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Article

Nation-Wide Clear-Cut Mapping in Sweden Using ALOS PALSAR Strip Images

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Abstract: Advanced Land Observing Satellite (ALOS) Phased Array L-band type Synthetic Aperture Radar (PALSAR) backscatter images with 50 m pixel size (strip images) at HV-polarization were used to map clear-cuts at a regional and national level in Sweden. For a set of 31 clear-cuts, on average 59.9% of the pixels within each clear-cut were correctly detected. When compared with a one-pixel edge-eroded version of the reference dataset, the accuracy increased to 88.9%. With respect to statistics from the Swedish Forest Agency, county-wise clear-felled areas were underestimated by the ALOS PALSAR dataset (between 25% and 60%) due to the coarse resolution. When compared with statistics from the Swedish National Forest Inventory, the discrepancies were larger, partly due to the estimation errors from the plot-wise forest inventory data. In Sweden, for the time frame of 2008–2010, the total area felled was estimated to be 140,618 ha, 172,532 ha and 194,586 ha using data from ALOS PALSAR, the Swedish Forest Agency and the Swedish National Forest Inventory, respectively. ALOS PALSAR strip images at HV-polarization appear suitable for detection of clear-felled areas at a national level; nonetheless, the pixel size of 50 m is a limiting factor for accurate delineation of clear-felled areas.

Keywords: ALOS PALSAR; radar backscatter; boreal forest; deforestation; clear-cuts; Sweden; Kyoto & Carbon Initiative

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1. Introduction

Methods for detecting land use change are of great interest for greenhouse gas reporting in line with international agreements. In the case of Sweden, most changes in mature forest occur at harvesting, turning the mature forest into clear-cuts, which are then re-planted after a few years. Hence, it is of interest to develop a methodology able to detect all clear-felled areas and sort out the large majority of legal fellings by comparison with notified fellings. The remaining detected forest changes are likely to be large damages, permanent land cover changes or illegal fellings and should, thus, be visited in field.

In Sweden, a nation-wide coverage of optical satellite images is acquired yearly by the government. These images are free to download for all citizens of Scandinavia and Finland through the Saccess database [1]. Among others, the images are used by the Swedish Forest Agency (SFA) for change detection to find clear-cuts and to compare these with the notifications. Each year approximately 50,000 to 70,000 clear-cuts are performed on a total of 150,000–300,000 ha. At the SFA, the current system of monitoring clear-cuts, is based on the use of data from optical satellites. Satellite data covering the whole country are used on an annual basis since 1999. The follow-up of all cutting activities in Sweden by change detection is done annually since 2003. This routine is an integrated part of the regeneration system with which all clear-cuts in Sweden are handled and monitored according to the forest legislation. By knowing the location, point in time and the size and shape of the cuttings, better and more effective follow-up activities can be performed by the SFA. In combination with about 50,000 Swedish National Forest Inventory (NFI) field plots, the optical images stored in the Saccess database are also used by the Swedish University of Agricultural Sciences for producing nation-wide forest maps [2].

Sweden is characterized by long periods of reduced solar illumination and frequent cloud-cover. To obtain the about 200 cloud-free SPOT scenes that are needed for a nation-wide coverage, several thousands programming attempts of the SPOT satellites are needed. In this respect, it is of interest to investigate the capability of spaceborne Synthetic Aperture Radar (SAR) as a complement for forest mapping due to its independence of sun illumination and cloud-cover and, thus, the possibility to obtain the needed imagery in a foreseeable way.

Compared to other spaceborne SAR missions, data acquired by the Advanced Land Observing Satellite (ALOS) Phased Array L-band type Synthetic Aperture Radar (PALSAR) have a threefold advantage for mapping forest activities:

(i) Strong sensitivity of the backscatter to forest structural properties, e.g., [3];
(ii) Acquisition strategy aimed at maximizing the information content of the data [4];
(iii) Acquisition plan to obtain full regional coverage within short time periods on a yearly basis [4].

With the ALOS Kyoto and Carbon (K&C) Initiative lead by the Japan Aerospace Exploration Agency (JAXA) Earth Observation Research Center (EORC), long strips of PALSAR backscatter images have been generated and made available to the science community to support investigations related to Conventions, Carbon Cycle Science and Conservation of the environment [4]. These images will be referred to as PALSAR K&C strip data. Over Sweden, nation-wide datasets of ALOS PALSAR dual-polarization (HH and HV) images were acquired each summer/fall between 2007 and 2010.

The potential of PALSAR K&C strip data to monitor forest cover changes in Swedish forest has been demonstrated in [5]. A simple threshold-based algorithm for clear-cut detection using time series of L-band HV-polarized SAR backscatter was developed and applied to PALSAR K&C strip data with 50 m pixel size, covering the counties of Västerbotten and Västra Götaland. Despite the single global threshold used to map clear-cuts at county level, the algorithm could correctly detect at least half of the area of each individual clear-cut for more than 90% of the clear-cuts recorded in a database of clear-felled areas for the county of Västerbotten [5]. While the detection method proved to be straightforward to detect clear-felled areas between acquisitions of the SAR images, it performed poorly at edges where the backscatter drop after felling was not always above the selected threshold.

For nation-wide clear-cut mapping, a robust, accurate and possibly fast clear-cut detection algorithm was considered. A change detection method based on an automatic image ratio thresholding approach [6] combined with a data fusion based multi-channel change detection (DF-MCD) method [7] proved to meet such requirements in initial tests to detect clear-cuts at a local scale [8]. The contribution of the PALSAR HH-polarized backscatter in a joint classification was marginal with respect to the detection achieved with HV data only [8].

The objective of this paper is to evaluate the performance of a modification of the detection method proposed in [6,7] for an operational scenario consisting of the production of nation-wide clear-cut maps from HV-polarization PALSAR K&C strip images covering Sweden. In a first step, the performance of the detection method is assessed for different pixel sizes of PALSAR HV-polarization backscatter data. Here, a comparison was also performed with the detection accuracy achieved with the simple thresholding detection algorithm [5]. Then, yearly clear-cut maps obtained from the PALSAR K&C strip data for the time period 2007–2010 are discussed. To get an understanding of the reliability of the PALSAR-based clear-cut maps, these have been compared with clear-cut maps produced by the SFA using optical satellite images. To further assess the contribution of PALSAR K&C strip data, statistics of county-wise clear-felled areas from these data are compared with corresponding estimates of clear-felled areas produced by the SFA using optical satellite images and the NFI obtained by upscaling plot-wise estimates to the county level. Finally, estimates of clear-felled areas from the PALSAR K&C strip data, SFA and NFI are compared with each other at a national level.

The PALSAR datasets are presented in Section 2. The datasets used for the assessment of the PALSAR-based clear-cut maps, from here onwards referred to as reference material, are described in Section 3. The clear-cut detection method and its implementation are outlined in Section 4. The performance of the detection method with respect to (i) the spatial resolution of the PALSAR data and (ii) the simple thresholding detection algorithm is discussed in Section 5. The nation-wide clear-cut maps from the PALSAR K&C strip data and the cross-comparison against the reference material from the SFA and the NFI are presented in Section 6. This paper concludes with a set of considerations on the results achieved and an outlook towards utilization of PALSAR images for clear-cut mapping at regional and national levels for an operational scenario.

2. ALOS PALSAR Data

ALOS PALSAR operated between January 2006 and April 2011, at L-band (wavelength: 23 cm), with a repeat-pass period of 46 days, in a multi-mode configuration. The PALSAR datasets used for this investigation consisted of images acquired in the Fine Beam Dual (FBD) mode, at HH- and HV-polarizations, with a 34.3 degree look angle.

The primary dataset consisted of PALSAR K&C strip images with 50 m pixel size, which were obtained with the aim of demonstrating the possibility to map forest status and forest variables at a national level over several years. The images were obtained from JAXA EORC through the K&C Initiative for each summer/fall of 2008, 2009 and 2010. In order to produce yearly maps of clear-cuts for Sweden, it was necessary to consider strip images achieving (i) complete coverage of the country and (ii) within the shortest possible time interval (e.g., within one repeat-pass cycle). Data acquired between the end of July and the beginning of September satisfied the requirements. Only in a few cases were image gap fillers from different time periods necessary. Table 1 presents a list of the strip data used for clear-cut detection, expressed in terms of the ALOS PALSAR Reference System for Planning (RSP) number (*i.e.*, satellite path number), acquisition date and satellite repeat-pass cycle number. Complete coverage of Sweden was achieved for the years 2008 and 2009. For 2010, a small gap occurred, representing 0.8% of the area of Sweden. Figure 1 shows a false color composite mosaic of the PALSAR K&C strip images acquired in FBD mode during 2009. Because the large majority of the images was acquired under unfrozen conditions, which are characterized by strong temporal consistency [3], the mosaic does not show an evident striping effect. In addition, PALSAR K&C strip data acquired during 2007 and available over the counties of Västerbotten in the north, and Västra Götaland and Jönköping in the south of Sweden were considered (see Figure 2 for their location). The two former counties were used as pilot study areas for the initial development of methods for clear-cut detection [9] and have been included to expand the time span of the SAR dataset, even if locally.

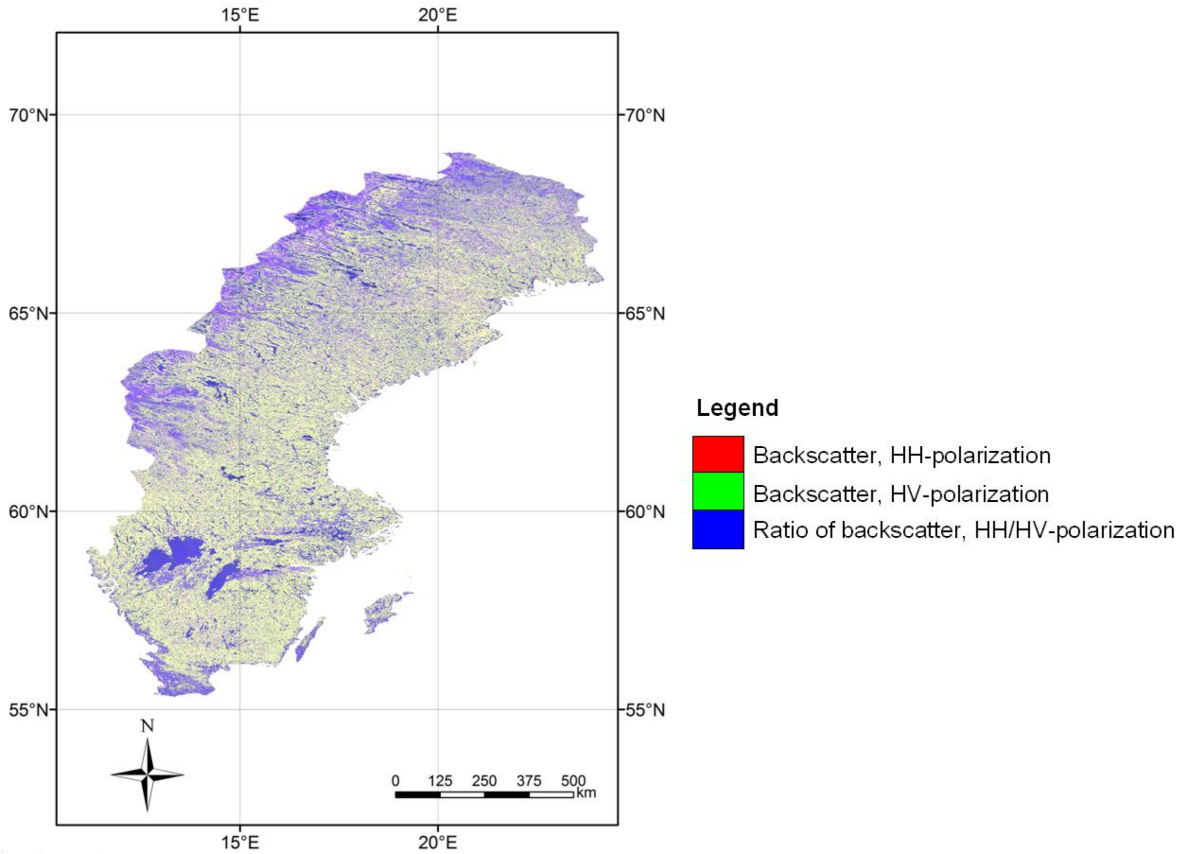
Table 1. Advanced Land Observing Satellite (ALOS) Phased Array L-band type Synthetic Aperture Radar (PALSAR) Kyoto and Carbon (K&C) strip data acquired during summer/fall of 2007, 2008, 2009 and 2010. For the 2007 dataset, N refers to data acquired over the county of Västerbotten in the north of Sweden and S refers to data acquired over the counties of Västra Götaland and Jönköping in the south of Sweden. RSP (Reference System for Planning) corresponds to the satellite path number; Date corresponds to image acquisition date; Cycle corresponds to the satellite orbital cycle number (1 cycle = 46 days).

2007			**2008**			**2009**			**2010**		
RSP	**Date**	**Cycle**	**RSP**	**Date**	**Cycle**	**RSP**	**Date**	**Cycle**	**RSP**	**Date**	**Cycle**
623 [N]	2007-07-22	12	613	2008-06-22	20	615	2009-06-13	28	615	2010-08-01	37
615 [N]	2007-07-24	13	615	2008-07-26	21	633	2009-07-13	28	634	2010-08-02	37
629 [S]	2007-08-01	13	634	2008-07-27	21	625	2009-07-15	28	607	2010-08-03	37
621 [N]	2007-08-03	13	607	2008-07-28	21	631	2009-07-25	28	626	2010-08-04	37
613 [N]	2007-08-05	13	626	2008-07-29	21	634	2009-07-30	29	618	2010-08-06	37
632 [S]	2007-08-06	13	629	2008-08-03	21	626	2009-08-01	29	629	2010-08-09	37
627 [S]	2007-08-13	13	621	2008-08-05	21	621	2009-08-08	29	621	2010-08-11	37
619 [N]	2007-08-15	13	605	2008-08-09	21	613	2009-08-10	29	613	2010-08-13	37
611 N	2007-08-17	13	624	2008-08-10	21	632	2009-08-11	29	632	2010-08-14	37
630 [S]	2007-08-18	13	627	2008-08-15	21	605	2009-08-12	29	605	2010-08-15	37
633 [S]	2007-08-23	13	619	2008-08-17	21	624	2009-08-13	29	635	2010-08-19	37
617 [N]	2007-08-27	13	611	2008-08-19	21	619	2009-08-20	29	627	2010-08-21	37
628 [S]	2007-08-30	13	630	2008-08-20	21	611	2009-08-22	29	619	2010-08-23	37
631 [S]	2007-09-04	13	603	2008-08-21	21	622	2009-08-25	29	611	2010-08-25	37

Table 1. *Cont.*

2007			2008			2009			2010		
RSP	**Date**	**Cycle**	**RSP**	**Date**	**Cycle**	**RSP**	**Date**	**Cycle**	**RSP**	**Date**	**Cycle**
634 [S]	2007-09-09	14	622	2008-08-22	21	617	2009-09-01	29	630	2010-08-26	37
			633	2008-08-25	21	609	2009-09-03	29	622	2010-08-28	37
			625	2008-08-27	21	628	2009-09-04	29	633	2010-08-31	37
			617	2008-08-29	21	620	2009-09-06	29	625	2010-09-02	37
			609	2008-08-31	21	623	2009-09-11	29	617	2010-09-04	37
			620	2008-09-03	21	607	2009-09-15	30	609	2010-09-06	37
			631	2008-09-06	21	629	2009-09-21	30	628	2010-09-07	37
			623	2008-09-08	21	627	2009-10-03	30	631	2010-09-12	37
			632	2008-09-23	22	630	2009-10-08	30	624	2010-10-01	38
			628	2008-10-17	22	603	2009-10-09	30	623	2010-10-30	38

Figure 1. Mosaic of ALOS PALSAR K&C strip images acquired in Fine Beam Dual (FBD) mode during 2009 over Sweden.



To assess the impact of spatial resolution on the performance of the clear-cut detection algorithm, a pair of standard ALOS PALSAR images (so-called path data) was considered. The path images covered a 70×70 km^2 area over a part of the county of Västerbotten. These images were acquired on 24 July 2007 and 10 September 2008 (satellite path number RSP: 615, Frame number: 1280). This image pair was also available as strip data. Compared to strip data, only a limited number of PALSAR path images can be obtained from JAXA yearly free of charge, within the ALOS K&C Initiative.

Processing of the ALOS PALSAR strip and path data consisted of calibration, spatial averaging, terrain geocoding to the Swedish RT90 map projection and compensation of backscatter for slope-induced effects [3]. For completeness, a summary of the processing sequence is provided.

PALSAR K&C strip data were provided in radar geometry with a pixel size of 37.5 m in the cross-track direction (corresponding to roughly 60 m on the ground) and 51.2 m in the along-track direction. To preserve the spatial resolution, the data have been geocoded to 50 m pixel size. Path data were provided in radar geometry with a pixel size of 9.4 m in the cross-track direction (corresponding to roughly 15 m on the ground) and 3.1 m in the along-track direction. To investigate the effect of spatial resolution on the clear-cut detection, the path data were geocoded to 10 m and 20 m pixel size. Direct resampling of the original path images from the radar to the desired map geometry would have implied keeping substantial speckle noise.

For this reason, the 10 m geocoded images were obtained after spatial averaging (*i.e.*, multi-looking) of the original images with factors 1 and 3 in the cross-track and the along-track direction, respectively. Similarly, the 20 m geocoded images were obtained by multi-looking the original images with factors 1 and 6. It is here remarked that the strip data have been generated by JAXA EORC by applying multi-look factors of 4 and 16. Terrain geocoding was performed with an automated approach [10]. The geocoding accuracy was typically below 1/3rd of the pixel size. To correct for distortions induced by sloped terrain, the backscatter was corrected for local incidence angle and true pixel area [3].

The strip data were divided into tiles of 50 × 50 km^2 to allow easier management of the large dataset. Each tile was identified by a string of characters corresponding to the first three digits of the easting and the northing coordinate of the top-left pixel. For example, tile "155 725" corresponds to the area with easting coordinates between 1,550,000 m and 1,600,000 m and northing coordinates between 7,250,000 m and 7,200,000 m. Each tile includes 1,000 × 1,000 pixels.

3. Reference Material

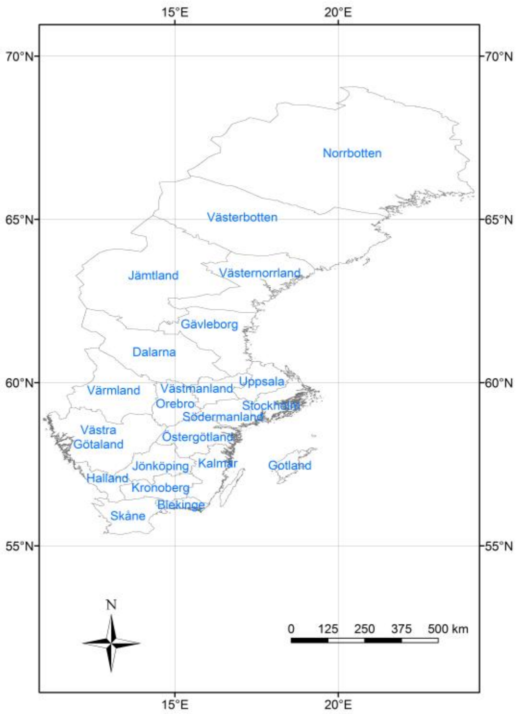
The performance of the clear-cut detection was assessed by cross comparing with two datasets of clear-cuts provided by the forest company Sveaskog and the SFA (points 1 and 2 below, respectively). Furthermore, an overall assessment of clear-felled areas was carried out at county and national levels by comparing the detected area in the PALSAR K&C strip data with independent estimates provided by the SFA (point 2) and the NFI (point 3). In addition, statistics from the SFA of notified areas of final fellings >0.5 ha [11] were included in the evaluation to act as a plausibility check for the results since they represent an upper bound of the total area detected as change (point 4).

(1) A GIS layer of clear-cuts in the county of Västerbotten provided by the forest company Sveaskog was used to (i) investigate the impact of pixel size (10 m, 20 m and 50 m) on the detection accuracy and (ii) compare with the results obtained with the simple thresholding detection algorithm [5] at 50 m pixel size, *i.e.*, the pixel size of the images used for nation-wide clear-cut mapping.

(2) A GIS layer of clear-cuts, covering the whole of Sweden, based on optical satellite imagery, generated by the SFA was used to assess the quality and the consistency of the changes detected in the PALSAR K&C strip data. For each clear-cut, the GIS database provides information about the acquisition date of the latter of the two images used for the detection.

The dataset consisted of detected clear-cuts for the time period of 2007–2010; nevertheless, the coverage was not overall homogeneous. For example, for the central part of the county of Dalarna (see Figure 2) clear-cuts were mapped until June 2009.

Figure 2. Map of Sweden with names and borders of 21 counties.



The method for detection of clear-felled areas by the SFA uses established change detection techniques to find and map clear-cuts from short-wave-infrared (SWIR) satellite data. The basic equation used for change detection is expressed as:

$$Difference = \left(Image_{Last} - Image_{First}\right) \times factor + 128 \quad (1)$$

In Equation (1), $Image_{Last}$ and $Image_{First}$ refer to the spectral values at pixel level in SWIR expressed in Digital Numbers (DNs) for the last and the first image used for change detection, the *factor* can vary from 1 to approximately 2.5 depending on whether the images used are the original ones or have been stretched. Equation (1) is based on 8-bit coded images (*i.e.*, spectral values in DNs between 0 and 255) and generates a one band change image, where all values greater than 128 indicate that trees have been removed. An increased removal of trees between the two images will likely increase the value of the *Difference*. The next step in the procedure is to manually define the threshold between “change” and “no change” pixels in the change image on the scale from 128 to 255. In this manual step, experts with local knowledge can set the threshold interactively, which guarantees high precision in detecting clear-cuts. Since 2006, mosaics of satellite scenes instead of single scenes are used in the change detection analysis, increasing the efficiency of the whole procedure. An analysis mask is also used to make sure that only changes in forestland are considered.

(3) The NFI is a stratified systematic cluster-sampling inventory with partial replacement of plots. Circular sample plots are clustered into permanent and temporary tracts, which are

systematically distributed over the whole country. Since the NFI is stratified on five survey regions with varying density and distributions of tracts, equations for stratified sampling are used for area estimates covering more than one stratum. To combine the permanent and temporary tracts, a standard minimum-variance weighting procedure is used [12,13]. The coefficient of variation is calculated in accordance with the NFI standard method [14], *i.e.*, assuming simple random sampling of tracts. This will generally give an overestimation of the estimated variance [12].

(4) Final fellings > 0.5 ha must be notified to the SFA at least six weeks in advance. Final felling includes all fellings with the exception of thinning and cleaning. Notification is made on a special form available from the SFA, which can be sent in paper format or digitally via a special service available on the Internet. The area to be felled and the regeneration methods to be used must be specified. A sketch of the area must be drawn on the form. A description of the intended conservation measures to be used and measures to protect the cultural heritage within the area must also be stated. The sketch of the area is stored in the SFA GIS database together with all the attributes accompanying the sketch.

4. Clear-Cut Detection Methodology

For detection of clear-cuts in ALOS PALSAR backscatter data, the unsupervised data fusion based multi-channel change detection (DF-MCD) method [7] was adopted. This approach guarantees complete automatization, requires a minimum of input parameters and offers computational efficiency. It is a bi-temporal change detection method, based on SAR image rationing and a Markov random field model, able to incorporate both spectral and contextual information from one or multiple SAR channels. It requires an initial guess change map as input along with one or multiple SAR ratio images. For the initial “change” and “no change” classification the generalized Kittler and Illingworth minimum-error thresholding algorithm (GKIT) [6] was used. A lognormal assumption for the SAR amplitude ratios was adopted throughout.

Besides multi-looking, no specific speckle filter was applied to the PALSAR data. The preliminary analysis on the suitability of the proposed detection algorithm on PALSAR HV-polarized path data with 20 m pixel size did not show improved detection statistics when applied to filtered data compared to unfiltered data [8]. Filtering was avoided also because PALSAR K&C strip data with 50 m pixel size are substantially smoothed because of the strong multi-looking. Filtering might also alter the statistics of the ratio images causing the lognormal assumption to become strongly violated and decreasing the chances of detecting small area changes or to achieving fine detail delineation.

For nation-wide clear-cut mapping, the detection algorithm was applied to the PALSAR K&C strip data in Table 1 on a track-by-track basis, *i.e.*, change was detected between two images acquired in two consecutive years, along the same satellite track. In the case of a pixel being covered by more image pairs, it was labeled as change, if it had been detected as such in at least one of the image pairs. To avoid that changes occurring in other land cover classes, such as cropland, would be confused with the detection of clear-cuts, the Swedish CORINE Land Cover dataset [15] was used to mask out non-forested areas. Temporal signatures of the backscatter for agricultural fields and clear-felled areas are in fact similar, *i.e.*, sudden decrease of backscatter at harvest. Finally, a majority filter was applied to remove detections consisting of one pixel or two contiguous pixels. The size of the filter was based on the evidence that many of the detections of one or two pixels were often erroneous when visually compared with the SFA database and dated imagery in Google Earth. The drawback was that many small-scale changes on the order of the pixel size (<0.5 ha at 50 m pixel size) were discarded from the analysis. This issue can have significant impact on the total statistics of the area felled, for example at county level, in particular when using data with 50 m pixel size since small clear-cuts are not accounted for (see Section 5).

The change map consists of a bitmap showing "change" and "no-change". For each pixel, the acquisition dates of the first and last PALSAR image were stored. These were used to assess the consistency of the results, both in terms of "change" and "no-change" areas, when compared with the reference material. For each pixel detected as change, the last PALSAR image acquisition date before the detected change and the first PALSAR image acquisition date after the detected change were stored as well. These dates represent the dates of detection using the PALSAR data and were used when comparing with the dates of felling/detection reported in the reference material.

5. Performance of Clear-Cut Detection: Impact of Spatial Resolution

The change detection approach applied to clear-cut mapping has been tested for a small number of clear-felled areas in the case of PALSAR path data with 20 m pixel size [8]. In order to state the suitability of the approach for the PALSAR K&C strip data with 50 m pixel size, an analysis of the detection accuracy for a pair of PALSAR images available both as path and strip data was performed. The performance was assessed with respect to the dataset of clear-felled areas from the company Sveaskog.

The impact of the spatial resolution of the PALSAR data on the detection was substantial. Figure 3 shows an example of a 28 ha large clear-cut in the county of Västerbotten. According to the Sveaskog GIS database provided by the company Sveaskog, the forest was felled on 4 April 2008. The images were acquired on 24 July 2007 and 10 September 2008. At 50 m pixel size (strip data), the bulk of the clear-cut was easily detected, whereas a detailed description of the edges was hindered by the low resolution of the PALSAR data. At 20 m pixel size (path data), the delineation of the edges improved, although small features were not detected. At 10 m pixel size (path data), the contours were even more easily detected and small features became more visible, although some discrepancies occurred at some locations along the edges of the clear-cuts.

To assess the performance of the detection with respect to the spatial resolution of the PALSAR data, an area of 50 × 50 km^2 within the county of Västerbotten was considered. Within this area, the Sveaskog GIS database included 98 clear-cuts of which 31 occurred between the acquisition of the two PALSAR images and 67 took place before. The 31 clear-cut polygons covered an area of 281 hectare. For the analysis, the clear-cut polygons in the GIS database were rasterized to the pixel size of interest and the percentage of pixels detected as change in the PALSAR dataset was computed. To assess the impact of clear-cut edges on the detection statistics, the assessment was carried out with the original rasterized polygons and a corresponding one-pixel edge-eroded version of this reference dataset. Here, the edge-erosion refers to the removal of one pixel along the border of a rasterized polygon. For the 31 clear-cuts that occurred between the dates of acquisition of the PALSAR images, Table 2 reports the statistical distribution of the percentage of correctly detected pixels for the 31 polygons in terms of the average value and the 10th and the 90th percentile. At 50 m, the erosion caused about half of the clear-cut areas to disappear.

Figure 3. Example of a detected clear-cut using ALOS PALSAR data (in red) at (**a**) 10 m, (**b**) 20 m and (**c**) 50 m pixel size. For reference, the border of the clear-felled area is outlined as recorded in the GIS database provided by the company Sveaskog. As background, a PALSAR image acquired after clear-felling is used.

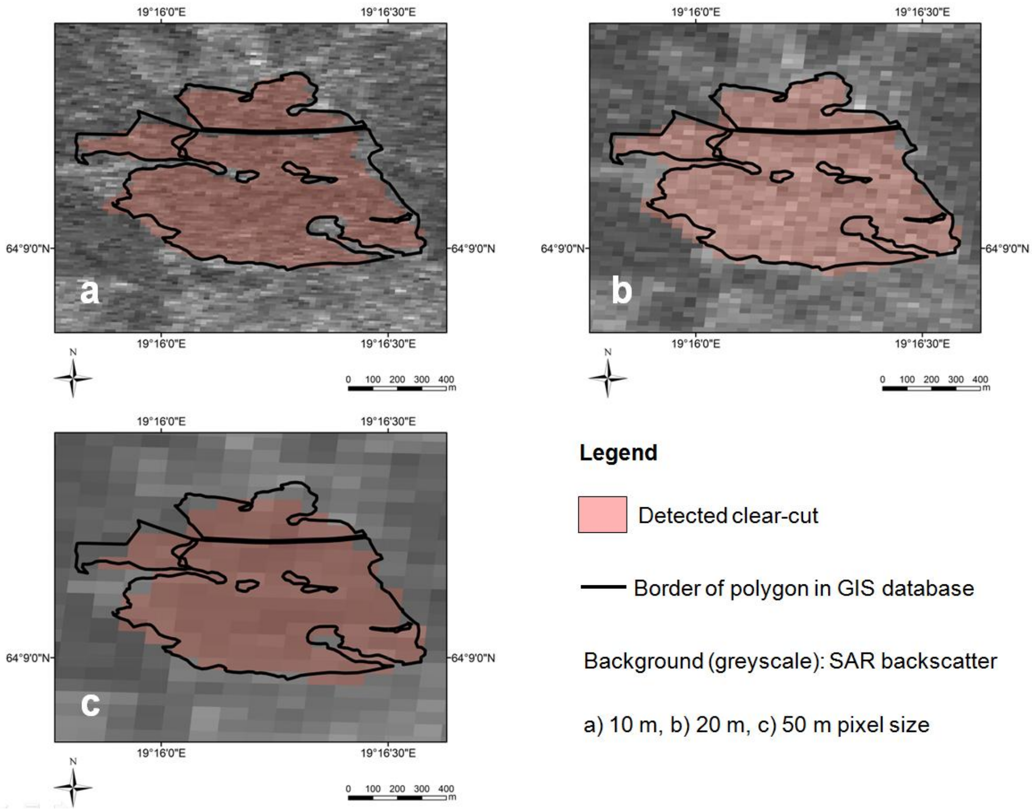


Table 2. Average value, 10th and 90th percentile of the clear-cut distribution of correctly detected pixels with respect to the pixel size of the ALOS PALSAR data. The reference dataset consisted of 31 clear-cuts, where clear-felling took place between ALOS PALSAR image acquisitions. The last line with an asterisk refers to the detection obtained with the simple thresholding algorithm proposed in [5].

Pixel Size (m)	Correctly Detected Pixels (Original/Edge-Eroded)	
	Average (%)	10th and 90th Percentile (%)
10	64.1/72.8	31–89/32–97
20	79.7/90.8	57–96/66–100
50	59.9/88.9	9–93/45–100
50*	58.0/78.8	22–88/41–100

The largest agreement between detected and actual clear-cuts was obtained at 20 m pixel size (Table 2). For the 31 clear-cuts where felling took place between the acquisition of the two PALSAR images, on average 79.7% of the reference pixels had been detected correctly. The detection accuracy increased substantially when compared with the edge-eroded polygons. In this case, on average more than 90% of the pixels were correctly detected. The rather high percentage of the 10th percentile at 20 m (57%) indicates that for 90% of the 31 clear-cuts used as reference the majority of the felled area was correctly detected. For the few clear-cuts characterized by significant missed detection, the discrepancy was patch-wise, which could probably be due to inaccuracies in the date of felling reported in the reference dataset (*i.e.*, one date while felling activities took place over multiple dates).

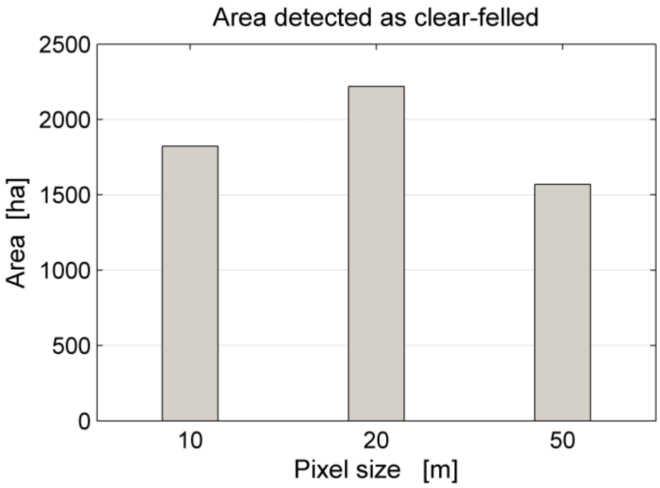
At 10 m and 50 m pixel size, the detection accuracy was lower; nonetheless, it improved when considering the edge-eroded version of the clear-cut polygons, thus confirming that mismatches were located primarily at the edges of the clear-cuts. This could be either due to incorrect delineation of the clear-cut in the GIS database or scattering effects at the edge between a clear-cut and a forest. The poorer agreement with respect to the GIS database at 10 m compared to 20 m was primarily due to undetected pixels along the border of a clear-cut, as is also shown in Figure 3. Missed detections at 10 m but not at 20 m could also be related to residual speckle, which was stronger in the former dataset because of the smaller multi-look factors. While at 10 m and 20 m the textural properties were retained as shown by the rather high level of agreement between the PALSAR-based and the Sveaskog clear-cuts, at 50 m sharp features such as the border of a clear-cut were blurred. In turn, the backscatter contrast between two images acquired before and after felling decreased, which therefore limits the possibility to correctly delineate clear-cuts.

Table 2 indicates that a more advanced algorithm for detection of clear-cuts from PALSAR data, as here proposed, is more suitable compared to an algorithm based on simple thresholding [5]. The detection accuracy increased by almost 2% (from 58.0% to 59.9%) when compared with the original 31 clear-cuts in the Sveaskog GIS database and by 10% (from 78.8% to 88.9%) when compared with the edge-eroded version of this reference dataset.

For the 67 polygons where clear-felling occurred before the acquisition of the PALSAR dataset, no pixel was classified as change, regardless of the spatial resolution of the PALSAR dataset. Further assessment of the detection error with respect to false detection was not possible, since the dataset available as reference provided only information on areas that had been subject to felling activities by Sveaskog.

To understand whether the spatial resolution of the PALSAR dataset could influence statistics derived from a map of detected clear-cuts, the total area detected as clear-felled for the 50×50 km^2 large region covered by the PALSAR data was computed for each of the three pixel sizes considered (10 m, 20 m and 50 m) here. The results differed depending on the pixel size (Figure 4). Compared to the total area detected as clear-felled at 20 m (2,218 ha), here assumed to be the most suitable pixel size for detecting clear-cuts, the estimate at 10 m (1,823 ha) was 18% smaller as a consequence of (i) small parcels not detected as change within larger clear-cuts and (ii) a rougher delineation at lower resolution because of the polygon to raster conversion. At 50 m, the total area detected as clear-felled was 1,569 ha, *i.e.*, 29% less than at 20 m. This result was due to (i) having discarded small clear-cuts (<0.5 ha) at 50 m pixel size and (ii) smaller areas detected as clear-felled at 50 m rather than at 20 m as a consequence of blurred clear-cut edges.

Figure 4. Total area detected as clear-felled for the 50 × 50 km^2 large region within the county of Västerbotten covered by the pair of ALOS PALSAR images available as path (10 m and 20 m pixel size) and strip (50 m pixel size) data. Image acquisition dates: 24 July 2007 and 10 September 2008.



6. Nation-Wide Clear-Cut Mapping

To show the geographic distribution of detected clear-cut areas in Sweden, the change map derived from the PALSAR K&C strip data for the time period of 2008–2009 is displayed in Figure 5. The change map is overlaid on a mosaic of average HV-backscatter images from the year 2009. Most clear-felled areas occurred in the north of Sweden and along the east coast. Clear-cuts were rare in the western part of the country, along the border with Norway, because the vegetation here is sparse and forest density is low. Size and frequency of the detected clear-cuts decreased towards the southern region. In the remainder of this Section, the yearly clear-cut maps obtained from the PALSAR K&C strip data are compared with the corresponding product by the SFA based on optical satellite imagery (Section 6.1). Finally, the estimates of total clear-felled areas at county level and national level from the PALSAR-based clear-cut maps are compared with corresponding estimates from the SFA and the NFI (Section 6.2).

6.1. Assessment of Clear-Felled Areas at Regional Level

Figure 6 shows an example of detected changes for an area within the county of Västerbotten with respect to the SFA database of clear-cuts between the summer/fall seasons of 2008 and 2009. The large majority of detected changes (in red) corresponds to clear-cuts recorded in the SFA database (white borders). Clusters of detected changes were also found in areas recorded as clear-felled before the acquisition of the PALSAR images (black borders). In this case, the date recorded by the SFA might be questionable. The SFA database defines as date of cutting the date on which the later optical satellite image forming an image pair was acquired. Hence, the temporal uncertainty in the felling date affects the interpretation whether the PALSAR-based detections are correct or not. Finally, some clusters of pixels were labeled as change where no information was available in the SFA database. Due to the considerable clustering, the result was interpreted as a possible failed detection by the SFA or a data gap (in space and/or in time) in the optical satellite dataset available at the SFA.

Figure 5. Map of detected clear-cuts (in red) from ALOS PALSAR K&C strip data for the time period 2008–2009 overlaid on a mosaic of the average HV-backscatter images acquired during 2009.

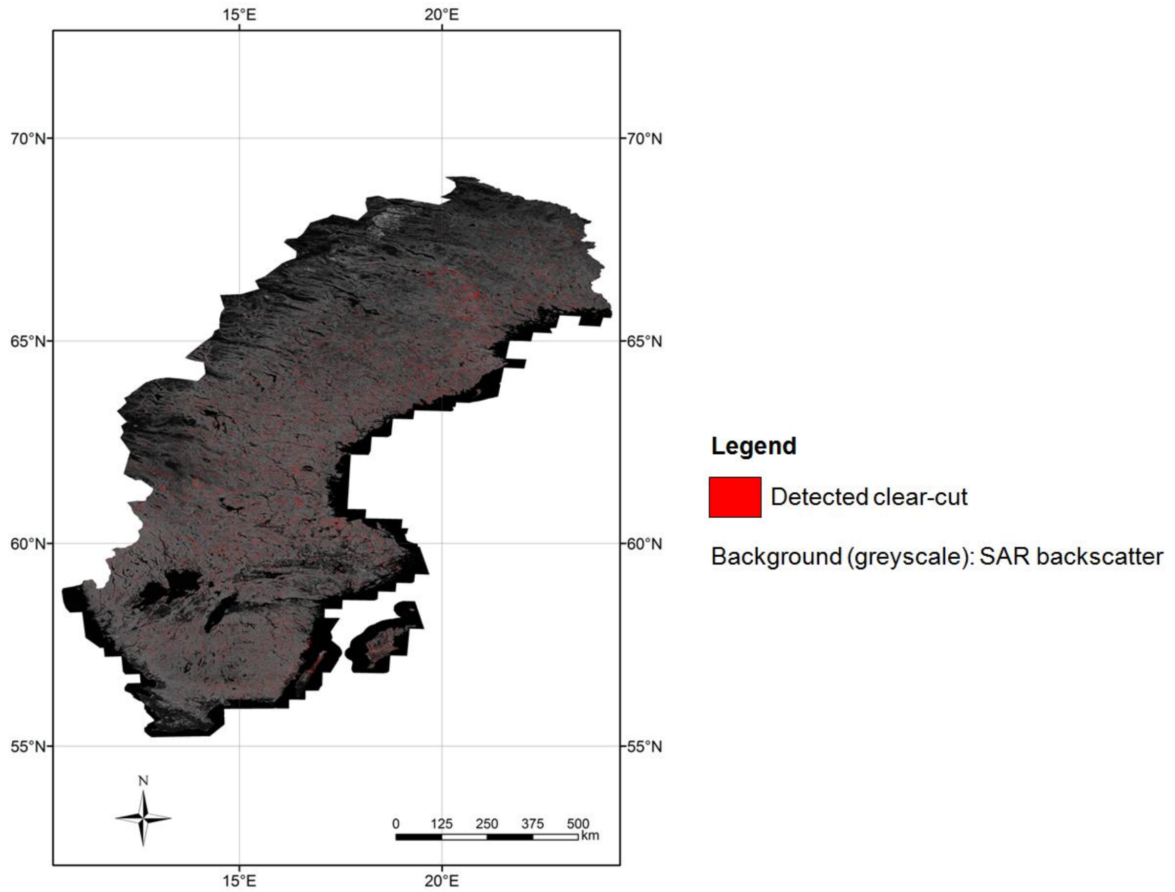
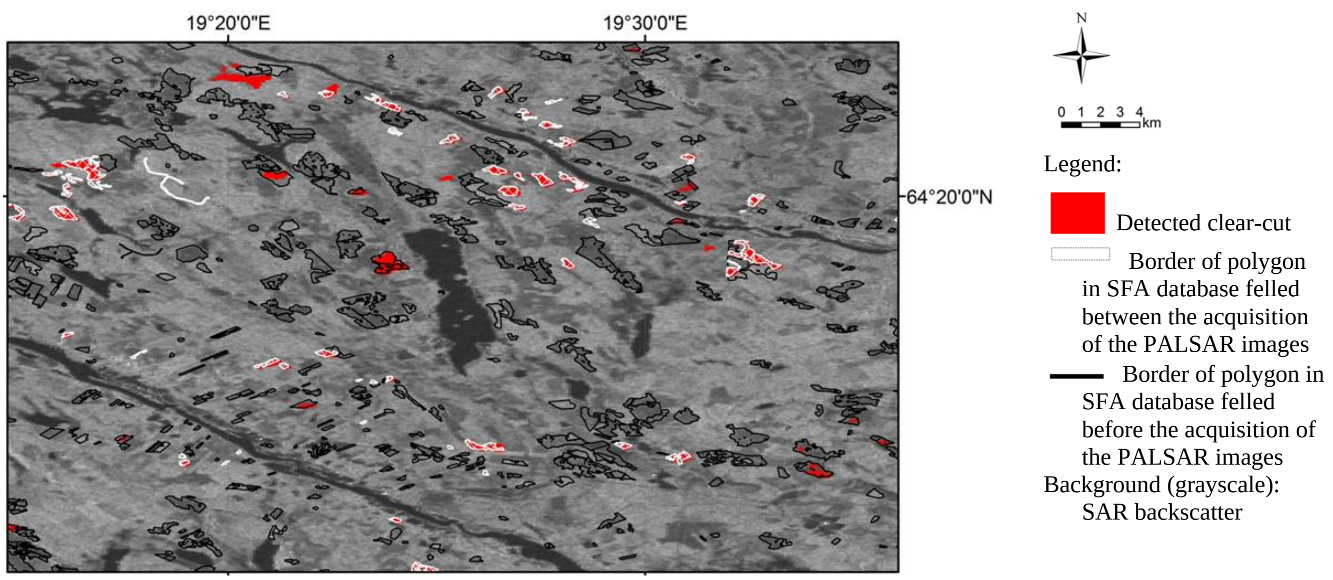


Figure 6. Clear-cuts detected in an ALOS PALSAR K&C strip image pair (in red). White polygons indicate clear-cuts recorded in the SFA database for the time frame of the PALSAR image acquisitions. Black polygons indicate clear-cuts recorded in the Swedish Forest Agency (SFA) database as felled before the acquisition of the PALSAR image pair.



Although the comparison between the detected clear-cuts and those recorded in the SFA database could benefit from the large number of clear-cuts in the reference dataset, a rigorous quantitative assessment of the agreement was hindered by the lack of exact information on felling date. From the PALSAR data, the dates spanning the shortest time interval bridging a detected change represent the dates of detection. The date recorded as detection in the SFA database corresponds to the latter date of the optical satellite images bridging a detected change. The issue of the timing of the satellite data is therefore crucial when addressing the quantitative assessment of the agreement between the PALSAR-based clear-cuts and the clear-cuts recorded by the SFA.

For this reason, the distribution of the pixel labeled as change by the detection algorithm with respect to the felling date recorded in the SFA database was investigated and three broad categories were defined:

(1) A detection was likely to be *correct* if it co-occurred spatially with a SFA clear-cut polygon, and the recorded felling date was *after* the date of acquisition of the first PALSAR image;
(2) A detection was likely to be *erroneous* if it co-occurred spatially with a SFA clear-cut polygon, and the recorded felling date was *before* the date of acquisition of the first PALSAR image;
(3) A detection was labeled as *not verifiable* if it did not co-occur spatially with any SFA clear-cut polygon.

Table 3 shows the percentage of pixels labeled as change with respect to these three categories for 50×50 km^2 sites (corresponding to tiles) located in 10 out of the 21 counties in Sweden. The sites were selected to provide a homogeneous coverage of Sweden. It is remarked here that these percentages express the likeliness of the agreement since no detailed information on the felling date were available.

Table 3. Likeliness of agreement between pixels detected as change in pairs of ALOS PALSAR K&C strip images and SFA clear-felled areas for ten sites in Sweden for the time periods 2008–2009 and 2009–2010. Each site corresponds to a 50×50 km^2 area (*i.e.*, an image tile).

Tile ID	County	Likeliness of Detection					
		2008–2009			2009–2010		
		Agree (%)	Not Agree (%)	Not Verif. (%)	Agree (%)	Not Agree (%)	Not Verif. (%)
165 735	Norrbotten	42	5	53	49	6	45
165 715	Västerbotten	77	0	23	93	1	6
155 700	Västerrnorrland	85	2	13	83	1	16
150 690	Gävleborg	79	2	19	88	1	11
135 680	Dalarna	56	1	43	-	-	-
160 670	Uppsala	76	3	21	84	1	15
135 665	Värmland	78	1	21	84	3	13
130 640	Västra Götaland	90	1	9	75	1	24
140 640	Jönköping	63	6	31	81	4	15
150 635	Kalmar	78	2	20	59	4	37

The likeliness of correct detection was generally high. For seven of the ten sites considered, the agreement was between 75% and 93%. For the remaining three sites, the lower percentage of likely correct detections was complemented by a high percentage of unverifiable results. The percentage of pixels likely to be erroneous was consistently between 1% and 6%. The percentage of unverifiable pixels was about 20% except for when the mismatch between the PALSAR data and the optical satellite data was substantial. To clarify the reason for the mismatch, the dates of detection recorded by the SFA and the dates of the PALSAR images available for the specific site were compared in detail.

For the site within the county of Dalarna, several detections in the PALSAR dataset did not correspond to detections in the SFA database. A closer look revealed that the database of the SFA did not include information after the end of June 2009. For 2008 and 2009, the PALSAR K&C strip data were acquired between 2008-08-20 and 2009-10-08. It is therefore believed that the large percentage of pixels labeled as unverifiable are due to missing information in the SFA database related to fellings that occurred after June and before the acquisition of the PALSAR images in 2009. Similar conclusions could be drawn for the sites within the counties of Jönköping (2008–2009) and Kalmar (2009–2010). For the other sites in Table 3, the last date of detection available in the SFA database was at most one month before the PALSAR image acquisition date, thus explaining the smaller percentage of unverifiable detections.

For the area within the county of Norrbotten, the low percentage of agreement was due to the way the date of detection is defined in the PALSAR and the SFA datasets. For several clear-cuts, the date of detection recorded by the SFA was 17 August 2008 whereas the first PALSAR image was acquired on 22 June 2008. It is likely that clear-cuts occurred before the acquisition of the radar data but were recorded by the SFA in August when the optical satellite image was acquired. This result was consistent across many large clear-cuts so that erroneous detection by the change detection algorithm can be excluded as a source for the large discrepancy. This interpretation is confirmed when looking at clear-cuts recorded by the SFA as felled during 2009. All clear-cuts recorded by the SFA in 2009 were also detected in the PALSAR dataset. A similar explanation hold true for the low percentage of agreement for the 2009–2010 period.

6.2. Assessment of Clear-Felled Area at County and National Level

The areal assessment of the yearly ALOS PALSAR clear-cut maps consisted of a comparison at county and national levels with statistics of clear-cuts from the SFA and the NFI (Table 4). While the SFA derives such statistics based on optical satellite imagery, the NFI upscales plot-wise measurements to provide county-wise and national estimates. In Table 4, the counties have been sorted according to their geographic location from north to south (see also Figure 2). The comparison was possible for all 21 counties in Sweden for 2008–2009 and 2009–2010. The availability of PALSAR K&C strip data in FBD mode acquired between 2007 and 2008 over parts of Sweden allowed the comparison only for three counties (*i.e.*, Västerbotten, Västra Götaland and Jönköping). The statistics were in turn compared to statistics of notified areas of final fellings recorded by the SFA for 2007–2008 [16], 2008–2009 [11] and 2009–2010 [17]. Total figures for the whole of Sweden are reported for 2008–2009 and 2009–2010. The yearly statistics in Table 4 have intrinsic differences because of the different time frames covered by the satellite data and the field inventory data. For this reason, average values over the time frame for which PALSAR data were available have also been computed. The statistics are reported in Table 5.

Table 4. County and national level statistics of clear-felled areas in hectare for three consecutive years from ALOS PALSAR K&C strip data (PALSAR), the Swedish Forest Agency (SFA), the National Forest Inventory (NFI), and notified areas of final fellings recorded by the SFA (Notified) [11,16,17].

County	2007–2008				2008–2009				2009–2010			
	PALSAR	SFA	NFI	Notified	PALSAR	SFA	NFI	Notified	PALSAR	SFA	NFI	Notified
Norrbotten	-	-	-	-	23,188	14,168	20,171	15,804	18,775	30,517	27,949	23,023
Västerbotten	21,696	21,578	16,216	23,330	23,915	21,520	33,729	20,394	18,112	20,563	21,417	30,428
Jämtland	-	-	-	-	17,016	22,061	27,098	20,435	11,609	20,990	11,362	29,387
Västernorrland	-	-	-	-	13,804	14,103	13,127	20,412	10,750	15,753	8,718	25,899
Gävleborg	-	-	-	-	12,698	14,429	1,615	17,356	12,097	17,330	3,291	19,300
Dalarna	-	-	-	-	14,529	13,720	7,694	18,313	13,701	10,186	34,572	24,562
Värmland	-	-	-	-	5,971	9,272	5,475	15,295	8,573	12,320	13,262	14,907
Örebro	-	-	-	-	3,422	5,690	2,345	7,868	4,376	9,598	11,109	9,370
Västmanland	-	-	-	-	2,210	3,873	318	4,173	1,773	4,322	0	4,824
Uppsala	-	-	-	-	4,431	3,557	12,314	5,520	4,035	4,284	6,312	6,980
Stockholm	-	-	-	-	1,904	1,614	0	1,488	1,075	1,545	2,708	2,878
Södermanland	-	-	-	-	1,131	2,023	4,288	2,930	1,510	2,113	1,361	5,248
Östergötland	-	-	-	-	2,170	2,099	8,344	8,150	2,899	-	24,813	9,777
Västra Götaland	7,753	12,789	12,311	13,898	4,967	9,054	11,787	17,306	7,807	16,640	12,934	22,638
Jönköping	2,710	4,580	3,431	6,338	2,830	3,782	4,616	9,623	3,744	8,190	4,104	10,642
Kronoberg	-	-	-	-	2,016	2,847	12,832	7,908	3,011	5,757	13,028	9,079
Kalmar	-	-	-	-	4,518	4,571	10,247	10,497	5,615	3,187	8,022	11,604
Gotland	-	-	-	-	1,538	711	0	0	2,485	953	0	0
Halland	-	-	-	-	617	914	0	3,518	810	2,325	1,709	3,773
Blekinge	-	-	-	-	860	2,407	577	3.041	1,413	2,436	5,691	3,380
Skåne	-	-	-	-	903	1,637	0	6,212	1,447	4,717	236	5,420
Total (Sweden)	**-**	**-**	**-**	**-**	**144,638**	**154,055**	**176,575**	**216,243**	**135,617**	**193,727**	**212,597**	**239,179**

Table 5. County and national level average statistics of clear-felled areas for the time period 2008–2010 from ALOS PALSAR K&C strip data (PALSAR), the Swedish Forest Agency (SFA), the National Forest Inventory (NFI) and the notified areas of final fellings recorded by the SFA (Notified) [11,16,17]. For Västerbotten, Västra Götaland and Jönköping, a three-year average value between 2007 and 2010 is reported. For details on individual years, please refer to Table 4.

County	PALSAR (ha)	SFA (ha)	NFI (ha)	Rel. RMSE of NFI(%)	Notified (ha)
Norrbotten	20,982	22,343	24,060	50.3	19,414
Västerbotten	21,241	21,220	23,787	45.1	24,717
Jämtland	14,313	21,526	19,230	60.4	24,911
Västernorrland	12,277	14,928	10,923	56.0	23,156
Gävleborg	12,398	15,880	2,453	72.4	18,328
Dalarna	14,115	11,953	21,133	50.5	21,438
Värmland	7,272	10,796	9,368	58.9	15,101
Örebro	3,899	7,644	6,727	62.0	8,619
Västmanland	1,992	4,098	159	100.0	4,499
Uppsala	4,233	3,921	9,313	48.0	6,250
Stockholm	1,490	1,580	1,354	70.3	2,183
Södermanland	1,321	2,068	2,825	63.3	4,089
Östergötland	2,535	2,099	16,579	51.9	8,964
Västra Götaland	6,842	12,828	12,344	57.7	17,947
Jönköping	3,095	5,517	4,050	28.3	8,868
Kronoberg	2,514	4,302	12,930	33.3	8,494
Kalmar	5,067	3,879	9,134	43.2	11,051
Gotland	2,012	832	0	-	0
Halland	714	1,620	854	66.1	3,646
Blekinge	1,137	2,422	3,134	88.9	1,692
Skåne	1,175	3,177	118	132.1	5,816
Total (Sweden)	140,618	172,532	194,586	15.0	239,183

Tables 4 and 5 show that the estimates of clear-felled areas were largest for the northern counties regardless of the dataset. The six northernmost counties accounted for approximately 65% of the yearly clear-felled area in Sweden. The order of magnitude of the area estimates was mostly consistent among the PALSAR, SFA and NFI datasets. Nonetheless, significant differences often occurred, typically when comparing one dataset with respect to the other two (Tables 4 and 5).

The estimates from the PALSAR dataset and the SFA dataset presented different levels of agreement depending on the year and geographical location (Table 4). While the area estimates from the PALSAR dataset decreased between 2008–2009 and 2009–2010 for the northern counties and increased for the southern counties, the SFA estimated an increase of area felled for most counties. As a consequence, the difference between the PALSAR and the SFA dataset of the area felled was substantially larger in 2009–2010, even if the SFA estimates of the counties of Östergötland and Kalmar were incomplete. The area estimates from the PALSAR dataset were mostly smaller compared to the SFA since potential changes smaller than 0.5 ha were not taken into account. Furthermore, the rather conservative delineation of clear-cuts in the PALSAR data at 50 m pixel size resulted in smaller detected areas compared to the true extent of a clear-cut. The discrepancy between estimates was more noticeable for the southern regions where clear-cuts are generally smaller compared to the north of the country. The estimate of the total clear-felled area for Sweden from the PALSAR data was smaller compared to the corresponding estimate by the SFA (144,638 ha *vs*. 154,055 ha for 2008–2009 and 135,617 ha *vs*. 193,727 ha for 2009–2010, see Table 4).

The agreement between the PALSAR and the NFI statistics, and in turn also between the SFA and the NFI statistics, was weaker (Table 4). The area estimates from the NFI were mostly larger compared to the values obtained from the two other datasets. Only for the counties of Västerbotten (2007–2008), Gävleborg (2008–2009 and 2009–2010), Örebro (2008–2009), Västmanland (2008–2009) and Skåne (2009–2010) were the estimates substantially smaller. It should be noted that the statistics from the NFI are here based on a total of about 10,000 field plots per year, where only about 50 of these were registered as harvested at the time of field inventory. In addition, there were no field plots registered as harvested in the counties of Stockholm, Gotland, Halland and Skåne in 2008–2009, and Västmanland and Gotland in 2009–2010. Thus, the estimated area of clear-cuts for these counties is zero, even if clear-felling has taken place. Despite lack of estimates by the NFI for some counties, the estimate of total clear-felled area for Sweden from the PALSAR data was substantially smaller compared to the corresponding estimate by the NFI (144,638 ha *vs*. 176,575 ha for 2008–2009 and 135,617 ha *vs*. 212,597 ha for 2009–2010, see Table 4).

Except for the counties of Norrbotten and Västerbotten for the time period 2008–2009, the area estimate based on the PALSAR data was either on the same order or smaller compared to the area of notified fellings recorded by the SFA (Table 4). The statistics of notified areas of final fellings (>0.5 ha) should be interpreted as a reference of the maximum area that is allowed to be clear-felled.

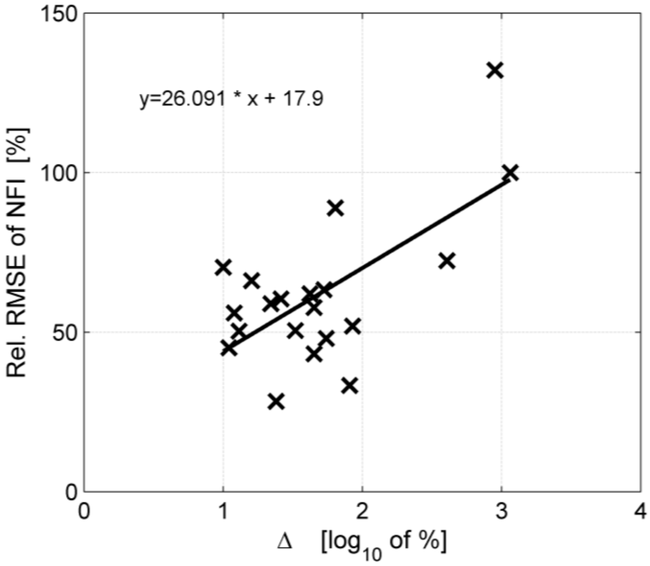
When averaged over several years, the impact of (i) different time periods used for the detection of the clear-cuts in the case of the PALSAR and the SFA datasets, and (ii) the number of sample plots from which the NFI inferred its areal statistics diminished. Therefore, the area statistics presented a stronger agreement for 2008–2010 (Table 5). Nonetheless, some counties were characterized by outliers, which concerned primarily the NFI dataset:

(a) Smaller estimates by the NFI for the counties of Gävleborg, Västmanland and Skåne;
(b) Larger estimates by the NFI for the counties of Dalarna, Uppsala, Östergötland, Kronoberg, and Kalmar;
(c) Smaller estimates in the PALSAR dataset for the counties of Jämtland, Örebro and Västra Götaland.

The relative Root Mean Square Error (RMSE) for the county-wise estimates of clear-felled areas according to the NFI (Table 5) shows that the three counties for which the NFI estimates are substantially smaller compared to the other two datasets (point (a) above) were also characterized by some of the largest estimation errors. Figure 7 shows a scatter plot of the relative difference in a logarithmic scale (Δ) between the PALSAR and NFI area statistics in Table 5 expressed as

$$\Delta = \log_{10}\left[100 \cdot \frac{(PALSAR - NFI)}{NFI}\right] \tag{2}$$

Figure 7. Scatter plot of relative root mean square error (RMSE) of Swedish National Forest Inventory (NFI) estimates of clear-felled areas (Table 5) with respect to the relative difference between PALSAR and NFI statistics according to Equation (2).



The corresponding values of relative RMSE of NFI values are reported in Table 5. The three counties with the largest relative differences (Gävleborg, Västmanland and Skåne) were also characterized by three of the four largest estimation errors. For the other counties, no relationship between the relative difference and the estimation error could be observed, thus leaving unexplained the discrepancy between the NFI estimates and the other datasets for the counties of Dalarna, Uppsala, Östergötland, Kronoberg, and Kalmar (point (b) above).

From the PALSAR and SFA area estimates in Table 5, the difference in percent was computed in order to highlight trends related to the geographic location (Table 6). For most counties, between 20% and 60% less area was detected as clear-felled in the PALSAR data. Only in a few cases, the difference presented a positive sign, implying larger clear-cut area detected in the PALSAR dataset than by the SFA. The difference was below 25% (in absolute terms) for most of the northern counties, as well as for the counties of Stockholm and Uppsala. It is unclear what caused the smaller estimate for the county of Jämtland. A relative difference between 30% and 50% was typical of the counties of central Sweden. The southernmost counties presented relative differences above 50% (in absolute terms). For the county of Gotland, almost three times as much clear-felled area was detected by PALSAR; it is unclear whether this is correct since the NFI did not provide estimates, which could have been used for inter-comparison. At the national level, the difference was 19% (21% when excluding the counties of Östergötland and Kalmar for which the SFA data records were incomplete). This result is consistent with the indication from the analysis in Section 5 where it was reported that at 50 m, approximately 30% less area was detected as felled when compared to 20 m. If the total area felled detected in the PALSAR dataset (140,618 ha, Table 5) is crudely scaled by 30%, the corresponding estimate (182,803 ha) falls between the estimates reported in Table 5 for the SFA (172,532 ha) and the NFI (194,586 ha).

Table 6. Difference in percent between PALSAR-based and SFA estimates of clear-felled area at county level for the average statistics in Table 5.

County	Difference (%) PALSAR *vs.* SFA
Norrbotten	−6
Västerbotten	0
Jämtland	−34
Västernorrland	−18
Gävleborg	−22
Dalarna	18
Värmland	−33
Örebro	−49
Västmanland	−51
Uppsala	8
Stockholm	−6
Södermanland	−36
Östergötland	-
Västra Götaland	−47
Jönköping	−44
Kronoberg	−42
Kalmar	31
Gotland	142
Halland	−56
Blekinge	−53
Skåne	−63
Total (Sweden)	−19

7. Conclusions

In this paper, it was investigated to which extent ALOS PALSAR strip images (HV-polarization) provided through JAXA's Kyoto and Carbon (K&C) Initiative with a reduced spatial resolution of 50 m could support mapping of clear-cuts at a national level in Sweden. PALSAR data were available for each summer/fall for the time period of 2008–2010 covering the whole of Sweden and for 2007 over three counties, thus allowing repeated assessments on a yearly basis of clear-felled areas. Clear-cut detection was performed using a contextual unsupervised data fusion based multi-channel change detection (DF-MCD) method proposed in [7]. The method required a forest mask that was needed to remove ambiguities due to changes in other land cover types, such as cropland.

At first, the performance of clear-cut detection based on PALSAR K&C strip images was tested against detection obtained using the corresponding full-resolution PALSAR path images. For 31 polygons of clear-cut forest in the county of Västerbotten, 29% less clear-felled area were detected at 50 m compared to 20 m, corresponding to the effective resolution of the PALSAR images. While the detection performed well within a clear-cut polygon (on average almost 90% of pixels correctly detected), the delineation of the clear-cut borders was often rough because of blurred edges. In addition, small-scale changes remained undetected.

Yearly regional clear-cut maps obtained from the PALSAR K&C strip images agreed with clear-cuts estimated by the Swedish Forest Agency (SFA) using spaceborne optical images for large parts of the country in over 80% of cases. The major reasons for discrepancies were the different dates of detection recorded in the two datasets and the lower resolution of the PALSAR data compared to the optical data.

The contribution of PALSAR K&C strip images in national monitoring of clear-cuts was finally benchmarked against the database of clear-cuts produced by the SFA using optical satellite images and clear-cut area estimates produced by the Swedish National Forest Inventory (NFI) based on forest inventory measurements. County- and nation-wide estimates of clear-felled area presented similar orders of magnitude; nonetheless, for some regions the estimates were significantly different. The reduced resolution of the PALSAR K&C strip images caused underestimation primarily in the southern counties of Sweden, where often clear-cuts remained undetected at 50 m resolution. Large discrepancies between the NFI and the other two datasets were a consequence of the small number of field plots on which the area estimate was based.

This study indicates that PALSAR K&C strip data are useful to support monitoring of clear-cuts in Swedish forests by providing indications on where these took place, thus being a candidate for complementing the operational mapping based on optical satellite data. The short time interval over which nation-wide coverage of PALSAR data is achieved (46 days) allows narrowing down to a short interval on detection date. The end of the ALOS mission in May 2011 was an unfortunate event since it prevented the addition of datasets to the database of already available images.

This study also demonstrates the limitations of PALSAR K&C strip data with regard to precise delineation of clear-felled areas. Clear-felled areas in the order of two ha or less would remain undetected whereas larger clear-cuts edges would not correspond to their true location. As a consequence, the 50 m pixel size limits the possibility to derive accurate statistics of the total clear-felled area at the county and national level. The use of full-resolution data (20 m pixel size) would provide a significant improvement with respect to the results achieved with the 50 m pixel size data. A nation-wide coverage of PALSAR images at full resolution is however associated with high costs in the order of 10 kEuro/year.

The launch of the follow-up ALOS-2 satellite in 2013 is promising in view of accurate clear-cut detection because of the availability of very high-resolution acquisition modes [18]. While the provision of nation-wide coverage in the highest possible resolution (1–3 m) seems unfeasible, the complement between Fine Beam mode images at 10 m resolution and, locally, of higher resolution data is foreseen as a possible approach to support operationally clear-cut mapping in Sweden with a radar-based data approach.

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References

1. Lantmäteriet. *Saccess Database*; 2010. Available online: http://saccess.lantmateriet.se/ (accessed on 15 May 2012).
2. SLU. *Skogskarta*; 2011. Available online: http://skogskarta.slu.se/ (accessed on 15 May 2012).
3. Santoro, M.; Fransson, J.E.S.; Eriksson, L.E.B.; Magnusson, M.; Ulander, L.M.H.; Olsson, H. Signatures of ALOS PALSAR L-band backscatter in Swedish forest. *IEEE Trans. Geosci. Remote Sens.* **2009**, *47*, 4001–4019.
4. Rosenqvist, Å.; Shimada, M.; Ito, N.; Watanabe, M. ALOS PALSAR: A pathfinder mission for global-scale monitoring of the environment. *IEEE Trans. Geosci. Remote Sens.* **2007**, *45*, 3307–3316.
5. Santoro, M.; Fransson, J.E.S.; Eriksson, L.E.B.; Ulander, L.M.H. Clear-cut detection in Swedish boreal forest using multi-temporal ALOS PALSAR backscatter data. *IEEE J. Sel. Topics Appl. Earth Obs.* **2010**, *3*, 618–631.
6. Moser, G.; Serpico, S.B. Generalized minimum-error thresholding for unsupervised change detection from SAR amplitude imagery. *IEEE Trans. Geosci. Remote Sens.* **2006**, *44*, 2972–2982.
7. Moser, G.; Serpico, S.B. Unsupervised change detection from multichannel SAR data by markovian data fusion. *IEEE Trans. Geosci. Remote Sens.* **2009**, *47*, 2114–2128.
8. Pantze, A.; Fransson, J.E.S.; Santoro, M. Forest Change Detection from L-Band Satellite SAR Images Using iterative Histogram Matching and Thresholding Together with Data Fusion. In *Proceedings of the IEEE 2010 International Geosciences and Remote Sensing Syposium*, Honolulu, HI, USA, 25–30 July 2010.
9. Fransson, J.E.S.; Olsson, H.; Eriksson, L.E.B.; Ulander, L.M.H.; Santoro, M. *K&C Science Report—Phase 1, Detection of Deforestation in Swedish Forest*; The ALOS Kyoto & Carbon Initiative, Science Team Reports Phase 1 (2006–2008); Japan Aerospace Exploration Agency: Tsukuba, Japan, 2010.
10. Wegmüller, U. Automated Terrain Corrected SAR Geocoding. In *Proceedings of the IEEE 1999 International Geosciences and Remote Sensing Syposium*, Hamburg, Germany, 28 June–2 July 1999.
11. Loman, J.-O. *Statistical Yearbook of Forestry 2010*; Swedish Forest Agency: Jönköping, Sweden, 2010.
12. Fridman, J.; Walheim, M. Amount, structure and dynamics of dead wood on managed forestland in Sweden. *For. Ecol. Manage.* **2000**, *131*, 23–36.
13. Axelsson, A.-L.; Ståhl, G.; Söderberg, U.; Petersson, H.; Fridman, J.; Lundström, A. National Forest Inventory Reports: Sweden. In *National Forest Inventories—Pathways for Common Reporting*; Tomppo, E., Gschwantner, T., Lawrence, M., McRoberts, R.E., Eds.; Springer: Dordrecht, The Netherlands, 2010; pp. 541–553.

14. Toet, H.; Fridman, J.; Holm, S. *Precisionen i Riksskogstaxeringens Skattningar 1998–2002* (in Swedish); Sveriges Lantbruksuniversitet, Institutionen för Skoglig Resurshushållning: Umeå, Sverige, 2007; Arbetsrapport 167.
15. Engberg, A. *Produktspecifikation av Svenska CORINE Marktäckedata* (in Swedish); SCMD-0001, Version 2.1; Lantmäteriet: Gävle, Sweden, 2002. Available online: http://www.lantmateriet.se/upload/filer/kartor/kartor_och_geografisk_info/GSD-Produktbeskrivningar/md_prod.pdf (accessed on 15 May 2012).
16. Loman, J.-O. *Statistical Yearbook of Forestry 2009*; Swedish Forest Agency: Jönköping, Sweden, 2009.
17. Loman, J.-O. *Statistical Yearbook of Forestry 2011*; Swedish Forest Agency: Jönköping, Sweden. 2011.
18. Okada, Y.; Hamasaki, T.; Tsuji, M.; Iwamoto, M.; Hariu, K.; Kankaku, Y.; Suzuki, S.; Osawa, Y. Hardware Performance of L-Band SAR System Onboard ALOS-2. In *Proceedings of the IEEE 2011 International Geosciences and Remote Sensing Symposium*, Vancouver, BC, Canada, 24–29 July 2011.