K&C Science Report – Phase 2

National clear-cut mapping in Sweden with ALOS PALSAR

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***Abstract*—A new clear-cut detection algorithm was developed and yearly maps of clear-cuts covering the entire Sweden for the period 2008-2010 were produced, based on an extensive dataset of ALOS PALSAR Fine Beam Dual (FBD) HV-polarized backscatter images. The new algorithm is able to detect clear-cuts with high accuracy and map the areal extent of the detected clear-cuts well. At 20 m pixel size (path data), 79.4% of the pixels in 31 clear-cuts were correctly detected. The majority of misclassified pixels were located along the clear-cut edges. The detection accuracy improved to 90%, when applying a one-pixel edge-eroded version of the reference dataset. At 50 m pixel size (strip data), the corresponding figures were 72.5% and 85.9% without and with one edge-eroded pixel, respectively. PALSAR strip data are judged to be sufficient for detection of clear-cuts and provide a rough delineation of the clear-cut extensions. A resolution of 10-20 m (e.g., PALSAR path data) is, however, recommended if higher precision is required. Nation-wide clear-cut mapping using strip data and the new detection algorithm proved to be very robust and computationally fast. For the period spanning the growing season of 2008-2009, a total of 168,279 ha were detected as clear-cuts. For the same period, the Swedish National Forest Inventory reported 168,645 ha. For 2009-2010, 156,910 ha were detected with PALSAR as clear-cuts. A comparison at county level with information from the Swedish Forest Agency and the Swedish National Forest Inventory shows an overall good agreement, but also local discrepancies likely due to time differences in the datasets. The results highlight the usefulness of ALOS PALSAR strip data in an operational scenario for clear-cut mapping at a national level.**

***Index Terms*—ALOS PALSAR, K&C Initiative, boreal forest, forest theme, deforestation, clear-cuts, Sweden.**

I. Introduction

In Sweden, a nation-wide coverage of optical satellite data is acquired yearly by the government. These images are free to download for all citizens of Scandinavia and Finland through the Saccess database (http://saccess.lantmateriet.se/). Among others, the images are used by the Swedish Forest Agency for change detection to find clear-cuts and to check the cutting permits of about 70,000 clear-felled areas nation-wide and yearly. In combination with about 50,000 Swedish National Forest Inventory field plots, the images are also used by the Swedish University of Agricultural Sciences for producing nation-wide forest maps (http://skogskarta.slu.se/). Sweden is, however, 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, about 1,500-2,000 programming attempts of the SPOT satellites are needed (in the past over 3,000 attempts). 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 forest mapping activities:

(i) strong sensitivity of the backscatter to forest structural properties, e.g. [1];

(ii) acquisition strategy aimed at maximizing the information content of the data with respect to such properties [2];

(iii) acquisition plan to obtain full regional coverage within short time periods on a yearly basis [2].

In the first phase of the Kyoto & Carbon Initiative project (hereafter referred to as the K&C project) on clear-cut mapping, the potential of ALOS PALSAR data was demonstrated [3]. This has motivated further investigations of PALSAR images for forest change detection and mapping. To fulfil the goals of the K&C project on nation-wide clear-cut mapping, efforts had to be paid to the development of a robust and fast clear-cut detection algorithm. The present study here reported, referred to as phase 2, is a continuation of the first phase.

II. Description of the Project

A. Relevance to the K&C drivers

The major scope of the present K&C project is to develop, verify and demonstrate a methodology for detection and delineation of clear-cuts in boreal forest and to produce yearly clear-cut maps of Sweden using multi-temporal ALOS PALSAR data. 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. Here, 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 comparisons with granted cutting permits. 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.

B. Work approach

In the first phase of the K&C project, the signatures of ALOS PALSAR backscatter were analyzed in order to understand which acquisition configuration is most suitable for the detection of clear-cuts. Then, a simple algorithm for clear-cut detection was developed and maps of clear-cuts were produced. For signature analysis, development of the detection algorithm and production of clear-cut maps, the counties of Västerbotten and Västra Götaland (i.e., prototype areas), in the north and in the south of Sweden, respectively, were selected (Fig. 1). The signature analysis revealed that the largest backscatter difference as a consequence of clear-cut was observed at HV-polarization. Unfrozen conditions were characterized by very stable signatures, whereas at HH-polarization the backscatter depended more on the environmental conditions [1, 4]. For this reason, the clear-cut detection algorithm was developed to exploit the temporal stability of multi-temporal HV data. Each summer/fall, at least two PALSAR Fine Beam Dual (FBD) HV images are acquired over Sweden; the partial degree of overlap of adjacent PALSAR swaths increases the number of observations. The advantage of working with a stack of measurements, even if small, is that detection performed with a simple thresholding algorithm is only marginally affected by backscatter variability due for example to residual speckle, calibration uncertainties or specific environmental conditions. Details on the detection algorithm can be found in [4]. The algorithm was applied to PALSAR strip data at 50 m pixel size acquired during the summer/fall of 2007 and 2008. To validate the detection algorithm, a database of clear-cuts obtained from the forest company Sveaskog was used. 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 reported in the database for the county of Västerbotten [4]. While the central part of the clear-cuts was identified well, discrepancies occurred at the edges. The accuracy assessment also revealed that the total felled area obtained with the PALSAR dataset differed by only 5% with respect to official statistics reported by the Swedish Forest Agency [4]. The results from Västra Götaland were characterized by a much larger degree of uncertainty, likely because of the small number of clear-cuts available for validation and the smaller size of clear-cuts in this area [4].

From the analyses carried out in phase 1, it could be concluded that detection of clear-cuts with PALSAR data is highly feasible. Open issues concerned the effect of (i) spatial resolution and (ii) underlying assumptions in the detection algorithm on the precision of the detection. The latter aspect has been addressed in [5-6]. These studies were focused on change detection automatization, and the possibility of achieving fine detail delineation of clear-cuts. Radiometric normalization and initial change/no change classification were achieved using histogram matching and automatic image ratio thresholding (GKIT) [7] combined in an iterative manner.

Figure 1. The K&C project prototype areas and local test sites in Sweden.

As an optional final change/no change classification step the data fusion based multi-channel change detection (MCD) method proposed in [8] was tested. This method is based on Markov random fields and can take into account the spatial contextual information from one or multiple SAR channels. A set of computationally fast histogram based techniques was applied to bi-temporal PALSAR backscatter path images with a pixel size of 20 m acquired the during summer of 2007 and 2008 over test sites within the two prototype areas. Various combinations of methods, channels (HH, HV or HH+HV), settings, and filtering options were evaluated for clear-cut detection performance. Pixel-wise detection accuracies of 90% could be achieved with a false error rate around or below 10%, when combining the GKIT and MCD method (Fig. 2). The contribution of the HH channel was, furthermore, marginal with respect to the detection achieved with HV data only. Most misclassified pixels were located along clear-cut edges indicating that most errors were due to layover, shadowing or image co-registration errors.

The satisfactory results from the test sites suggested using the improved algorithm for fulfilling the goal of the second phase of the K&C project, i.e. the production of yearly clear-cut maps for entire Sweden using PALSAR strip data acquired during the summer/fall of 2008, 2009 and 2010. Nevertheless, it had to be ensured beforehand that the algorithm would perform equally well with the PALSAR strip data, which present a lower spatial resolution (pixel size of 50 m) compared to PALSAR path data (pixel size of 20 m).

C. Satellite and ground data

In the second phase of the K&C project, three sets of ALOS PALSAR FBD HV-polarized images (with 34.3 degrees look angle) were considered.

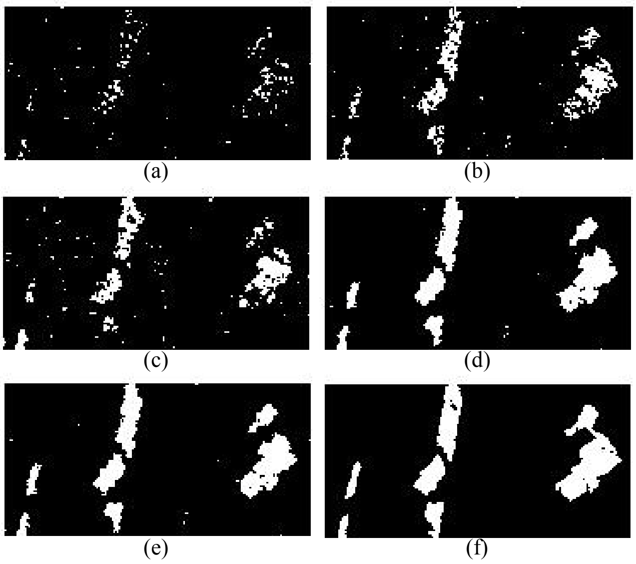


Figure 2. Clear-cut detection maps from unfiltered ALOS PALSAR images acquired over hemi-boreal forest in southern Sweden (3600×1800 m^2). White pixels are classified as clear-cuts. (a) HH change map from GKIT, (b) HV change map from GKIT, (c) HH change map from GKIT+MCD, (d) HV change map from GKIT+MCD, (e) Dual channel (HH+HV) change map from GKIT+MCD, and (f) Reference map derived using SPOT-5 SWIR images.

1) Strip data at 50 m pixel size covering the county of Västerbotten and acquired during the summer/fall of 2007 and 2008 (first project phase, [4]). These were used to compare the performance of the new clear-cut detection algorithm with respect to the former detection algorithm.

2) A pair of path images (70×70 km^2) over part of Västerbotten acquired on 2007-07-24 and 2008-09-10 (RSP: 615, Frame number: 1280). These images were used to assess the impact of spatial resolution on the performance of the new detection algorithm. The original data, with pixel size of 9.4 m in slant range and 3.1 in azimuth, were multi-looked to obtain pixel sizes of 10 m and 20 m in ground range. The same dataset was also available as strip data at 50 m pixel size.

Figure 3. Mosaic of ALOS PALSAR FBD strip images acquired during 2009 covering Sweden (red: HH-polarized backscatter; green: HV-polarized backscatter; blue: HH/HV-polarized backscatter ratio).

3) Strip data at 50 m pixel size covering Sweden and acquired during the summer/fall of 2008, 2009 and 2010 (see Table 1). These images were used for nation-wide mapping of clear-cuts with the new detection algorithm on a yearly basis. To be able to provide yearly maps of clear-cuts, it was necessary to consider strips achieving (i) complete coverage of Sweden, (ii) within the shortest possible time interval (e.g., within one repeat-pass cycle), (iii) for each of the three years. Data acquired between the end of July and the beginning of September satisfied the requirements. Only in a few cases, gap fillers from different periods were necessary. Table 1 presents a list of the strip data used for clear-cut detection, expressed in terms of the 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, which represents 0.8% of the Swedish territory. Fig. 3 shows a false color composite mosaic of ALOS PALSAR FBD strip images acquired during 2009.

The processing of the PALSAR images has been described in [1]. Each image strip was calibrated according to [9] and geocoded to 50 m pixel size in the Swedish RT90 coordinate system. Topographic normalization of the backscatter for local incidence angle and pixel area was then applied. Co-registration accuracy between overlapping images was typically 0.2-0.3 times the pixel size. The images were finally 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 included 1,000 ×1,000 pixels.

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 (http://www.lantmateriet.se/upload/filer/kartor/kartor/SCMDspec.pdf) was used to mask out non-forested areas. Temporal signatures of the backscatter for agricultural fields and clear-cut areas are in fact similar, i.e. sudden decrease of backscatter at harvest.

To assess the performance of the clear-cut detection, three datasets were used.

1) The GIS layer of forest clear-cut polygons provided by the forest company Sveaskog [4] served to allow a comparison

Table 1. ALOS PALSAR strip data acquired during summer/fall of 2008, 2009 and 2010 used for nation-wide clear-cut detection of Sweden.

2008			2009			2010		
RSP	Date	Cycle	RSP	Date	Cycle	RSP	Date	Cycle
613	20080622	20	615	20090613	28	615	20100801	37
615	20080726	21	633	20090713	28	634	20100802	37
634	20080727	21	625	20090715	28	607	20100803	37
607	20080728	21	631	20090725	28	626	20100804	37
626	20080729	21	634	20090730	29	618	20100806	37
629	20080803	21	626	20090801	29	629	20100809	37
621	20080805	21	621	20090808	29	621	20100811	37
605	20080809	21	613	20090810	29	613	20100813	37
624	20080810	21	632	20090811	29	632	20100814	37
627	20080815	21	605	20090812	29	605	20100815	37
619	20080817	21	624	20090813	29	635	20100819	37
611	20080819	21	619	20090820	29	627	20100821	37
630	20080820	21	611	20090822	29	619	20100823	37
603	20080821	21	622	20090825	29	611	20100825	37
622	20080822	21	617	20090901	29	630	20100826	37
633	20080825	21	609	20090903	29	622	20100828	37
625	20080827	21	628	20090904	29	633	20100831	37
617	20080829	21	620	20090906	29	625	20100902	37
609	20080831	21	623	20090911	29	617	20100904	37
620	20080903	21	607	20090915	30	609	20100906	37
631	20080906	21	629	20090921	30	628	20100907	37
623	20080908	21	627	20091003	30	631	20100912	37
632	20080923	22	630	20091008	30	624	20101001	38
628	20081017	22	603	20091009	30	623	20101030	38

with respect to the detection achieved with the multi-temporal algorithm used in the first phase of the K&C project. In addition, the dataset was used to assess the impact of spatial resolution on the detection accuracy.

2) A GIS layer of clear-cuts provided by the Swedish Forest Agency using ancillary data and optical satellite remote sensing imagery (http://www.skogsstyrelsen.se/Aga-och-bruka/Skogsbruk/Karttjanster/Skogens-Kalla/) was used to assess the quality and the consistency of the changes detected with the new algorithm for the period 2008-2009. At the time of writing, information on clear-cuts were available for 15 out of 21 counties in Sweden until September 2009. In addition, statistics from the Swedish Forest Agency of notified areas of final fellings > 0.5 ha were included in the evaluation [10].

3) The performance of the new clear-cut detection algorithm was also compared to statistics of clear-felled areas estimated by the Swedish National Forest Inventory for the period 2008-2009. Information on clear-felled areas for the period of 2009-2010 will be available during the spring of 2011.

III. Results and Discussion

The results achieved in the second phase of this K&C project are here grouped into three themes:

1) assessment of stability of the new clear-cut detection algorithm;

2) assessment of the performance of the new clear-cut detection algorithm with respect to spatial resolution of the ALOS PALSAR data and to the detection algorithm developed in phase 1;

3) generation of yearly nation-wide clear-cut maps.

A. Assessment of algorithm stability

Testing the algorithm stability was necessary to identify and correct for possible weaknesses prior to its utilization for the nation-wide detection of clear-cuts. When testing the algorithm on PALSAR strip data, the threshold value proposed by [8] for stopping the refinement iteration turned out to be too low. In several cases, the algorithm converged to a final solution after a large number of iterations (> 20). The resulting map was always characterized by substantial overestimation of the change features. To get insight in this issue, the trend of the residual difference between change maps at the last and second last iteration (hereafter referred to as the fractional difference) was plotted with respect to the iteration number. Fig. 4 shows an example of such plots for five tiles in the county of Västerbotten. The level of 1×10^{-3} corresponds to the threshold set in [8]. Fig. 4 shows that the fractional difference decreased after a small number of iterations, reaching either saturation or increasing afterwards. When looking at the change maps produced after the first three iterations, it was noticed a clear detection of areas of major change and an improvement of the delineation with respect to the previous iteration. For further iterations, either only some small additional changes were detected (case of saturated trend) or substantial additional changes were detected (case of increasing trend). Based on these observations, it was decided to iterate the refinement three times and keep the output as the final change map. In this way, robustness of the detection algorithm was ensured.

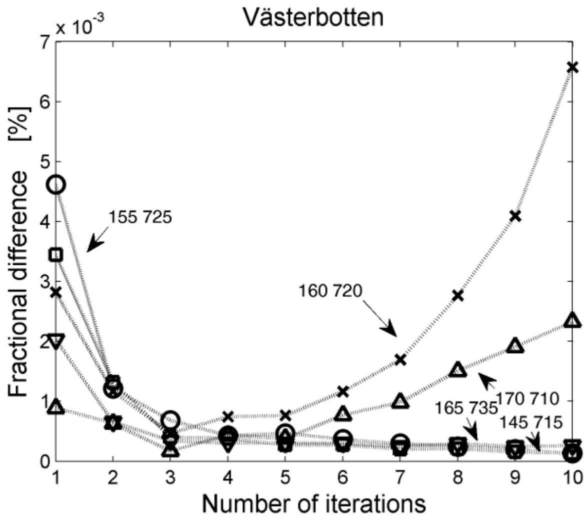


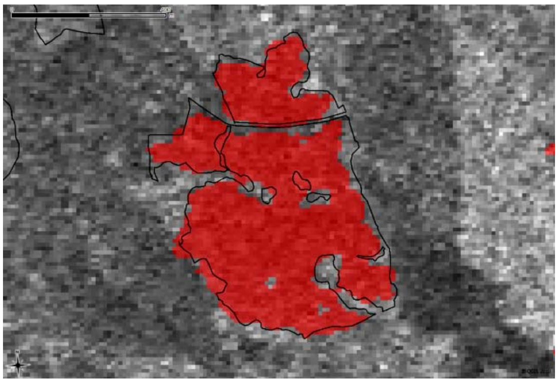
Figure 4. Trend of fractional difference with respect to iteration number. Each trend refers to change detection in a 50×50 km^2 area in the county of Västerbotten. Each area is identified by the tile number (see text for details).

B. Impact of spatial resolution on clear-cut detection

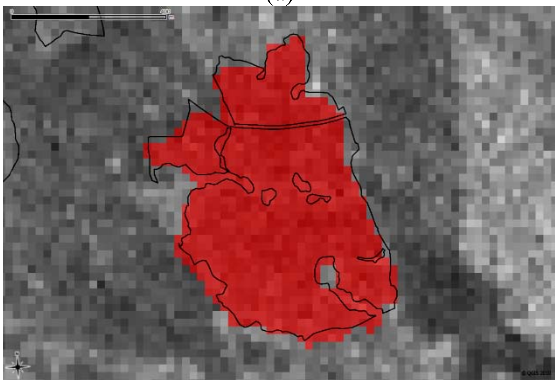
The impact of the spatial resolution of the ALOS PALSAR data on the detection performance was substantial. Fig. 5 shows an example in the case of a 28 ha large clear-cut, where felling took place on 2008-04-04. The PALSAR images were acquired on 2007-07-24 and 2008-09-10. For the PALSAR strip data (pixel size of 50 m), the bulk of the clear-cut was detected well, whereas a detailed description of the edges was hindered by the low resolution of the SAR data. At 20 m pixel size, the description of the edges improved, although small features were not detected. At 10 m resolution, the contours were further better detected and small features became more visible.

The indication given by visual interpretation of the clear-cut maps was confirmed by statistical analysis. In the analysis, an area of 50×50 km^2, corresponding to tile “165 725” was selected. For this area, both strip and path images were available. The Sveaskog GIS database reported 98 clear-cuts of which 31 occurred between the acquisition of the two images and 67 took place before. For the analysis, the GIS data were rasterized to the pixel size of interest. To further assess the impact of polygon edges, the assessment was carried out with the original rasterized map and a corresponding one-pixel edge-eroded version. At 50 m, the erosion caused about half of the polygons to disappear. For each polygon, the percentage of correctly detected pixels was computed. For the 31 polygons, Table 2 reports the statistical distribution of the polygon-wise percentage of correctly detected pixels in terms of the average value and, the 10th and the 90th percentile.

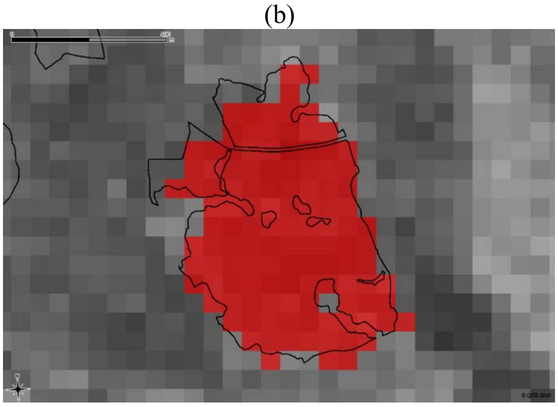
Table 2 shows that the largest agreement between detected and actual clear-cuts was obtained at 20 m pixel size. For the 31 polygons here evaluated, on average 79.4% of the reference



(a)



(b)



(c)

Figure 5. Example of a detected clear-cut using ALOS PALSAR data (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 reported in the Sveaskog GIS database. As background, the PALSAR image acquired after clear-felling has been used.

Table 2. Average value and, 10th and 90th percentile of the polygon-wise distribution of correctly detected pixels for different pixel sizes. The reference dataset consisted of 31 polygons, where clear-felling took place between ALOS PALSAR data acquisitions. The last line with the asterisk refers to the clear-cut map obtained with the algorithm developed in phase 1 [4].

Pixel size (m)	Correctly detected pixels (original / edge-eroded)	
	Average (%)	10th and 90th percentile (%)
10	62.7 / 71.5	34-87 / 38-95
20	79.4 / 90.6	56-96 / 67-100
50	72.5 / 85.9	33-98 / 52-100
50*	58.0 / 78.8	22-88 / 41-100

pixels had been detected correctly. The detection accuracy increased substantially when comparing against the edge-eroded map. In this case, on average more than 90% of the pixels were correctly detected. At 10 m and 50 m pixel size, the detection accuracy was lower; nonetheless, it improved when considering an edge-eroded version of the clear-cut mask used as reference. The 10th percentile indicates that at 10 m and 50 m, for some clear-cuts the detected area did not match with the area reported in the GIS database, whereas at 20 m there was mostly a strong agreement. The larger discrepancy at 10 m compared to 20 m is related primarily to residual speckle. The 20 m dataset was obtained with stronger multi-look factors. In addition, although multi-channel filtering was applied [11] to preserve resolution, the small number of images (two) was not effective to suppress speckle sufficiently. Table 2 also includes the results at 50 m for the multi-temporal algorithm developed in phase 1 of the K&C project [4]. The detection accuracy was slightly lower, which indicates that the idea of pursuing a more advanced algorithm for detection of clear-cuts from PALSAR data was correct.

The results indicate that the new algorithm is able to detect clear-cuts with high accuracy, matching the areal extent of a clear-cut. There is, however, an issue on spatial resolution if detailed delineation of a clear-felled area is aimed at, as shown in Fig. 5. It should be noted that a possible further explanation for the substantial improvement of the detection statistics shown in Table 2 when considering an edge-eroded version should point at the vector-to-raster transformation of the GIS polygons.

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.

C. Nation-wide clear-cut maps

The new detection algorithm was applied to the ALOS PALSAR strip data on a track-by-track basis, i.e. change was detected between two images acquired on different years along the same satellite track. For each pixel detected as change, the last PALSAR acquisition date before the detected change and the first PALSAR acquisition date after the detected change were stored as well.

Fig. 6 shows an example of detected changes in the county of Västerbotten with respect to the Swedish Forest Agency's database. The large majority of detected changes (colored in red) correspond to clear-cuts reported in the Forest Agency's database (white polygons). Some small clusters of detected changes have also been found in polygons reported as felled before the acquisition of the PALSAR data (black polygons). In this case, the date reported by the Forest Agency might be questionable. The Forest Agency's database defines as date of cutting the date on which the latter optical satellite image forming an image pair was acquired. Hence, the temporal uncertainty in the felling date affects the interpretation whether

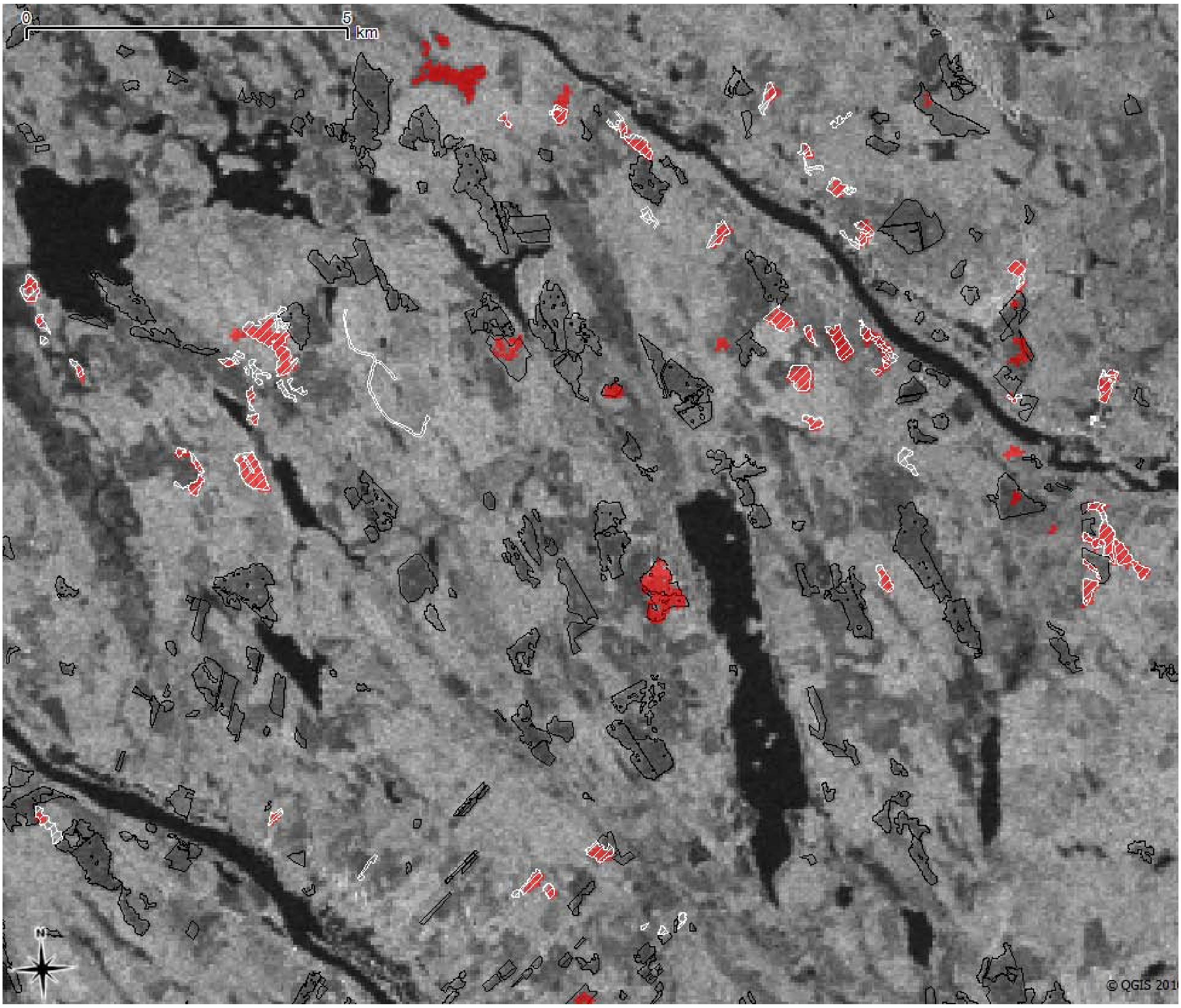


Figure 6. Clear-cuts detected in an ALOS PALSAR strip image pair (red). White polygons indicate clear-cuts reported in the Swedish Forest Agency's database for the time frame of the PALSAR image acquisitions. Black polygons indicate clear-cuts reported in the Forest Agency's database as felled before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

the PALSAR-based detections are correct or not. Finally, some clusters of pixels were labeled as change where no information was available in the Forest Agency's database. Due to the considerable clustering, the result was interpreted as a possible failed detection by the Forest Agency or a data gap (in space and/or in time) in the optical satellite dataset available at the Forest Agency.

A rigorous quantitative assessment of the agreement between the Swedish Forest Agency and the PALSAR datasets was hindered by the lack of exact information on felling date in the Forest Agency's database. For this reason, we looked at the distribution of the pixel labeled as change by the detection algorithm with respect to the felling date reported in the Forest Agency's database and defined three categories:

1) detection likely to be correct if both PALSAR and Forest Agency datasets showed a clear-cut, and the felling date was reported to have occurred after the acquisition of first PALSAR image;

2) detection likely to be erroneous if both PALSAR and Forest Agency datasets showed a clear-cut, and the felling date was prior to the date of acquisition of the first PALSAR image;

3) detection not verifiable if a pixel was detected as change but there was not corresponding information in the Forest Agency's database.

Table 3 shows the percentage of pixels labeled as change with respect to these three categories for a number of tiles located in different counties of Sweden. It is here remarked that these percentages express the likeliness of the agreement since no detailed information on cutting date were available.

Table 3. Likeliness of agreement between pixels detected as change from ALOS PALSAR images and Swedish Forest Agency's clear-cut polygons for tiles from six counties in Sweden. Each tile corresponds to a 50×50 km^2 large area.

Tile ID	County	Likeliness of detection		
		Not verifiable (%)	Errone-ous (%)	Correct (%)
130 640	Västra Götaland	11	10	79
165 715	Västerbotten	12	12	76
150 690	Gävleborg	18	9	73
165 735	Norrbotten	20	8	72
160 670	Uppsala	17	14	69
135 680	Dalarna	31	15	54

The likeliness of correct detection was generally high, with percentages of 70% or above in most cases. In case of lower agreement, the percentage of unverifiable results increased conversely. The percentage of pixels likely to be erroneous was within 8-15%. This could be considered as an approximate indication on the detection error. The percentage of pixels for which the verification could not be carried out was not the same all over Sweden. In some areas, the amount of detected pixels for which no corresponding information were available in the Forest Agency's database was considerable (e.g., central part of the Dalarna county in Table 3). Considering that the likeliness of error is in the same order among counties in Sweden, it is believed that the large percentage of pixels labeled as unverifiable is due to missing information in the Forest Agency's database. Further investigations are needed to verify this.

The assessment of the 2008-2009 nation-wide ALOS PALSAR clear-cut map consisted of a comparison of county-wise statistics of clear-cuts between 2008 and 2009 from the Swedish Forest Agency and the Swedish National Forest Inventory. These statistics were in turn compared to statistics of notified areas of final fellings reported by the Forest Agency [10] (Table 4). The PALSAR-based estimates are larger than those reported by the Forest Agency and the National Forest Inventory, but below the level reported on notified felling by the Forest Agency. Furthermore, the figures of clear-felled areas differ a lot at county level when compared across the different datasets. One explanation of the large discrepancy might be that the detected clear-cuts are registered within different time frames, even though the detection, in all cases, has been carried out during a time period of one year.

For the majority of the counties presented in Table 4, a substantially larger clear-felled area is detected by PALSAR compared to the Forest Agency. For eight of the counties, larger areas of clear-cuts are also estimated by the National Forest Inventory compared to the Forest Agency. It should be noted that the statistics from the National Forest Inventory are here based on a total of about 10,000 field plots, where only about 50 of these were registered as harvested at the time of field inventory. As an example there were no field plots registered as harvested in the counties of Stockholm and Halland. Thus, the estimated area of clear-cuts for those two counties is zero, even if clear-felling has taken place.

Table 4. County-wise statistics of clear-felled areas between 2008 and 2009 from the Swedish Forest Agency, Swedish National Forest Inventory, ALOS PALSAR strip data and notified areas of final fellings > 0.5 ha as reported by the Forest Agency [10], for all counties in Sweden except the counties of Östergötland, Kronoberg, Kalmar, Gotland, Blekinge and Skåne, where no statistics were available from the Forest Agency at the time of writing.

County	Swedish Forest Agency (ha)	Swedish National Forest Inventory (ha)	ALOS PALSAR (ha)	Notified areas of final fellings (ha)
Stockholm	1,568	0	2,209	1,488
Uppsala	2,997	10,688	5,383	5,520
Södermanland	811	4,288	1,427	2,930
Jönköping	1,693	5,125	3,708	9,623
Halland	690	0	891	3,518
Västra Götaland	6,430	13,041	6,400	17,306
Värmland	5,218	6,750	7,750	15,295
Örebro	2,880	1,838	5,235	7,868
Västmanland	3,205	876	2,585	4,173
Dalarna	12,107	5,836	17,503	18,313
Gävleborg	14,804	3,531	15,282	17,356
Västernorrland	5,647	14,136	15,536	20,412
Jämtland	24,412	19,665	19,077	20,435
Västerbotten	23,046	38,305	26,649	20,394
Norrbotten	15,424	16,509	25,355	15,804
Total	120,931	140,590	154,990	180,435

The statistics of notified areas of final fellings (> 0.5 ha) in Table 4 should be interpreted as a reference of the maximum area that is allowed to be clear-felled. However, in six of the investigated counties, at least one of the other datasets of clear-cut statistics report an area exceeding the notified area of final felling. A more detailed analysis is recommended to find out more about the underlying error sources.

Total figures of detected clear-cuts were also compared against official statistics provided by the Swedish National Forest Inventory at national level. Table 5 shows yearly figures of total area detected as clear-felled with ALOS PALSAR strip data and the total forest land area subject to final felling according to estimates from the National Forest Inventory [10]. The agreement for 2008-2009 is remarkable. At the time of writing, the statistics from the National Forest Inventory for the period 2009-2010 were not available so that no further conclusion on the reliability of the PALSAR-based estimate can be drawn. However, the decrease of total area detected as clear-cut is consistent with the slight decreasing trend of total felled area reported by the Forest Agency for the last 15 years [10].

Table 5. Total area detected as clear-felled per growing season from ALOS PALSAR and the Swedish National Forest Inventory. The figure within parenthesis refers to the clear-felled area reported in [10].

Time period	ALOS PALSAR (ha)	Swedish National Forest Inventory (ha)
2008-2009	168,279	168,645* (170,000)
2009-2010	156,910	Not available

* In the counties of Stockholm, Halland and Skåne, no field plots were registered as harvested at the time of field inventory.

IV. Conclusions and Recommendations

In the second phase of the K&C project a new clear-cut detection algorithm was developed and evaluated, and clear-cut maps were produced based on ALOS PALSAR strip data covering the entire Sweden over three subsequent years, i.e. 2008, 2009 and 2010.

The new detection algorithm proved to perform better compared to the approach developed during phase 1, confirming the necessity of an advanced method for change detection if high accuracy is aimed at. With respect to spatial resolution, the best detection result was achieved at 20 m pixel size (path data), where on average 79.4% of the pixels of 31 clear-cuts used as reference were correctly detected. The majority of misclassified pixels were located along the clear-cut edges, indicating that most of the errors were due to layover, shadowing or image co-registration errors. This is confirmed when comparing an edge-eroded version of the reference clear-cut map. The detection accuracy improved and over 90% of the pixels were then correctly detected. In the case of strip data (pixel size of 50 m) the corresponding figures were 72.5% and 85.9% without and with one edge-eroded pixel, respectively. Furthermore, 67 stands clear-felled before the acquisition of the PALSAR data were used as reference for false detections. The error rate for these stands was 0%. PALSAR strip data with 50 m pixel size are, therefore, judged to be sufficient in order to detect clear-cuts and to provide a rough delineation of the clear-cut extensions. However, a resolution of 10-20 m such as for PALSAR path data is recommended if higher precision is required.

The independence of cloud cover and day/night cycle capability allows ALOS PALSAR to obtain repeated full image coverage within one growing season. Complete image coverage of Sweden was achieved for the growing seasons 2008 and 2009, whereas a small gap remained for the 2010 mosaic. To avoid gaps in the mosaics, it is recommended that acquisition of PALSAR data should be guaranteed over more than two cycles.

The developed detection algorithm using PALSAR FBD HV-polarized backscatter data proved to be very robust and computationally fast in terms of performance. In order to produce a clear-cut map over Sweden, it took about 90 minutes to run the algorithm on a standard computer using PALSAR strip data with 50 m pixel size.

The areas detected as clear-cut are in good agreement with other information sources (i.e., Swedish Forest Agency and Swedish National Forest Inventory). The likeliness of correct detection was generally high, with percentages of 70% or above at several locations in Sweden. In case of lower agreement, the percentage of unverifiable results increased conversely. The percentage of pixels likely to be erroneous was within 8-15%. At national level, the total area detected as clear-cut for 2008-2009 was exceptionally close to the estimate provided by the Swedish National Forest Inventory (168,279 ha vs. 168,645 ha). Discrepancies were, however, observed at county level, depending on information source.

Combining the issues of spatial resolution and the benefits of complete spatial coverage at national level, the use of high resolution and large swath acquisition techniques (http://www.eorc.jaxa.jp/ALOS/en/kyoto/jun2010_kc14/presen/3-11_KC14_ALOS-2_Workshop_KC-pres_March2010.pdf) as proposed for the forthcoming ALOS-2 mission is one possible future direction of research activities for nation-wide mapping. However, as a direct continuation of the research carried out in the second phase of the K&C project, further evaluation is needed of the proposed clear-cut detection methodology and related results. Once data are available from the Swedish Forest Agency and the Swedish National Forest Inventory for 2010, it is of high interest to perform an accuracy assessment of clear-cut detection between 2009 and 2010. In addition, the time frame 2008-2010 should be investigated as the results based on data from a longer time period (using about twice as much data) will be of higher confidence.

The research carried out in the second phase of the K&C project has clearly demonstrated the possibilities to produce yearly clear-cut maps for entire Sweden using ALOS PALSAR strip data acquired during the summer/fall of 2008, 2009 and 2010 with promising results for future potential operational use.

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