ANOVA when the factor SI was treated as a categorical variable (Table 1). Adding the quadratic term SI^2 improved the relationship between radiance change and site index significantly (Table 2).

The effect of spruce indicator (SPRUCE), a binary variable denoting whether the patch was managed as a young spruce stand or not, was marginal in two of the studied spectral bands (TM1 and TM3, Figure 4B) and was not statistically significant in the other two bands (TM2 and TM4) (Table 1). Factor VOLRET that includes stem volume of seed and remnant trees left after clearfelling for seed production or for biodiversity considerations had no effect on radiance change in the model. Among the site groups, only *Rich paludified forests* had significant positive effect on mean values for patches in the difference image (Table 3).

The analysis of factors that might cause patch-wise area differences between the patch areas classified from difference image to that represented in the forestry database revealed that the type of patch neighbours rather than patch variables themselves are responsible for the discrepancies in the two area representations. The patch neighbours in the difference image could be classified either as no-change areas or as changed areas. The change between the image dates could be in two directions. The neighbours could have been clearcut between the image dates then representing "Bright Neighbours" in the difference image. The neighbours could have been also in some stage of regeneration representing "Dark Neighbours" in the difference image taken at the time. The neighbourhood effect had an influence in two directions. The patch area classified from the difference image was greater than the area of the patch represented in the forestry database if the patch had regenerating dark neighbours. The patch area classified from the difference image was less than the area of the patch represented in the forestry database if the patch had neighbours that were clearcut between the image dates. There was also some statistically significant but weak effect of patch shape and patch area

Table 2. P-values of variables if they were entered last into the full linear model for the average pixel values of regenerating patches on Landsat TM difference image bands TM1–TM4

	TM1	TM2	TM3	TM4
AGE (Time past since clearcut)	**<0.001**	**<0.001**	**<0.001**	**<0.001**
THIN (Pre-commercial thinning)	**<0.001**	**<0.001**	**<0.001**	**<0.001**
SI (Site index class by Orlov)	**<0.001**	**0.005**	**0.008**	**0.002**
SI^2	**<0.001**	**0.007**	**0.012**	**0.003**
SITE (Site group)				
Fresh boreal forest	0.238	0.117	0.158	0.263
Dry boreal forest	0.124	0.297	0.264	0.184
Minerotrophic bog forest	0.109	0.135	0.116	0.139
Fresh boreo-nemoral forest	0.179	0.132	0.225	0.218
Ombrotrophic bog forest	0.213	0.644	0.205	0.459
Rich paludified forest	**0.016**	**0.004**	**0.011**	**0.006**
SPRUCE (Spruce indicator)	0.105	0.166	0.078	0.811
VOLRET (Volume of retention trees)	0.848	0.628	0.804	0.935
Adj. R^2	**0.189**	**0.198**	**0.201**	**0.183**

Note: significant p-values of variables ($p<0.05$) are shown in bold

Table 3. Parameter estimates and significance tests of linear model for average pixel values of regenerating patches on Landsat TM 3 difference image

	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	–38.838	4.207	–9.231	**<0.001**
AGE (Time past since clearcut)	–2.138	0.294	–7.262	**<0.001**
THIN (Pre-commercial thinning)	5.364	1.497	3.583	**<0.001**
SI (Site index class by Orlov)	7.299	2.753	2.651	**0.008**
SI^2	–1.216	0.485	–2.505	**0.012**
SITE (Site group)				
Fresh boreal forest	–6.023	4.259	–1.414	0.158
Dry boreal forest	11.064	9.902	1.117	0.264
Minerotrophic bog forest	–7.346	4.667	–1.573	0.116
Fresh boreo-nemoral forest	2.693	2.217	1.215	0.225
Ombrotrophic bog forest	–10.452	8.238	–1.269	0.205
Rich paludified forest	5.503	2.164	2.544	**0.011**
SPRUCE (Spruce indicator)	–2.729	1.544	–1.768	0.078
VOLRET (Volume of retention trees)	0.795	3.212	0.248	0.804
Adj. R^2	0.201			

Table 4. Relationship of the relative area difference of regenerating patches from Landsat TM3 image on stand variables

Variable	Estimate	Std. Error	t value	Pr(>|t|)	R^2	p-value
AGE (Time past since clearcut)	–0.009	0.010	–0.929	0.354	0.000	0.354
THIN (Pre-commercial thinning)	0.103	0.048	2.142	0.034	0.019	0.034
SI (Site index class by Orlov)	–0.002	0.025	–0.063	0.950	0.000	0.950
SITE (Site group)					0.000	0.756
Fresh boreal forest	0.017	0.176	0.098	0.922		
Minerotrophic bog forest	–0.008	0.241	–0.032	0.974		
Fresh boreo-nemoral forest	0.083	0.070	1.189	0.236		
Ombrotrophic bog forest	–0.168	0.241	–0.697	0.487		
Rich paludified forest	0.040	0.075	0.538	0.591		
SPRUCE (Spruce indicator)	0.071	0.051	1.390	0.166	0.005	0.166
SHAPE	–0.346	0.167	–2.075	0.039	0.017	0.039
DARK_NBR (Dark neighbour's ratio)	–0.446	0.039	–11.396	<0.001	0.409	<0.001
BRIGHT_NBR	0.462	0.061	7.576	0.000	0.233	0.000
AREA	0.050	0.017	2.979	0.003	0.041	0.003

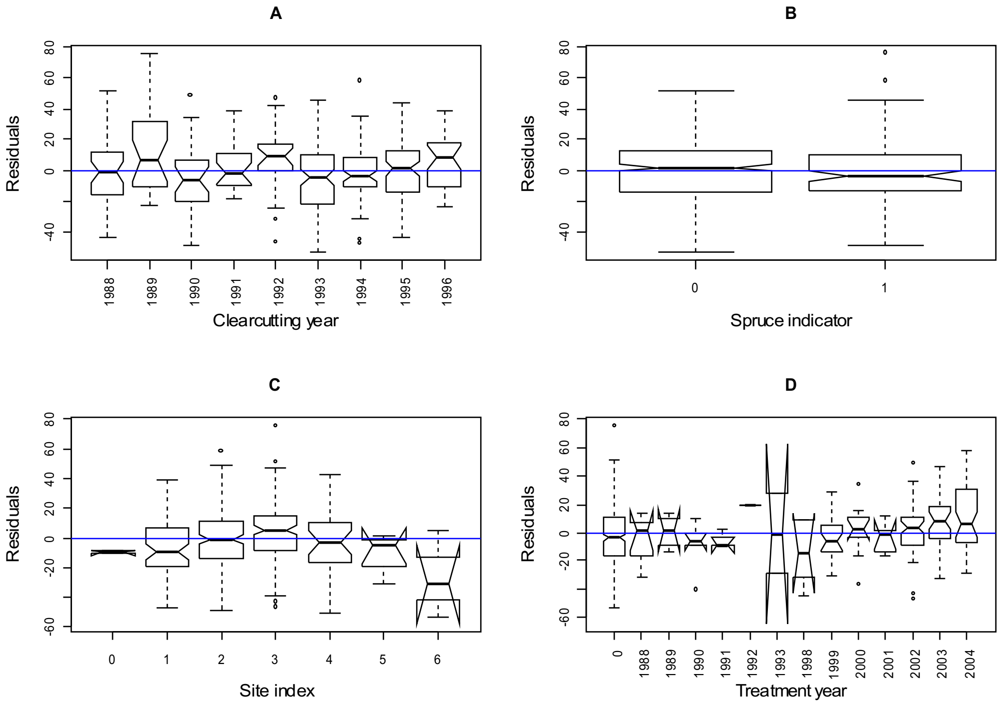

Figure 4. Residual boxplots of linear trend of mean radiance change on clearcut year of regenerating patches on the difference image in the red spectral band Landsat TM3 (A – by clearcut year, B – by spruce indicator, C – by Orlov site index class, D – by treatment year)

on the classification results of regenerating patches (Table 4). Larger patches had relatively greater errors than did the smaller ones. Greater errors in area estimations could also be attributed to the patches that have a more irregular shape.

Discussion

Reflectance of snow-covered patches on satellite images made in winter in seasonal snow cover conditions depends on the type and density of vegetation and the depth and age of snow. When there are no shrubs and trees on a patch, snow depth and snow age are primarily responsible for reflectance variability over the area. Increasing cover of stems and branches together with their shadows cast onto the bright snow background reduce the radiance of the regenerating patches.

Our analysis revealed the radiance change in regenerating forests that had regenerated to an age of 9–17 years following disturbance when the second image (in 2005) in the pair was imaged. Young stands have the highest radiance values; further development leads to a slow decrease in the visible and near infrared spectral regions. Though the successional trajectory is quite nonlinear, particularly in the first 30–40 years of development, a linear model fits the average successional trajectory quite well in the first 10–20 years following clearcutting in seasonal snow-cover conditions.

Forest regrowth rates after clearcut harvesting varied both within and across yearly age classes. Change towards decrease in radiance values after the disturbance is a proxy for increasing the amount of aboveground (above snow in winter) stems and branches of shrubs and trees on a patch. We attributed some of the within-age variability in forest regrowth rates to vegetative differences with more favorable growing conditions for fast forest regrowth than it was observed in less favourable growing conditions.

A relationship was found between radiance change expressed in the difference image and site index by Orlov (see Figure 4C) as expected. The relationship tended towards increasing change within site classes 0 to 3 that have progressively faster forest regrowth with decreasing site index number. The patches with greater site index number have higher (close to zero) mean values on the difference image. In less favourable growing conditions with Orlov site index class from 4–6 the trend was reverse. On the patches with extremely low site index numbers post-harvest silvicultural treatments were either not performed or were occasional.

The marginal effect of the Spruce index, a binary variable denoting whether the patch was managed as a young spruce stand or a deciduous stand, means that the chance for discrimination of young spruce-dominated stands from deciduous-dominated stands in winter images is low in most cases. Utilizing separate hardwood and softwood tree cover categories could not possibly improve the fit of the radiance change regression model covering the period of the first two decades of regeneration.

The overall coefficient of determination (R^2) values of the linear model explaining average pixel values of regenerating patches on Landsat TM difference images in bands TM1–TM4 were relatively low (0.183–0.210, see Table 2). Similar results have been found by other studies (e.g. Song et al. 2007). Evidently there are driving factors that are beyond the control of this study and cause the low R^2 values.

The analysis of forestry database attributes that might cause patch-wise area differences between the patch areas classified from difference image to that represented in the forestry database revealed that the relative boundary length of dark neighbours and bright neighbours rather than the patch parameters themselves were responsible for the discrepancies in the two area representations. Bright neighbours were clearcuts adjacent to studied patches that were felled between the two image dates and caused the classified from the difference image patch to be less than the respective area represented in the database. Dark neighbours were areas adjacent to the studied patches that had passed more than 18 years since disturbance but were not classified into no-change class, i.e. showed radiance decrease between the two dates of the images and caused the classified from the difference image patch to be greater than the respective area represented in the database. The lack of significant relationship between database attributes and area estimation errors implies that stratification of image area according to growing conditions in forest regeneration studies using winter images is not a requisite.

Conclusions

We assessed the influence of forestry database attributes on radiance of regenerating patches on a difference image of a two-date Landsat TM image pair. Both images were taken in late winter in seasonal snow cover conditions in a northern temperate forest area. The study also investigated the most sensitive to patch parameters Landsat TM spectral band in the visible and near infrared spectral region (TM1–TM4).

A significant effect of patch age – time passed since disturbance of clearcut logging on radiance difference of regenerating patches on a difference image in all studied spectral bands (TM1–TM4) was found. All of the Landsat TM bands used in the study were found to be equally sensitive to stand variables and suitable for monitoring of forest regeneration.

Regenerating clearcut areas as significantly changed areas in forests have been discerned from unchanged areas with thresholding of a two-date difference image. The threshold has been set to keep the total area of patches classified from the difference image equal to the total area of the patches represented in the forestry database. The results of the study have shown that there is no significant effect of stand variables on patch-wise differences between the patch areas classified from difference image to that represented in the forestry database. There is a significant effect of the type of neighbours – either bright neighbours or dark neighbours – on the estimation of the patch area on a difference image.

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ОЦЕНКА ВЕДУЩИХ ФАКТОРОВ, ВЛИЯЮЩИХ НА ИЗМЕНЕНИЕ ЗНАЧЕНИЙ ЯРКОСТИ ЗИМНИХ ИЗОБРАЖЕНИЙ В ВОССТАНАВЛИВАЮЩИХСЯ ВЫРУБКАХ СМЕШАННЫХ ЛЕСОВ, ПО ПОЛУЧЕННЫХ СО СПУТНИКА LANDSAT TM

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Резюме

Для изучения параметров, влияющих на формирование средней яркости пикселов возобновляющихся лесосек сплошных рубок, использовались зимние снимки, полученные с помощью сканера Thematic Mapper (TM) спутника Landsat. В данной работе для выявления временных изменений возобновления лесосек использовались методы разностных изображений, в ходе которого производится вычитание более раннего по времени снимка из позднего по времени снимка, преобразованного в шкалу яркости первого из них. Из таксационной базы данных лесничеств были выбраны лесосеки сплошных рубок и при помощи спутниковых снимков проанализированы факторы, влияющие на формирование средней яркости пикселов возобновляющихся лесосек на разностном снимке. Также были изучены параметры, влияющие на разность площадей объектов, полученных в результате классификации снимков при помощи порогового значения и из таксационной базы данных лесничеств.

В ходе данной работы изучены такие факторы: возраст, проводимые лесохозяйственные работы по улучшению произрастания, бонитет (по шкале Орлова), тип условий местопроизрастания, доминирующая порода древостоя, количество сохраняемых материнских деревьев и деревьев, оставленных на перестой. Для изучения второй проблемы были использованы формы изучаемых объектов, площадь по таксационной базе данных, приграничные пикселы, которые за период между снимками стали светлее – недавно проведенные сплошные рубки и те, которые за этот же период стали темнее – возобновляющиеся лесосеки сплошных рубок.

Было выяснено, что наибольшее влияние на формирование средней яркости пикселов возобновляющихся сплошных рубок на разностном снимке оказывает параметр возраст – время, прошедшее с момента вырубки. Это характерно для всех изученных каналов (TM1–TM4). Проанализировав зависимость площадей сплошных рубок от вышеперечисленных факторов, выяснилось, что параметры из таксационной базы данных лесничеств не оказывают влияния на различие площадей объектов, полученных в результате классификации снимков при помощи порогового значения. Наибольшее влияние оказывают приграничные пикселы, как относящиеся к классу недавно проведенных сплошных рубок, так и возобновляющихся лесосек сплошных рубок.

Ключевые слова: мониторинг изменений леса, возобновляющиеся лесосеки сплошных рубок, зимние снимки Landsat TM