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FOREST EDGES ON MEDIUM RESOLUTION LANDSAT THEMATIC MAPPER SATELLITE IMAGES

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LIST OF ORIGINAL PUBLICATIONS

The thesis is based on the following papers, which are referred to in the text by the relevant Roman numerals:

I Peterson, U., Püssa, K. and Liira, J., 2004. Issues related to delineation of forest boundaries on Landsat TM winter images. International Journal of Remote Sensing, 24, 5617–5628.

II Liira, J., Püssa, K. and Peterson, U., 2006. The radiance contrast of forest-to-clearcut edges on a medium-resolution Landsat Enhanced Thematic Mapper satellite winter image. International Journal of Remote Sensing, (in press).

III Püssa, K., Liira, J., and Peterson, U., 2005. The effects of successional age and forest site type on radiance of forest clear-cut communities. Scandinavian Journal of Forest Research, 20 (Suppl. No.6), 79–87.

The participation of the author in preparing the listed publications is following: 40% (paper I), 60% (paper II) and 70% (paper III).

INTRODUCTION

Forest ecosystems are constantly undergoing changes in response to several natural and anthropogenic factors. These changes range from the subtle transitions that occur in response to long-term processes, such as single tree dynamics or forest community succession, to drastic, rapid conversions such as fires, insect damage and also human activity, (e.g. clearcut logging) (Peterken, 1996; Esseen *et al.*, 1997; Bengtsson *et al.*, 2000; Kuuluvainen, 2002a). In order to provide vital information for nature conservation and sustainable management, it is important to assess the current status of forests and changes therein (Björse & Bradshaw, 1998; Noss, 1999; Terstad, 1999; Kuuluvainen, 2002b).

The use of remote sensing in ecological research and ecosystem management has increased significantly in recent decades (Holmgren & Thuresson, 1998; Pax-Lenney *et al.*, 2001; Cohen & Goward, 2004; McDermid *et al.*, 2005; Fassnacht *et al.*, 2006). Remote sensing has been found to be particularly useful when there is a need for (1) complete spatial coverage, especially over large areas; (2) monitoring or frequently repeated measurements; or (3) measurements in inaccessible or sensitive locations (Fassnacht *et al.*, 2006). For environmental monitoring and management, we can identify two broad types of information that can be derived from remote sensing data: the status and location of resources, land cover or land use, and their changes over time and space (Skole, 1997; Holmgren & Thuresson, 1998; Coppin *et al.*, 2004; Remmel *et al.*, 2005). There are several remote sensing programmes and networks that intend to provide this kind of information, e.g. Global Observation of Forest and Land Cover Dynamics (GOFC-GOLD) (Townshend & Brady, 2006) and the Northern Eurasia Regional Information Network (NERIN) (http://www.fao.org/gtos/gofc-gold/net-nerin.html).

Satellite remote sensing systems

A variety of remote sensing sensors operate throughout the electromagnetic spectrum from visible to microwave wavelengths. The most important spectral regions for remote sensing to date are the visible, near infrared and infrared wavelengths. Satellite data can be classified into three broad groups according to sensor spatial resolution: low-, medium- and high resolution data (Lillesand & Kiefer 2000). Low resolution satellite data, obtained for example from AVHRR (Advanced Very High Resolution Radiometer), the SPOT Vegetation Sensor (*Système Pour l'Observation de la Terre*) and MODIS (Moderate Resolution Imaging Spectrometer), cover extensive areas 1000 to 3000 km in width and have a pixel size from 0.25 to 1.1 km. Medium resolution satellite data acquired for example from Landsat, SPOT and the IRS (Indian Remote Sensing) satellite cover areas 60 km to 180 km in swath width and have a pixel size from 10 m to 30 m. High resolution satellite data provided for example by IKONOS, QuickBird, OrbView 3 and EROS cover areas of from 4 to 10 km in width and have a small pixel size from 1(Quickbird from 0.6 m) to 3 m.

Medium resolution satellite data have a reasonably small pixel size and wide swath width, which have made this a convenient and cost–effective source for mapping and description of ecosystems over large areas (Goward *et al*., 2001; McDermid *et al.*, 2005). In temperate regions it is quite difficult to obtain high quality, cloud-free time-series of yearly images over an extended time period. Therefore medium resolution data are a considerable source due to their acceptable quality, reasonably short revisit time interval and availability an observation period of two decades, which is sufficient for cost–effective historical inventory and continuous monitoring (Cohen & Goward, 2004).

Landsat data are available since 1972 (Lauer *et al*., 1997). The Thematic Mapper scanner operates in seven bands of visible and infrared spectral region with a resolution of 30 m (with an exception of 120 m spatial resolution in the thermal band). Band 1: 0.45–0.52 μm (blue), band 2: 0.52–0.60 μm (green), band 3: 0.63–0.69 μm (red), band 4: 0.76–0.90 μm (near infrared), band 5: 1.55–1.75 μm (mid-infrared), band 7: 2.08–2.35 μm (mid-infrared), band 6: 10.4–12.5 μm (thermal infrared). The ETM+ adds a panchromatic band (0.5–0.9 μm) at 15 m resolution (Lillesand & Kiefer 2000).

Landsat data can be used for the description of ecosystems by their condition and changes therein (forest fragmentation), thematic classification (e.g. forest classification – assessing timber volume, stage of succession) (Hall *et al*., 1991; Coppin & Bauer, 1994; Woodcock *et al*., 2001), deriving estimates of the biophysical characteristics of vegetation (LAI, biomass, canopy moisture content, canopy cover) (Chen & Cihlar, 1996; Turner *et al*., 1999; Gemmell *et al.*, 2002), for studying temporal dynamics of vegetation (both seasonal and interannual dynamics) (Woodcock *et al*., 2001; Coppin *et al*., 2004) and large-area mapping (Cohen & Goward, 2004; McDermid *et al*., 2005). From Landsat images one can reasonably easyly identify broad types of forest, find recent clearcuts and follow forest regeneration after clearcut logging (Walsh, 1980; Danson & Curran, 1993; Stibig *et al*., 2004).

Using remote sensing for forestry applications

There are several forestry-specific applications for which remote sensing can be used. These include the mapping and monitoring of changes in forested landscapes, mapping of clearcut areas and updating of existing forest inventories (Kushwaha, 1990; Coppin & Bauer, 1996; Joyce & Olsson, 1999; Pax-Lenney *et al*., 2001; Song *et al*., 2002; Makela & Pekkarinen, 2004). The detection of change between two or more periods is one of the most important uses of satellite remote sensing data in forestry applications (Cohen & Fiorella 1999; Lawrence & Ripple, 1999; Yuan *et al.*, 1999; Joyce & Olsson, 2000).

The mapping of land cover using remotely sensed images most commonly involves the determination of the reflectance or radiance of each pixel in order to assign it to one of a number of land cover classes (Atkinson *et al.*, 1997). The assumption is made that the signal of a pixel originates solely from the land area represented by that pixel. A distinctive feature of low- and medium resolution satellite images is the fact that usually more than one ground object is incorporated into the space of a corresponding single pixel, i.e. the pixel's overall spectral signature consists of each object's spectral signature in proportion to its area fraction on the ground (Shaw & Burke, 2003). In transitional regions a strong contrast is possible between neighbouring areas, and the contribution of neighbouring pixels to the radiance of edge pixels can be quite significant. Various sampling designs have been used to compare the accuracy of the derived forest map with a reference data set (Cohen and Justice 1999; Congalton and Green 1999; Cihlar 2000; Justice *et al.* 2000; Foody 2002). Error estimation is often restricted to large areas, and boundary areas are excluded from comparisons, mainly in order to avoid misregistration problems and to enhance high confidence with the reference data set (Richards, 1996; Wickham *et al.*, 1997; Cohen *et al.*, 1998; Mickelson *et al.*, 1998). Such accuracy assessments can be biased (Hammond & Verbyla, 1996; Muller *et al.*, 1998; Zhu *et al.*, 2000), and may not be representative of the entire image area, because the main source of errors – forest edges – is omitted. The improvement of the understanding of the causes of classification errors is considered to be of critical importance in habitat mapping (Congalton and Green, 1999; Yang *et al.*, 2001).

The monitoring of forest area and particularly the detection of changes over the years rely on correctly determined forest edge locations. Studies of the sensitivity of land-cover misclassification have found that the probability of classification errors tends to be higher at the edge between two land-cover types than in the patch interior (Congalton, 1988).

The location and accuracy of the delimited forest edges depends on the sharpness of the boundary, the spatial resolution of the available data and the subsequent methods used to detect them (Fortin and Edwards, 2001). Edges are sometimes differentiated as being either sharp and abrupt, or gradual and fuzzy (Forman and Moore, 1992; Strayer *et al.*, 2003). The sharp or abrupt boundary is best illustrated by a straight edge with a high contrast of forest and grassland or forest and clearcut.

Edge characteristics, stand attributes, biotic factors and edge location can determine the contrast between forested and nonforested areas and thus affect edge influence on vegetation (Næsset, 1998, Harper *et al.*, 2005). In remote sensing, forests are treated as assemblages of three-dimensional objects – trees that cast shadows on a contrasting background (Li & Strahler, 1985; Asner & Warner, 2003).

One of the possible sources of errors in forest edge delineation are shadows cast by trees. The common observation made about forests using Landsat-type instruments is likely to be affected by inter-canopy and between-canopy shading (Oker-Blom & Kellomäki, 1983; Seed & King, 2003). Shadowing is closely linked to the characteristics of plant canopies and is an important contributor to the radiance or reflectance properties of forests (Seed & King, 2003). The proportion of the shaded area in an image is the function of the solar elevation, solar azimuth angle, and viewing angle, spatial distribution of the objects and the spectral transmittance of the objects (Levin *et al.*, 2004). Hence shadows cast by trees can be one of the sources of errors in edge delineation (Holmgren & Thuresson, 1998). The spatial resolution of the civilian medium resolution satellite images is much coarser than that of the aerial photographs, and the distinction between edges and shadows is not well defined for short and commonly occurring objects (Shettigara & Sumerling, 1998). As concerns forests, the width of the shadow zone cast by boundary trees 20-25 m in height (a common stand height in mature northern temperate forests) corresponds to over one pixel in the Landsat ETM+ multispectral and over two pixels in panchromatic images, if the forest edge is perpendicular to the solar azimuth at image acquisition time.

Boreal and boreo-nemoral forests in the Northern temperate zone are characterized by temporal variations, both by seasonal and successional changes in reflectance. This has been shown to be another major cause of errors in forest mapping and change detection (Mas, 1999; Rogan *et al.*, 2002). The seasonal changes in forest reflectance may be much greater than those caused by subtle, long-term successional changes (Lambin, 1996, Nilson *et al.*, 2003). The successional changes in forest reflectance following clearcutting do not proceed linearly in time (e.g. Horler & Ahern, 1986; Peterson & Nilson, 1993; Song *et al.*, 2002). The nonlinear nature of reflectance change implies that the adequate characterization of forest development with remote sensing requires multiple images over time to minimize change omission errors (Song *et al.*, 2002; Lunetta *et al.*, 2004).

Studies from various biogeographic regions of the world have shown that changes in forest area, particularly those resulting from clearcutting, can be estimated using medium spatial resolution images (Cohen *et al.*, 1998; Woodcock *et al.*, 2001; Wilson & Sader, 2002; Betts *et al.*, 2003). Clearcuts are relatively small patches represented by a small number of pixels on medium resolution satellite images. These small clearcut patches are generally surrounded by mature forests and have a different reflectance than forests.

Specific features of winter images

Winter in boreal and hemi-boreal latitudes is the season with the greatest target to background contrast on predominantly two-class images composed of forest and non-forest classes. Dry snow cover causes a significant radiometric contrast between open areas and forests. The reflectance of snow is very high in the visible and near infrared part of the spectrum, where Landsat Thematic Mapper (TM) spectral bands 1 – 4 are located.

The surface brightness of a snow-covered area is a function of the type and density of vegetation and the depth and age of the snow (Robinson & Kukla, 1985; Winther & Hall, 1999). If an area is devoid of vegetation, snow depth and age are primarily responsible for brightness variability over the area. Brightness increases rapidly with snow depth. Once the depth reaches approximately 15 cm, a further increase in reflectivity with increasing depth is slow, and the age and state of the snow surface become the critical variables affecting surface brightness (Robinson & Kukla, 1985). The differences in spectral reflectance between different snow/ice cover types (frost, fine granular snow, medium granular snow and coarse granular snow) are relatively small in the visible bands, but large in the longer wavelength bands of the mid-infrared spectral region (Xiao *et al.*, 2002).

Landsat Thematic Mapper images from late winter – a non-traditional season – were used for forest mapping by Peterson (2003). The results of the study showed that forest mapping with winter images can give relatively accurate results, with overall accuracy exceeding 90% when compared to forest boundaries derived from a co-registered map with forest boundaries delineated from orthophotos. Both commission and omission errors tended to fall within a two-pixel-wide zone (60m) around the forest patches, i.e. forest boundary areas.

It can be hypothesized that shadows cast by trees on forest edges on to the bright snow of the surrounding open area make northwest-facing forest edges less sharp than edges facing in other directions. If this holds true for medium resolution satellite images, change studies should carefully consider images taken under different atmospheric and solar elevation conditions in order to distinguish real changes at forest edges from those stemming from conditions with different solar elevation and atmospheric haze.

This study was focused on investigating factors that influence the determination of forest boundaries on medium resolution satellite images, with particular emphasis on winter images.

We tested a method for forest mapping using thresholding (I). The aim of our study was to analyse the difference in radiance between neighbouring pixel rows at both sides of a forest edge on a medium resolution Landsat Thematic Mapper (TM) image, in order to determine the Landsat TM band and the threshold level at which forest edges are most clearly detected (I). The second aim was to assess differences in forest to non-forest edge contrast with respect to their azimuthal direction. It was hypothesized that shadows cast by trees situated on forest edges on the bright snow of the surrounding open area make north- or north-west-facing forest edges less sharp than edges facing in other directions.

We also characterized the radiance contrast at distinct forest edges of recently created clearcuts (up to ten years old) of mixed-wood boreal and boreo-nemoral forest types in Estonia (II). In this study a Landsat Enhanced Thematic Mapper (ETM+) satellite image was used. This radiance contrast was investigated in the visible and near infrared spectral regions (ETM+ bands 1–4) with a 30 m pixel size and ETM+ panchromatic band with a 15 m pixel size. Particular attention was devoted to the testing of the dependence of radiance contrast at forest edges on stand parameters and on the edge's azimuthal direction. We tested how the stand parameters at the forest edge and the azimuthal direction of the edge affect the contrast of radiance at a forest edge).

We also focused on the factors influencing the radiance of northern temperate forest clearcut areas (III). We aimed to find differences in the radiance of forest clear-cut communities from a variety of site conditions at different stages of the growing period. We tested the dependence of radiance in Landsat Thematic Mapper image bands 1–5 and 7 and normalized difference vegetation index (NDVI) on forest age, gap size and forest type within the first 10 years following clearcut logging in three key stages in the phenological cycle of clear-cuts, which corresponded to (1) winter with snow-covered ground and leafless deciduous vegetation, (2) rapid seasonal growth increase in May before *Betula* spp. budburst, and (3) the seasonal maximum in mid-summer (July).

MATERIAL AND METHODS

Study area and satellite image data

A Landsat TM sub-scene, Path 187 Row 19 according to the Landsat World-wide Reference System, dated March 10, 1996 covering a 50 km × 50 km area on the ground was selected for the first (I) study. We chose the study area due to its average forest cover and flat terrain. The most abundant forest types found in the region are deciduous and mixed deciduous forests (about 80%), composed of birch (*Betula pendula* and *B. pubescens*) and aspen (*Populus tremula*), with some Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) trees. Most of the outer boundaries of the forests in the study area have not been managed since the 1970s and even longer.

A Landsat 7 ETM+ image acquired on March 6, 2003, Path 187 Row 19, covering a 50 km × 40 km area on the ground, was used in the second (II) study. Data from Landsat 7 ETM+ bands 1–4 in the visible and near infrared spectral region with a nominal pixel size of 30 m, and the panchromatic band with a nominal pixel size of 15 m, were used in the analysis. About 60% of the studied forests were birch-dominated stands, 15% were Norway spruce dominated stands, 7% were Scots pine dominated stands, and 18% were stands of other deciduous species (mostly European aspen). The studied stands were state-owned forests managed for timber production. Clearcut felling in the stands was carried out as a normal commercial operation.

Three Landsat satellite images were used for the third (III) study: a late winter Landsat 5 TM image acquired on March 10, 1996 Path 187 Row 19, a Landsat 5 TM spring image acquired on May 1, 2000 (186/19) and a Landsat 7 ETM+ peak summer image acquired on July 10, 1999 (186/19). The size of the study area was 60 km x 45 km on the ground. The three Landsat TM images, made on March 10, 1996; May 01, 2000; and July 10, 1999, are henceforth referred to as winter, spring and summer images.

Five forest site type groups were investigated in this study: 1) dry boreal forests (*Vaccinium vitis-idaea* site type and *Oxalis – Vaccinium vitis-idaea* site type), 2) fresh boreal forests (*Oxalis – Vaccinium myrtillus* site type and *Oxalis* site type), 3) fresh boreo-nemoral forests (*Hepatica* site type and *Aegopodium* site type), 4) rich paludified forests (*Dryopteris* site type, *Filipendula* site type), 5) minerotrophic swamp forests (minerotrophic mobile water swamp forest site type). The forest type group nomenclature follows Paal (1997).

A database of Estonian state-owned forests together with maps of forest stand boundaries in vector format provided by the Estonian National Forest Survey was used for studies II and III. The database was used to extract forest stand parameters and the dates of clearcut logging.

Image processing

We used digital number (DN) thresholds to assign pixels to one of the two classes ‘forest’ and ‘non-forest’ in the first study. Conversion of the Landsat TM recorded data to ground reflectances was not considered necessary in this study. The threshold value was established as the average between the 2^{nd} and 98^{th} percentile values in the bimodal frequency distribution of the brightness of the Landsat TM bands. Thresholds were identified separately for each spectral band and were applied as global thresholds over the whole sub-scene area.

For the analysis of DN change about the selected threshold level (the average between the 2^{nd} and 98^{th} percentile values in the frequency distribution), in the first study (I) we established two additional classifications of the satellite image at a +10 DN level and at a –10 DN level of the reference/preliminary threshold.

A directional edge enhancement filter was applied to the geometrically corrected satellite image. Azimuthally oriented features were identified with a diagonal filter, since the solar azimuth at the time of the Landsat overpass was close to the south-east. Directional filtering was used to identify forest edges that were differently exposed to solar irradiance direction, in order to give the forest edge fragments an identifier and to assign an attribute of direction to the boundary segments, according to their relative position at the edge of a forest patch. Filtering also performed the task of keeping forest to open-area boundaries sharp, discarding the transitional, forest to forested-wetland boundaries, and eliminating from the analysis sinuous forest boundaries. The filtered image was used to construct a raster mask for the identification of mean DN values from a satellite image, separately for inner and outer one-pixel-wide buffer zones for every forest boundary segment. In the further analyses, the mean radiance values of each pixel zone within a segment were treated as observations, in order to avoid local spatial autocorrelation effects.

Forest area made up about 49% of our study area. We identified 575 major forest patches in the study area (on image) having edges with clearly expressed azimuthal direction. The respective set of edge fragments at least 10 pixels long was identified using directional filtering: 1417 north-east (NE), 1144 north-west (NW), 1278 south-east (SE) and 1184 south-west (SW) edge fragments, for a total of 5015 edge fragments.

In the second (II) study we applied a thresholding method that had been approved in the first study to create a map in which pixels were assigned to the respective forest or non-forest classes. The boundary zones in this study were defined in the same way as in the first study, extending one-pixel-wide rows into the forest and one-pixel-wide rows into the clearcut area from the edge itself. The width of the boundary zone so defined is comparable to the dimensions of the maximum tree height in the stands, and the actual forest edge and the stand shadow cast by forest boundary trees are located within the boundary pixels. Boundary zone pixel arrays were split into boundary segments representing single forest stand edges from the vector format stand map. The classification by thresholding was repeated with the threshold varied by ±5 DN and ±10 DN in order to quantify the sensitivity of forest-to-clearcut edge contrast to different forest-to-nonforest thresholding levels. The study comprised a total of 454 individual stand boundaries with forest on one side and clear-felled areas on the other. Only straight boundary segments at least 100 m in length separating clearcuts up to 10 years old and adjacent stands with a minimum height of 5 meters were selected.

In the third (III) study, a forest-stand data layer of Estonian state-owned forests was used on all satellite images to extract forest stand polygons, together with the data on site type and the year of clear-cut logging. 493 clear-cuts for winter, 689 for spring and 663 for the summer image of various ages from 1 to 10 years were selected. Those chosen were on relatively flat land. The selected polygons were restricted to a minimum of 2 ha in size. A clearcut mask was created from the polygons and a one-pixel-wide buffer was added inside to exclude mixed pixels from the areas of neighbouring stands. The average values of radiance in the Landsat TM bands were calculated for the clear-cut core areas.

Statistical data processing

In our first (I) study, the contrast of radiance on a forest edge was defined and tested as a regression slope value of the change of radiance intensity from the last pixel zone inside the forest to the first (neighbouring) pixel zone of the open area. Selection of the optimal TM band and threshold value proceeded in two steps. In the first step, General Linear Model (GLM) analysis was applied to detect major differences in edge radiance contrast (estimated regression slope values) between four Landsat TM bands, four intermediate cardinal points, and at three different levels of threshold value. All Landsat TM bands have a scale for DN of from 0 to 255, but the intermediate radiance values around the observed forest edge vary within different ranges for different bands. Therefore, in order to produce comparable results between TM bands, we standardized the digital number values of the satellite image within each Landsat TM band.

In the second step, we carried out a sub-sample GLM-analysis — the detailed analysis of a certain band or threshold value in light of the results of the first step.

In the second (II) study, the radiance contrast at recently created forest-to-clearcut edges was defined as the difference between the mean DN value of the (last) boundary pixel zone of the clearcut area and the mean DN value of the (first) boundary pixel zone of forest adjacent to the clearcut. The radiance contrast was calculated for the spectral (TM1-TM4) and panchromatic (PAN) bands of the Landsat ETM+ scanner. All forest parameters pertain to the adjacent forest stand sub-compartment.

The significance test of the effect of adjacent forest parameters (the mean height of the stand, the stem volume of the deciduous trees in the first layer, the stem volume of the pine trees of the first tree layer, the stem volume of the spruce trees of the first tree layer, the stem volume of the coniferous trees of the second tree layer) and clearcut edge parameters (the age of the clearcut – the time elapsed since edge creation in years, the shadow angle of the forest-to-clearcut edge) on radiance contrast in the boundary zone was performed using regression analysis.

Edge azimuth angle has been recalculated into horizontal shadow angle (subsequently we use the term ‘shadow angle’), relative to the direction of the Sun vector on the horizontal plane.

In the presentation of regression model parameters, we used standardized slope values, which makes it possible to compare the effect between different factors considered in this study. Standardization is also justified, since the regression parameters of the retained models are applicable only to the current Landsat ETM+ image, and the current values cannot be directly transferred to other circumstances.

In the third (III) study the dependency of the measured radiance of the forest clearcut areas on continuous variables, namely clearcut age and clearcut area, and factor-variable forest type group, was tested with General Linear Model (GLM) analysis for all six Landsat TM bands separately (TM1 – TM5 and TM7). In winter image analyses we used four Landsat TM bands (1–4); in the spring and summer images we also included Landsat TM bands 5, 7 and the Normalized Difference Vegetation Index (NDVI) into the analysis. The second level interactions between factors describe the changes in radiance with increasing age and increasing area of clearcut in different forest type groups. The rate of change of TM band radiance with clearcut age was estimated as the regression slope of the model for radiance. The Newman-Keuls multiple comparison test was used to describe differences in reflectance between forest type groups.

All significance tests were carried out in Statistica Version 6.0.

RESULTS

In the first study (I) we analysed the effect of factors influencing radiance contrast at forest edges, in order to find the optimal method for the delineation of forest boundaries on medium-resolution satellite images.

The testing of factors in the GLM analysis showed that the threshold value, cardinal point direction and Landsat TM band have a significant effect on (standardized) radiance intensity in the forest border-area. The second and third order interactions between the factors demonstrate the existence of statistically significant differences in the radiance contrast between pixels of the last forest pixel zone and pixels of the first open area pixel zone at different threshold levels, in different spectral bands, and also that threshold value effect varies between spectral bands. Slope parameter estimation at three threshold levels shows that the regression slope at the forest boundary is steepest at the intermediate threshold level (test of contrast within the model; P=0.0001), at the average radiance level of the image. Additional classifications at a –10 DN and +10 DN level of the intermediate threshold level had significantly gentle slope.

Therefore sub-sample GLM analysis was performed in order to compare brightness contrast between spectral bands and intermediate cardinal points at an intermediate threshold level. Brightness contrast at the forest boundary varied significantly between spectral bands and did not depend on cardinal point direction (cardinal point direction and all interaction terms non-significant). The slopes of the brightness in Landsat TM spectral bands 2, 3 and 4 were significantly steeper than the slope in spectral band 1 (P=0.0001). The three steepest slopes were statistically homogeneous and cannot be ranked.

Our results suggest that the most effective determination of the forest boundary on a wintertime satellite image could be carried out using average satellite image brightness intensity in Landsat TM bands 2, 3 or 4.

In the second study (II), we investigated the factors of the radiance contrast at a recently created forest-to-clearcut edge in the visible and near infrared spectral regions (ETM+ bands 1–4) and in the ETM+ panchromatic band on a Landsat ETM+ image. We found that about 30% of the variation in the radiance contrast was described by the parameters of stand structure, edge and clearcut area.

The testing of the effects of stand structure, clearcut area and edge parameters on radiance contrast showed that in all Landsat ETM+ bands except TM4, the reflectance contrast depended on the height of the predominant tree species, the stem volume of the coniferous tree species in the first and second tree layers of the adjacent forest, clearcut age and edge orientation. The radiance contrast observed in TM4 was less sensitive and did not depend on the clearcut age and the stem volume of the pine in the first layer.

The standardized slope values of the regression models showed that the stem volume of the spruce in the first layer and the pooled volume of coniferous species in the second layer (predominantly spruce regrowth) have the strongest effect on the radiance contrast of forest edges. The volume of deciduous trees did not have a significant effect on radiance contrast in any of the TM bands.

There was a strong non-linear radiance contrast pattern at the forest-to-clearcut edge and the shadow angle. The contrast was the greatest for edges that were parallel or almost parallel to the Sun vector (shadows parallel to forest edge, shadow angle close to zero), and the radiance contrast decreased with increasing shadow angle. Shadows nearly perpendicular to the forest edge caused the fuzziest edge zones on the image.

The radiance difference between two pixel zones of recently created forest-to-clearcut boundary may be predicted by shadow size and intensity, which is determined by stand height and edge segment orientation. In the case of small differences between solar illumination and edge orientation angles, the shadows of trees are cast parallel to the edge, and thus the radiance contrast is strongest. As illumination azimuth and edge azimuth diverge, the shadowing of clearcut areas becomes more important, and the radiance contrast of forest-to-clearcut edges decrease.

In the third study (III), we tested the dependence of reflectance in Landsat TM bands 1–5 and 7 and NDVI on clearcut age, clearcut area size and forest site type group within the first 10 years following clearcut logging in three different seasons (winter, spring and summer).

The testing of factors in the GLM analysis showed that in winter images, forest type (as the main effect) had a significant effect on radiance in all of the analysed Landsat TM bands. There was a non-linear dependence on the age of Landsat TM visible bands (TM1-TM3). Only TM band 4 (near-infrared) did not show any changes in radiance in a winter image succession during the first 10 years after clear-cut. Generalized trends of radiance along the age gradient for different forest types occupied a very narrow range on Landsat TM images. These trends were statistically similar for all forest site type groups. As concerns clearcut area radiance, the influence of clearcut area size in the forest was statistically significant and different between forest site type groups in visible bands, but not at near-infrared frequency.

In the spring image the radiance depended on the forest site type group (as main effect) and clearcut age in Landsat TM bands 1, 2, 3 and 5, while TM bands 4 and 7 were insensitive to all studied forest or clear-cut parameters. Changes in radiance in relation to the successional age of clearcut areas were statistically different between forest site type groups in Landsat TM bands 1, 2, 3 and 7. Differences in the radiance pattern of forest site type groups were caused by the revealed linear or non-linear age trends in TM bands 1, 2, 3 and 5 for most of the forest site type groups except fresh boreal forests. Clearcut area size had no statistically significant effect on the radiance of clearcut areas in the spring image. The vegetation index NDVI similarly depended on clearcut age in all forest site type groups, while the area effect was forest site type group specific.

In summer, when green vegetation biomass is seasonally at a maximum, the radiance of all TM bands and NDVI values depended on the clearcut area age. These linear trends of radiance were only forest site type group specific for TM band 4 and NDVI, and non-linear trends of radiance were type specific for TM band 5. The size of the clearcut did not have a statistically significant effect on radiance, and there were no forest site type group specific differences.

DISCUSSION

In the first study (I) we tested a method for forest mapping using the thresholding of a Landsat TM image made in late winter in plain snow cover conditions. The snow cover offers good conditions for the mapping of forests using medium-resolution satellite images in winter in mid-latitude to boreal regions. Snow cover causes a significant radiometric contrast between bright open areas and dark forests in the visible and near infrared spectral regions. While verifying the optimal forest delineation threshold, we hypothesised that the brightness contrast at the forest boundary is greatest around the optimal threshold, and that the contrast of radiance between neighbouring pixels will decrease when diverging from the optimal threshold. Our study (I) showed that the radiance contrast was greatest at the intermediate threshold level, therefore in future analysis we used only this threshold level.

There were no differences in the brightness contrast at forest edges in the three Landsat TM bands (TM2, TM3 and TM4) in the visible and near-infrared spectral region. No clear preference could be given to any of the Landsat TM visible bands in forest boundary delineation. Only Landsat TM band 1 was significantly less effective. It should be noted that the blue spectral region tends to be more saturated than other visible and near-infrared spectral regions with low atmospheric haze level on later dates in March.

We also hypothesized that the shadows cast by trees on forest edges onto the bright snow of the surrounding open area make the radiance gradient dependent on the azimuthal direction of the forest edge. It follows that we could not use one global threshold level over the whole scene area due to the azimuthal differences of the forest edges because these azimuthal differences may induce systematical errors in the estimates of forest area. The results of our study support the methodology of using one global threshold level over the whole sub-scene area, since we did not detect significant differences in the contrast of differently exposed forest edges (I). The model slope values were found to be homogeneous in all cardinal directions, at least in the case of edges whose position remained unchanged over several decades. Ground observations of the area revealed that these long unchanged (old) forest edges in the study area consist mostly of deciduous trees and demonstrate a gradual transition in structure. The old forest edges are probably not distinct enough that the effect of azimuth orientation on boundary zone radiance contrast – the shadow effect – could occur. We can assume that the shadow zones are not well defined, particularly if deciduous trees predominate in the forest border, and therefore we were unable to observe the effect of cardinal point direction on the old forest edge. However, one could expect that the shading effect should be more pronounced at young clearcut area edges than at permanent forest edges bordering on agricultural land.

The shadow effect has been widely observed in remote sensing, but mostly considering inside canopy shadowing (e.g. Li & Strahler, 1985; Leblon *et al.*, 1996; Seed & King, 2003). Shadowing can explain a remarkable portion of the variance in a remotely sensed image of a forest stand, as demonstrated by the geometric-optical modelling of forest canopies (e.g., Li & Strahler, 1985; Nilson, 1990). The amount of incoming solar radiation transmitted through tree canopies and the radiance of cast shadows is largely influenced by crown volume and architecture. Canopy architecture – branching pattern, foliage and shoot clumping – has been demonstrated to influence crown light transmittance and canopy shadowing (Ross, 1981; Oker-Blom & Kellomäki, 1983; Kuulu-vainen & Pukkala, 1987; Leblon *et al*. 1996; Seed & King, 2003).

The results of our second study in recently created forest-to-clearcut boundary areas provided the evidence that radiance contrast may be dependent on forest stand composition, the three-dimensional structure of stands and also clearcut area parameters or edge azimuth, and that these effects can be detected on medium spatial resolution Landsat images (II).

According to our analyses of radiance contrast at forest-to-clearcut edges in the winter image, deciduous trees do not significantly affect forest edge radiance contrast, while coniferous species do (II). Coniferous and deciduous trees have different crown structures. Deciduous trees have more open crown architecture and coniferous trees tend to have closed crown architecture, which decreases light transmission through the crown (Seed & King, 2003). Further-more, deciduous trees are leafless in winter, and their crowns are relatively transparent to incoming solar radiation. It has been observed that the reflectance of snow shadowed by deciduous trees (birch) is higher than snow shadowed by spruce and pine (Vikhamar & Solberg, 2003) and, according to our own reflectance measurements of shadows cast on a snow surface, the reflectance of the shadow of deciduous trees is more variable than that of the shadow of coniferous trees.

We also observed that coniferous species (Norway spruce and Scots pine) have a different shadowing effect – the effect of pine on edge radiance was weaker than that of spruce. This effect could be induced by the different crown structure of these species. Internal crown structure has been mentioned as one of the significant factors determining the reflectance of the forest canopy (Li & Strahler, 1985; Chen & Leblanc, 1997).

In studying the radiance of early successional (up to 10 years old) clearcuts, the contrast at forest-to-clearcut edges varied significantly as a function of clearcut age, suggesting the presence of at least short-term responses (within 10 years) of the boundary zone to clearcut edge creation (II).

The decrease in edge contrast with fragmentation age, observed even during the first ten years after clearcut logging (II), could be attributable to successional changes on the clearcut side of the boundary and not so much to changes on the forest side of the boundary. In the first years after clearcut logging, the main factor in the development of the vegetation is the herbaceous layer (Lõhmus, 1970). The tree cover of regenerating clearcut areas in the first 10 years of the succession is relatively low, but the proportion of shaded ground increases continuously, and finally the vegetation canopy stratifies into sunlit and shaded tree crowns. Nilson and Peterson (1994) showed that the decrease in the sunlit background fraction leads to a decrease in reflectance during the early period of the succession, i.e. the period when trees and shrubs establish the gaps in the vegetation. We expected that the rapidly increasing density and height of sapling stems, the litter of herb plants above the snow surface and the shadows cast on the snow induce the clearcut area's radiance to decrease during the first decade of forest regrowth. Therefore in the following step (III) we focused on radiance in clearcut areas with different age and size from five different forest site type groups in three phenological stages (winter, spring, summer).

Over all three seasons, there was a non-linear dependence of radiance on the forest clear-cut age, but the forest-type-specific trends in radiance with age were mostly observed in the spring image. As we found in the winter image, even if successional trends of reflectance were observed in TM bands 1–3, clearcut areas do not show any significant variations of reflectance between habitat type conditions during the first 10 years of the reforestation (III). This observation supports the idea of the usefulness of winter images for the mapping of forest clear-cuts.

Peterson (1992) showed that after clearcut logging the most rapid recovery is noted in fertile mesic growing conditions. Our study supported this suggestion, particularly in the spring image. The clearcut areas on more fertile and fresh soil conditions (e.g. the *Aegopodium* forest site type) had predominantly higher radiance levels than regenerating forests on dry sandy soils (III). In his earlier study, Peterson (1992) found that the maximum seasonal value of NDVI, near-infrared reflectance and the rate of change of these indices in spring and early summer all decreased with the decreasing availability of moisture and nutrients in the soil of clearcut areas. According to our observation in the summer image, at maximum vegetation biomass the age of the clearcut area had a strong effect on radiance in all TM bands and on the NDVI, particularly in the first years of the succession. Then, on the clear-cut areas with ages of 5–7 years, the radiance in all TM bands and the NDVI saturates in the case of dense leaf canopies. This could be expected, as the radiance in the visible and the near-infrared spectral region is dependent on the amount of photosynthetically active biomass (Pinter *et al*., 2003). These trends are comparable in all studied forest types, although there are some forest-type-specific trends in NDVI and in radiance in the near-infrared spectral region, which may be attributable to differences in tree species composition (Verhoef & Bunnik, 1981).

In conclusion, late winter images with snow-covered ground are the images with the best phenological timing for the measurement of forest area on medium resolution satellite images. The high radiance difference between forest and non-forest area, the equal suitability of several Landsat TM bands and the small error rate caused by cast shadows facilitate the delineation of forest edges.

Finally, because of the stability of the radiance contrast at forest edges over several years after clearcutting that is rather similar over forest type groups during forest regeneration medium resolution satellite images can be considered a suitable tool for monitoring forest change regionally.

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SUMMARY IN ESTONIAN

METSASERVAD KESKMISE RUUMILISE LAHUTUSEGA SATELLIIDI LANDSAT SKANNERI THEMATIC MAPPER SATELLIIDIPILTIDEL

Kasutades kaugseireandmeid satelliidipiltide näol on võimalik anda kogu Eesti ala katvaid hinnanguid metsades toimuvate muutuste, metsadesse raiutud lageraiealade ning alles metsastumise algjärgus olevate sööti jäänud alade pindala suhtes. Lageraiealade raiumine metsadesse on viimase viieteistkümne aasta kestel olnud põhiliseks metsaga metsamaa pindala ning sellega seotud maastikumustri muutust mõjutavaks teguriks.

Antud töö hõlmab keskmise ruumilise lahutusega satelliidipiltidelt metsaserva asendi määramise metoodilist käsitlust, kuna pilditöötluse tulemusena ilmnevad metsapiiri muutused avalduvad eeskätt metsa servaaladel.

Käesoleva töö eesmärgiks oli hinnata satelliidipiltidelt mõõdetud heleduse kontrastsust metsa- ja raiesmikukoosluste servaaladel. Satelliidipiltideks olid keskmise ruumilise lahutusega satelliidi Landsat skannerite Thematic Mapper (TM) ja Enhanced Thematic Mapper (ETM+) hilistalvised pildid märtsikuust, raiesmike heledust mõjutavaid tegureid käsitleva artikli lähteandmestikuna lisaks ka pildid mai algusest ning juuli keskpaigast. Kasutatud satelliidipiltide piksli suurus skannerite spektraalkanalites oli 30 m maapinnal ning Landsat ETM+ pankromaatses kanalis oli 15 m maapinnal. Talvistel lausalise lumikattega oludes tehtud piltidel on metsaservade heleduse kontrastsus suurem kui teistel aastaaegadel tehtud piltidel ning seega servaalade heleduse sõltuvus metsaserva orienteeritusest ilmakaarte suhtes, metsaservas kasvava puistu parameetritest ning serva vanusest – lageraidest möödunud ajast – eeldatavalt kõige selgemini väljendunud. Kuna talvel on metsi ümbritsevad lagedad alad ühetaoliste objektidena, lagedate lumeväljadena, võib eeldada, et heledale lumele puistute heidetud varjude tõttu on ilmakaarte suhtes erineva ekspositsiooniga metsaservades heleduse kontrastsus metsalt lagedale alale erinev. Vaadeldes olukorda, kus metsaservade seas domineerivad pikaajaliselt, aastakümneid samas paigas püsinud välisservad ilmnes (I), et keskmise ruumilise lahutusega satelliidipiltidel spektri nähtavas ja lähisinfrapunases piirkonnas metsaserva heleduse gradient metsaserva asimutaalsuunast ei olene. Niisugune järeldus toetab talvistel piltidel klassi "mets" eristamiseks ühetaolise klassifitseerimisotsuse rakendamist kogu pildivälja piires.

Uurides metsaalade siseservi, raiesmike servi, selgus (II), et servaalade heleduse kontrastsus on suurem neis raiesmike servades, mille asimuut on satelliidipildi tegemise hetkel olnud päikese tasandiga samas sihis. Servaalade heleduse kontrastsus vähenes metsaserva asimuudi ja päikese tasandi vahelise suurenedes. Metsaserva puistu puude kõrgus ning okaspuude tüvemaht osutusid puistu parameetriteks, mille seos metsaserva heleduse gradiendiga oli tugevaim.

Metsa ja raiesmiku servaala heleduse kontrastsus vähenes lageraidest möödunud aja pikenedes. Kõigil uuritud puistu parameetritel, samuti metsaserva asimutaalsuunal ning lageraidest möödunud ajal oli ühetaoline mõju metsaserva heleduse kontrastsusele nii spektri nähtavas kui ka lähisinfrapunases piirkonnas.

Uurisime ka Landsat TM satelliidipiltidelt mõõdetud raiesmikukoosluste

heleduse olenevust metsakasvukohatingimustest, lageraidest möödunud ajast aastates, raiesmiku pindala suurusest ning pildistamise ajast kasvuperioodi kestel (kevadel ja suvel) ning talvel (III). Tulemused näitasid, et raiesmike eristamiseks keskmise ruumilise lahutusega satelliidipiltidelt on kõige sobivamaks talvised pildid, kuna neil ei kajastu kasvukohatüübist tulenevad erinevused. Metsa kasvukohatüübispetsiifilised muutused heleduses avaldusid kõige selgemini kevadisel pildil.

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THE RADIANCE CONTRAST OF FOREST-TO-CLEARCUT EDGES ON A MEDIUM RESOLUTION LANDSAT ENHANCED THEMATIC MAPPER SATELLITE WINTER IMAGE♣

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Forest logging results in decreased and fragmented forest area and the increased appearance of edge habitats. The monitoring of forest area and particularly, the detection of changes over the years relies on correctly determined forest edge locations.

Our objective was to characterize the radiance contrast at the sharp forest edges of recently created clearcuts of boreal and boreo-nemoral forests in Estonia. Radiance data were derived from a medium resolution Landsat Enhanced Thematic Mapper (ETM+) satellite image taken in late winter, in March. In the winter image there is a high radiance contrast at the forest to clearcut boundary area. This radiance contrast was investigated in the visible and near infrared spectral regions (ETM+ bands 1–4) with 30m-pixel-size resolution in the spectral bands and 15 m-pixel-size in the ETM+ panchromatic band. The analyses of radiance contrast at clearcut to forest edges reveal the effects of stand parameters, clearcut age and azimuthal exposure. The results of the analyses show that the radiance contrast between forest and clearcut area depends on the stand height and stem volume of coniferous trees in the first and the second tree layer. The stem volume of deciduous trees had no statistically significant effect on the variation of radiance contrast at the forest edge. A significant non-linear effect of the edge exposure to sun was found, indicating a shade length effect. Shade and forest structure affect edge detection on medium resolution satellite images.

Keywords: Landsat TM, forest edges, forest management, image classification, monitoring methods, radiance contrast, winter image.

♣ Radiance contrast of forest clearcut edges

INTRODUCTION

Studies from various biogeographic regions of the world have shown that clearcut forest harvest activity can be estimated using medium spatial resolution images (e.g. Cohen *et al.* 1998; Woodcock *et al.* 2001; Wilson and Sader 2002; Betts *et al.* 2003). Various sampling designs have been used to compare the accuracy of the derived forest map with a reference data set (Cohen and Justice 1999; Congalton and Green 1999; Cihlar 2000; Justice *et al.* 2000; Foody 2002). Error estimation is often restricted to large areas, with boundary areas excluded from comparisons, mainly to avoid misregistration problems and to enhance high confidence with the reference data set (Cohen *et al.* 1998; Mickelson *et al.* 1998; Richards 1996; Wickham *et al.* 1997). Such accuracy statements can be biased (Hammond and Verbyla 1996; Muller *et al.* 1998; Zhu *et al.* 2000) and may not be representative of the entire image area, because the main source of errors – the forest edges – is skipped. Improving the understanding of the causes of classification errors is considered to be of critical importance in habitat mapping (Congalton and Green 1999; Yang *et al.* 2001).

In remote sensing, forests and woodlands are treated as assemblages of three-dimensional objects – trees that cast shadows on a contrasting background (Li and Strahler 1985). The common observation made about forests using Landsat-type instruments is likely to be affected by inter-canopy and between-canopy shading. Shadowing is closely linked to the biophysical characteristics of plant canopies and is an important contributor to the radiance or reflectance properties of forests. Although shadowing is present in the observations, medium-resolution satellite images have too low a spatial resolution to make it possible to observe shadows directly.

The radiance of the forest canopy is an area-weighted sum of four radiance components: the sunlit crown, the shaded crown, the sunlit background and the shaded background.

Studies on the sensitivity of land-cover misclassification have found that classification errors tend to be higher at the edge between two land-cover types than in the patch interior (Congalton 1988).

In addition to the spatial resolution of satellite data, the location and accuracy of the delimitation of forest edges also depend on the sharpness of the boundary, and the subsequent methods used to detect them (Fortin and Edwards 2001). Edges are sometimes differentiated as being either sharp and abrupt, or gradual and fuzzy (Forman and Moore 1992; Strayer *et al.* 2003). The sharp or abrupt boundary is best illustrated by a straight edge with high contrast of forest and grassland or forest and clearcut. On medium resolution satellite images, positional errors at edges of contrasting neighboring patches may be caused by characteristics of the forest and non-forested area and by the shadows cast by trees (e.g. Næsset 1998). The area extent (shadow length) and brightness of the shadows cast depends on the solar altitude, tree height, stand density, and tree species composition (Holmgren and Thuresson 1998).

The solar elevation at pre-boreal latitudes is not high at the time of satellite overpass in late winter, in March (about 25–30º). The width of the shadow zone cast by boundary trees of 20–25 m in height (a common stand height in mature northern temperate forests) corresponds to over one pixel in the Landsat ETM+ multispectral and over two pixels in panchromatic images, if the forest edge is orientated perpendicular to the solar azimuth at image acquisition time. There is not a distinctive boundary, but a jagged transitional zone between shadowed and non-shadowed regions on clearcuts, induced by the varying height of trees – at or near the forest edge. The resolution of remotely sensed images determines the smallest spatial resolution unit at which boundary locations can be delimited (Fortin *et al*. 2000; Fagan *et al*. 2003). Pixel size in medium resolution satellite images is several times greater than the average size of tree crowns in a forest, and the edge area includes pixels with various proportions of forested and non-forested land. The forest-to-non-forest boundary area interpretation is also confounded because the signal represented by a pixel on a satellite image is not derived solely from a ground area represented by the pixel itself, but also comes from neighbouring areas (Townshend 1981). Such effects constitute an inherent source of uncertainty in satellite image interpretation because signals from beyond a pixel's area will contribute to the value assigned to it (Huang *et al.* 2002). This is a consequence of many factors, including atmospheric effects and image resampling, the optics of the instrument, the detector, and electronics (Markham 1985; Schowengerdt 1997; Townshend *et al*. 2000). Forest-to-clearcut edges are therefore often not sharp step edges on medium resolution satellite images, but take the form of brightness ramps over a number of pixels.

The results of the previous study on the forest to non-forest boundary radiance contrast on winter images indicated no statistically significant differences in boundaries facing in the four cardinal directions (Peterson *et al.* 2004). Only permanent forest edges were included in this study. These permanent forest edges incorporate a zone of shrubs in the outermost part of the border area, causing a gradual change of radiance at forest to non-forest edges.

One can expect that, in the case of edges with a sharp change from forest to open land (e.g. recent forest clearcuts), the contrast of radiance should be magnified and the boundary effects depending on stand structure and edge cardinal direction should be detectable.

Our objective is to characterize the radiance contrast at distinct forest edges of recently created clearcuts (up to ten years old) of mixed-wood boreal and boreo-nemoral forest types in Estonia, using a medium resolution Landsat Enhanced Thematic Mapper (ETM+) satellite image. To provide a strong radiance contrast at forest edges we used a late winter (March) image. The high clearcut-to-forest radiance contrast in the winter image allows us to evaluate whether there are significant factors that could affect forest to non-forest classification results on medium resolution satellite images.

In this study we attempt to answer the following questions:

Do the stand parameters at the forest edge (i.e. stand height and tree canopy composition) and azimuth direction of the edge have an effect on the contrast of radiance at a forest edge? Are these effects revealed on winter- time (leaf-off forest) medium resolution Landsat ETM+ images? To what extent does the contrast of radiance at a forest edge depend on the regrowth of trees and shrubs on recently created clearcuts within ten years following clear-cut logging?

MATERIAL AND METHODS

Study area

The study area chosen for this study is located in Central Estonia (centered at 58º20'N, 26º30'E) and represents a typical northern temperate forest of mixed stands dominated by Birch (*Betula pendula*), Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*) and European aspen (*Populus tremula*). The size of the study area is about 50 km by 40 km and the terrain is undulating with altitudes ranging between 40 and 80 m above sea level. The stands were state-owned forests managed for timber production. Clearcut felling was carried out as a normal commercial operation. A GIS database of Estonian state-owned forests (Estonian National Forest Survey) was used to extract forest stand parameters and the dates of clearcut logging. The study comprised a total of 454 individual stand boundaries with forest on one side and clear-felled areas on the other.

Considering the spatial resolution of the Landsat scanner (30 m and 15 m), only straight boundaries of stands adjacent to clearcuts of at least 100 m in length were selected. The stand maps were used to select the forest stands with sufficient border length. Small and narrow patches of clearcuts were avoided, since clearcut area radiance is significantly dependent on the opening size (Püssa et al. 2005). A relatively small patch size also makes it difficult to isolate the boundary radiance gradient caused by one edge from the influences of another edge on the other side of the opening. The azimuth of forest-to-clearcut boundaries was also extracted from the vector-layer stand maps.

The studied clearcuts were logged up to 10 years before the image acquisition date, i.e. the year of logging was between 1994 and 2003. Most of the clearcuts are predominantly oblong rectangular in shape. Forest edges faced different azimuthal directions, although the predominant management practice orients the longitudinal axis of clearcuts in north-south direction, perpendicular to the prevailing wind direction.

The stands on the forest side of the boundary represented different combinations of tree species. About 60% of the studied forests were Birch-dominated stands (*Betula pendula* and *B. pubescens*), 15% – Norway spruce (*Picea abies*) dominated stands, 7% – Scots pine (*Pinus sylvestris*) dominated stands, and

18% were stands of other deciduous species (mostly European aspen (*Populus tremula*)).

The mean stand age of the studied forests was 61 years (Std.Dev. 22) and the mean height of the first tree layer was 22 m (Std.Dev. 6).

Satellite data

A medium resolution satellite Landsat 7 Enhanced Thematic Mapper (ETM+) image acquired on 06 March 2003, Path 187 Row 19 in the Landsat Worldwide Reference System, was used in this study (see figure 1). Solar elevation at the image acquisition time was 24º, and the solar azimuth was 159º (reference to the North). The snow cover had remained at a thickness of about 15 cm for two weeks before the time of data capture and was measured at 13 cm at the Estonian Meteorological and Hydrological Institute weather station at Tõravere, located within the study area. Daily maximum air temperatures remained below 0ºC since the beginning of February 2003. Last snowfall with measurable precipitable water of 1 mm was on February 23 (data of Tõravere weather station), ten days before the image date. There was no significant snow in the tree crowns on the image acquisition date.

The image was georeferenced using 1 m resolution 1:10,000 panchromatic digital orthophoto quadrangles. The images were geometrically registered to the Estonian National Coordinate System (Lambert-Est) using the nearest neighbour resampling algorithm and a linear transformation. For the registration of both multispectral and panchromatic images, the total root mean square error was kept below 0.4 pixels. Atmospheric correction was not applied because statistical analyses relied on relative radiance differences of neighbouring pixels within one scene and within a restricted area. The relative uncalibrated units of the scanner data, the so-called digital numbers (DN), in the 8-bit radiometric scale, were used in the analysis.

Data from Landsat 7 ETM+ bands 1–4 in the visible and near infrared spectral region with a nominal pixel size of 30 m, and the panchromatic band with a nominal pixel size of 15 m, were used in the analysis. Data from bands 5 and 7 were not used due to the very low dynamic range in these bands in low illumination conditions with snow-covered ground in late winter.

We used a thresholding method (Peterson et al. 2004) to create a map in which pixels were assigned to one of the two classes of interest: forest and non-forest. Figure 1 presents a subset of the studied area and a bimodal frequency distribution of image pixel brightness values of the Landsat ETM+ visible red spectral band (TM3) for this image fragment. Other Landsat ETM+ visible and near infrared spectral bands and the panchromatic band have a similar frequency distribution.

After applying post-classification treatments, such as the elimination of small patches, misclassification errors are quite small. From previous studies, we know that the most suitable value of thresholding on a winter image for classification into forest and non-forest was the average of the 2nd and 98th percentile in pixel brightness of the Landsat ETM+ bands (Peterson et al. 2004).

The validation of thresholding was performed using a vector format national base map at scale 1:10,000, which was also rasterized into two classes "forest" and "non-forest". A set of map sheets, 5 km x 5 km on the ground, was cross-tabulated against the classified image. The commission and omission errors of the two classes were less than 5%. The boundary zone was defined as extending one pixel wide zone into the forest and one pixel wide zone into the clearcut area from the edge itself. The width of the boundary zone is comparable to the dimensions of the maximum tree height in the stands, and the actual forest edge and shadow edge are located within the boundary pixels. Boundary zone pixel arrays were split into boundary segments representing single forest stand compartment edges from the vector format stand map (see figure 2).

The classification by thresholding was repeated with the threshold varied by ±5 DN and ±10 DN in order to quantify the sensitivity of forest-to-clearcut edge contrast to different forest-to-nonforest thresholding levels. Our preliminary tests showed that the contrast differences in boundary area did not change significantly with variations in the threshold value of the Landsat TM visible and near infrared image (Peterson et al. 2004).

Statistical treatment

Radiance contrast at forest-to-clearcut edges was defined and tested as the difference between the mean DN value of the (last) boundary pixel zone of the clearcut area and the mean DN value of the (first) boundary pixel zone of forest adjacent to the clearcut. The radiance contrast was calculated for the spectral (TM1-TM4) and panchromatic (PAN) bands of the Landsat 7 ETM+ scanner. All forest parameters pertain to the adjacent forest stand subcompartment. We included only those clearcut areas thatwere less than 10 years old and were adjacent to forest with a minimum stand height of 5 meters.

Edge azimuth angle has been recalculated into horizontal shadow angle (further we use term 'shadow angle'), relative to the direction of the Sun vector on the horizontal plane. The azimuth of the forest edge was transformed into shadow angle as follows: edges with the Sun vector azimuth (159°) and the opposite direction of the Sun vector azimuth (159°+180°=339°) were set to be equal to 0°, i.e. the direction of the forest edge where shadows cast by trees are parallel to the forest edge. Forest edges perpendicular to the Sun vector and casting shadows with maximum length on the clearcut area (azimuth of edge 249°) received a shadow angle value of +90°, and edges perpendicular to the Sun vector and casting shadows into the forest area (azimuth of edge 69°) were given a shadow angle value of –90° (see figure 3). All other azimuth directions of forest edges were recalculated according to these endpoint values.

The evaluation of the effect of forest and clearcut edge parameters on radiance differences in the boundary zone was performed for Landsat TM bands TM1 (blue), TM2 (green), TM3 (red), TM4 (near infrared) and PAN (panchromatic) using regression analysis in the Statistica version 6.0 program package.

The regression model that describes the radiance contrast at the forest edge consisted of (1) the mean height of the adjacent forest stand (ST_HEIGHT), (2) the stem volume of the deciduous trees (DEC_I) in the first tree layer, (3) the stem volume of the pine trees in the first tree layer (PINE_I, (4) the stem volume of the spruce trees in the first tree layer (SPRUCE_I) (5) the stem volume of the coniferous trees in the second tree layer (CON_II), (6) the age of the clearcut – the time in years since edge creation (CL_AGE), and (7) the shadow angle of the forest-to-clearcut edge (S_ANGLE). The square term of shadow angle (S_ANGLE^2) was included in the model to test for non-linear trends in the contrast of reflectance at the forest edge. The non-linear change in the perpendicular length of the tree shadows relative to the edge in the open area can be expected to be in accordance with the change in edge azimuth relative to the sun vector. In the presentation of regression model parameters, we used standardized slope values, which makes it possible to compare the effect size of one or another factor considered. Standardization is also justified, since the regression parameters of the retained models are applicable only on the current Landsat ETM+ image, and the current values cannot be carried over directly into other circumstances.

RESULTS

About 30% of the variation of the radiance contrast at forest-to-clearcut edge was described by the complex of stand structure, clearcut area and edge parameters (see table 1).

The testing of the effects of the stand structure and clearcut area parameters in the regression model of radiance contrast (see table 1) showed that the reflectance difference depended on the height of the predominant tree species (ST_HEIGHT), the stem volume of the coniferous tree species in the first and second tree layers (PICEA_I, PINUS_I and CON_II) of the adjacent forest, and on clearcut age (CL_AGE) and edge orientation (S_ANGLE^2) in all Landsat ETM+ bands except TM4. The radiance contrast observed in TM4 was less sensitive and did not depend on the clearcut age and stem volume of the pine in the first layer.

The standardized slope values of the regression models show that the stem volume of the spruce in the first layer and the pooled volume of coniferous species in the second layer (predominantly spruce regrowth), have the strongest effect on the radiance contrast of forest edges (see table 1).

The volume of deciduous trees (DEC_I) did not have a significant effect on radiance contrast in any of the TM bands.

Taking into account the effects of stand structure, there was a strong non-linear radiance contrast pattern at the forest-to-clearcut edge and the shadow angle (S_ANGLE^2 significant). The contrast was the greatest for edges (see figure 4) that were parallel or almost parallel to the Sun vector (shadows parallel to forest edge, shadow angle close to zero) and the radiance contrast decreased with the increasing shadow angle. Shadows nearly perpendicular to the forest edge caused the fuzziest edge zones on the image.

The radiance difference between two pixel zones is predictable by shadow size and intensity, which is determined by stand height and edge segment orientation. In the case of small differences between solar illumination and edge orientation angles, the shadows of trees are cast parallel to the edge, and thus the radiance contrast is strongest. As illumination azimuth and edge azimuth diverge, the shadowing of clearcut area becomes more important, and the radiance contrast of forest-to-clearcut edges decrease.

DISCUSSION

The snow cover in winter in mid-latitude to boreal regions offers good conditions for the mapping of forest clearcuts using medium or high-resolution satellite images. Snow cover causes a significant radiometric contrast between bright open areas such as clearcuts and dark forests in the visible and near infrared spectral region. Late winter images with snow-covered ground are the images with the best phenological timing for the measurement of forest clearcut areas regionally, because the radiance of the visible bands of these images does not differ between forest type groups of the same clearcutting age (Püssa et al. 2005).

The radiance or reflectance contrast of the forest to clearcut boundary area is affected both by the properties of the clearcut area and the adjacent forest stand parameters. Relationships between forest-stand variables and remotely sensed radiance or reflectance have been studied and discussed within the last twenty years (see review by Holmgren and Thuresson 1998). Our study results suggest that the radiance contrast in the forest-to-clearcut boundary area is dependent on forest stand composition, the three-dimensional structure of stands and also clearcut parameters, and that these effects can be detected on medium spatial resolution and low radiometric resolution Landsat images (see figure 4). It is particularly interesting that on Landsat TM images it is possible to detect the dependence of the radiance contrast on the geometry of the edge. The shadow size cast by trees differentially affects the radiance difference of neighboring pixels at forest edges in different azimuth directions.

Shadowing can explain a remarkable portion of the variance in a remotely sensed image of a forest stand, as demonstrated by the geometric-optical modeling of forest canopies (e.g., Li and Strahler 1985; Nilson and Peterson 1994). The amount of incoming solar radiation transmitted through tree canopies and the formation of the radiance of cast shadows is influenced primarily by crown volume. Canopy architecture – branching pattern, foliage and shoot clumping has been demonstrated to influence crown light transmittance and canopy shadowing (Ross 1981; Oker-Blom and Kellomäki 1983; Kuuluvainen and Pukkala 1987; Leblon et al. 1996; Seed and King 2003).

One interesting illustration for the effect of canopy architecture on edge contrast is the remarkable symmetry of the radiance response to shadow azimuth from –90° to 90° (Figure 4, A), although the lightning in –90° and 90° is very different. The fuzziness increases in both ends, the explanation in the sun lit end (–90°) and the shadowed end (+90°) are somewhat different. The stands in this study were all rather old with a mean height of 22 meters. Thus the lower branches have been pruned and the bottom of the forest is fairly open, meaning that the sun shining at a low elevation may penetrate deep into the sun lit forest edge. Also the low position of the sun means that the forest edge, the tree wall, becomes near perpendicular to the sunrays, and thus it appears very lit, causing fuzziness in the 'not shadowed edge' of forest.

In winter deciduous trees are leafless, and their crowns are relatively transparent to incoming solar radiation. The reflectance of snow shadowed by deciduous trees (birch) is higher compared to snow shadowed by spruce and pine (Vikhamar and Solberg 2003) and, according to our own reflectance measurements of cast shadow on snow surface, reflectance in the shadow of deciduous trees is more variable than in the shadow of coniferous trees (unpublished data). Shadows cast by coniferous tree canopies are more uniform and opaque to incoming solar radiation and have less sun flecks and half-shadow penumbra spots (Leblon et al. 1996). Due to differences in shoot clumping and the amount of sun flecks and penumbra, shadows cast by pine trees have a higher reflectance than shadows cast by spruce (Vikhamar and Solberg 2003). According to our analysis of reflectance contrast at forest-to-clearcut edges in the winter image, deciduous trees do not significantly affect forest edge radiance contrast, while coniferous species do, and the effect of pine is weaker than that of spruce. This increase in radiance contrast cannot be explained only by cast shadows inside a stand, but also by the extra darkness of shaded crowns (forest internal shading) under large trees. These effects of internal and external shadowing are amplified by the stand tree height. The role of deciduous trees in generating shadow in winter images has been explained by model simulations of Nilson's canopy reflectance model (Nilson and Peterson 1994). Model simulations have shown that, after the maximum canopy closure is attained, the latter does not change much with stand age, since the increase in tree dimensions is mostly compensated by the decrease in the number of trees. As a result, the total amount of tree trunks and branches casting shadow undergoes little change.

Forest edges whose position has remained unchanged for several decades did not show such an azimuth orientation effect on boundary zone radiance contrast (Peterson et al. 2004), as we observed in this study for young clearcut edges. This could be explained by the observation that old forest edges are not as distinct, and have a gradual transition of structure, and therefore the shading effect is more pronounced at young clearcut area edges than at permanent forest edges bordering on agricultural land or old clearcuts. In this study, radiance contrast at forest-to-clearcut edges varied significantly as a function of clearcut age, suggesting the presence of at least short-term responses (within 10 years) of the boundary zone to clearcut edge creation. The statistically significant decrease in edge contrast with fragmentation age, observed even during the first ten years after clearcut logging, is in our opinion attributable to changes on the clearcut side of the boundary and not so much to the changes on the forest side of the boundary. Clearcut area radiance decrease is induced by the increased density and height of sapling stems and by the shadows cast on the bright background of snow. The slight but statistically significant radiance decrease with clearcut age was also noted in our earlier study considering the effects of successional age and forest site type on the radiance of clearcut communities during the first 10 years after clear cutting (Püssa et al. 2005). Changes in the edge structure of a forest stand – the lateral spread of boundary area tree crowns (Mourelle et al. 2001; Muth and Bazzaz 2002), works in the opposite direction, towards an increase in radiance contrast with a bright open area and more dense tree crowns (Cienciala et al. 2002). One can also expect an inward spread of the boundary zone towards the interior of the stand, caused by wind throw and the smoothing of the radiance contrast in the boundary zone (Zeng et al. 2004). However, in northern temperate forests lateral spread of the tree line evidently has a minor effect on the formation of boundary area contrast, and is surpassed by radiance decrease in clearcut areas.

CONCLUSIONS

Winter images have proved to be a suitable tool for forest–clearcut boundary detection in visible and near-infrared spectral bands in Landsat-type medium spatial resolution satellite images.

The results of this research can be used to improve the methods for the estimation of clearcut area and in forest landscape monitoring. The study makes a point of considering specific edge effects in landscape-scale estimations of forest change.

The quality of forest edge detection is affected to a large extent by the forest stand height adjacent to the clearcut, by conifer stem volume and by the edge azimuthal orientation, which were the most important factors determining the radiance contrast of forest to clearcut areas in the studied mixed forests in

Estonia. All of the investigated parameters had similar effects on the boundary radiance contrast in both spatial resolutions.

The information gained from this study can be used in developing methods to evaluate the fuzziness or accuracy of the delineation – which may serve for better decision-making. Further studies are needed to quantify the observed patterns of edge effects on images of higher resolution and in leaf-on phenological conditions.

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FIGURES AND TABLE

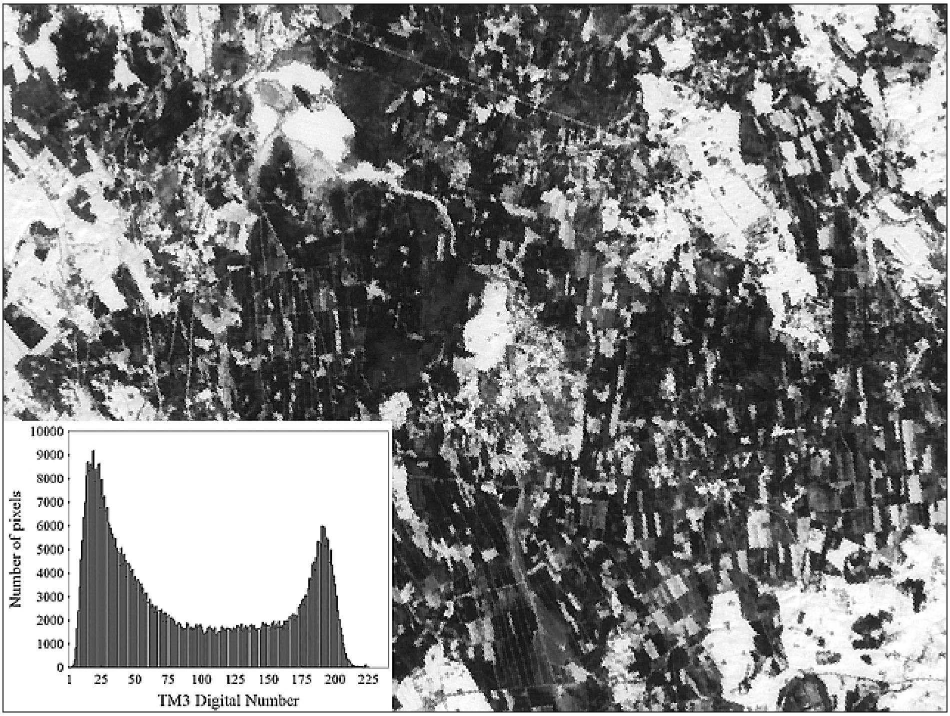

Figure 1. A fragment of the study area from Landsat ETM+ image in band 3 (TM3) covering an area 21.2 km x 16 km on the ground centered at 58º20'N, 26º30'E, situated in the western part of Tartumaa county, Estonia. The image was acquired on 06 March 2003, Path 187 Row 19, in plain snow-cover conditions. A frequency distribution of image pixel brightness values in DN units for this image fragment is shown on the histogram.

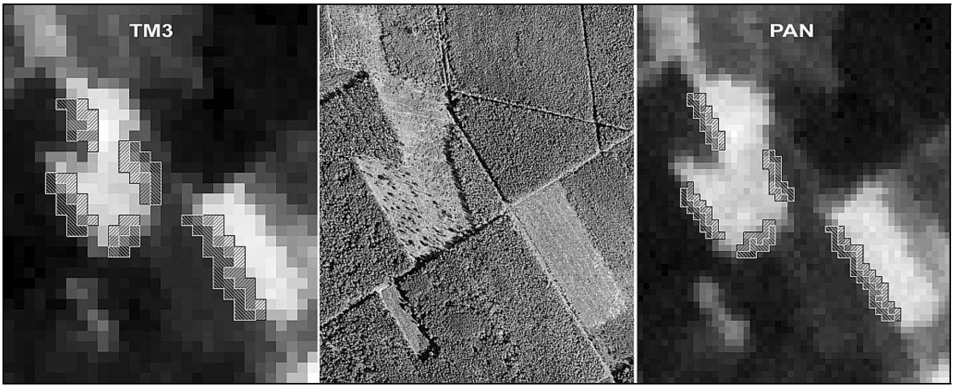

Figure 2. The sub-sample (750 x 900 m) of Landsat ETM+ images in band 3 (TM3; pixel size 30 m) and PAN (pixel size 15 m) bands in comparison to orthophoto (from year 2002, a year before acquisition of the satellite image). Two clearcut areas are seen as brighter areas. Edges with boundary zones, whose radiance is analyzed, are marked with boxes. A white box frames the first pixel zone inside a forest and a black box denotes the first pixel zone inside a clearcut area. In analyses, the average radiance value of pixels within a closed box were used.

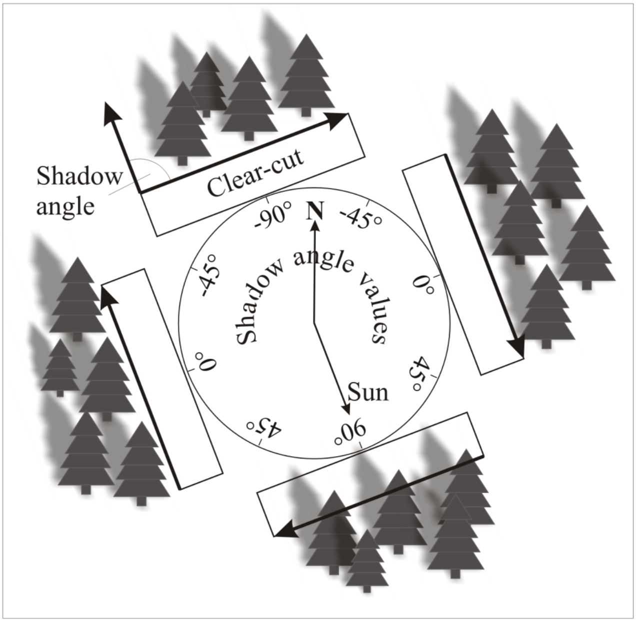

Figure 3. The scheme of the transformation principle for converting edge azimuth values into horizontal shadow angle values. The shadow angle is the angle between the edge vector and the shadow vector. Please note that edge vector direction is set using the rule that the forest is always on the left hand side.

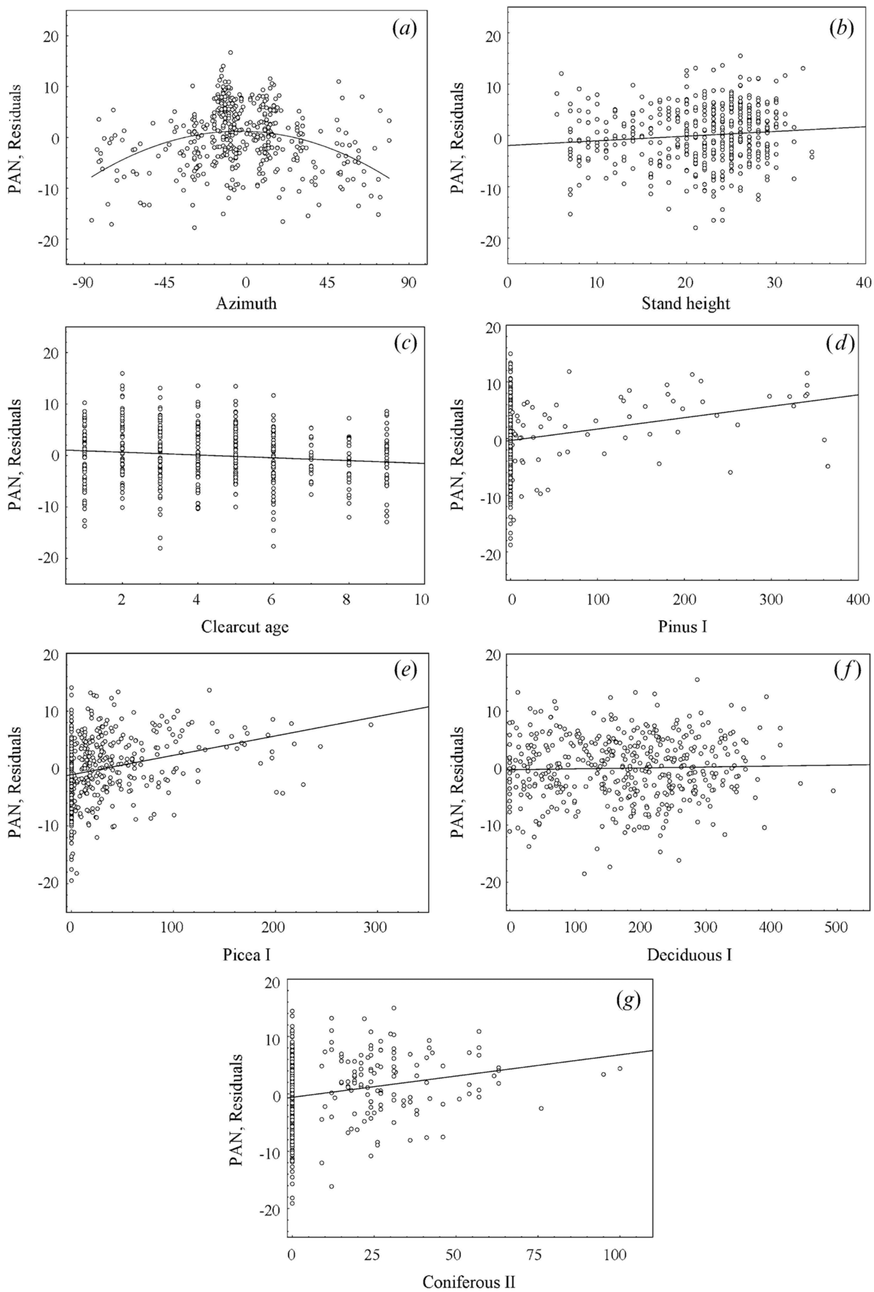

Figure 4. An illustration of model arguments effects on radiance contrast at forest-to-clearcut edges in the Pancromatic band of the Landsat ETM+ image. Instead of observed radiance contrast values, the model semi-residuals have been presented on the Y-axis. Semi-residuals illustrate the effect of factor of interest, when all other factor effects in the model have been taken into account (i.e. their effect has been removed).

Table 1. The standardized slope values and factor significances of regression analysis of radiance contrast at the forest – clear-cut edge. Labels denote: NS – Non-significant, * – P<0.05; ** P<0.01; *** P<0.001.

	TM1		TM2		TM3		TM4		PAN	
S_ANGLE	–0.077	NS	–0.068	NS	–0.076	NS	–0.008	NS	–0.054	NS
S_ANGLE²	**–0.212**	***	**–0.215**	***	**–0.245**	***	**–0.239**	***	**–0.313**	***
ST_HEIGHT	**0.112**	*	**0.152**	**	**0.171**	**	**0.251**	***	**0.165**	**
CL_AGE	**–0.122**	**	**–0.113**	**	**–0.112**	**	–0.074	NS	**–0.099**	*
PINUS_I	**0.099**	*	**0.104**	**	**0.114**	**	0.028	NS	**0.178**	***
PICEA_I	**0.281**	***	**0.268**	***	**0.265**	***	**0.229**	***	**0.233**	***
DEC_I	0.015	NS	0.029	NS	0.025	NS	0.060	NS	0.042	NS
CON_II	**0.243**	***	**0.216**	***	**0.204**	***	**0.144**	***	**0.193**	***
Model adj. R^2	**0.263**	***	**0.273**	***	**0.296**	***	**0.277**	***	**0.339**	***

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Publications

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