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Deforestation monitoring in the Amazon River estuary by multi-temporal Envisat ScanSAR data

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Abstract. In this study, we have capitalized on the all-weather, all-day operational capability of spaceborne synthetic aperture radar (SAR) systems and used multi-temporal (from 2002 to 2006), multi-track (track 174, 360 and 447) Envisat ScanSAR amplitude images for deforestation mapping and change detection in the Amazon River estuary. A synergistic approach to deforestation mapping was adopted using SAR backscattering anomalies, the neighbouring forest constraint and DEM-derived slopes based on the three following characteristics: (1) backscattering is reduced in regions suspected to have undergone deforestation; (2) open regions without neighbouring forests were identified for removal; and (3) false-alarms linked to water bodies are mitigated using the shape threshold of flat-slope objects. Our results show that deforestation in the Amazon River estuary continues to be a serious problem, particularly along the rivers, streams or roads, which are more susceptible to anthropogenic activities than other areas. Up to 2006, the deforested portion accounts for 4.6 per cent (3,096,000 pixels) of the entire study site of approximately 458,000 square kilometers (67,320,000 pixels). However, this figure, validated by Landsat ETM images, may have over-estimated deforestation to some extent. Nevertheless, multi-temporal analysis using SAR systems, as done in this study, have a clear potential for surveillance of deforestation in the Amazon, particularly in light of the frequent cloud cover typical of the area and the limitations of deforestation monitoring by means of optical satellite imagery.

1. Introduction

The Amazon rainforest is a moist broadleaf forest that covers most of the Amazon Basin of South America. Amazon is the largest remaining tract of rainforest in the world, being more extensive than the other two main rainforests of the world in the Congo Basin of Africa and the rainforests of Indonesia and Malaysia in Southeast Asia. Deforestation in Amazon is a significant contributor to global green house gas (GHG) emissions and biodiversity loss. Quantitative monitoring of deforestation in the Amazon for evaluation and decision-making is crucially needed. Conservation of rainforests, including the Amazon rainforest, has attracted widespread attention in society. Several projects have been launched and implemented. Forestwatchers [1] launched a citizen-based conservation initiative based on volunteer computing with free or donated catalogues of high-resolution satellite imagery to monitor selected patches of rainforests around the globe. Brazil's National Space Research Institute (INPE) [2] has launched the DETER initiative with the aim of near-real-time deforestation tracking of the Amazon rainforest.

Most existing monitoring systems, including DETER, are based on optical data acquisition which can be severely limited by intense cloud cover that is frequent in areas covered by rainforests. Compared with optical remote sensing, synthetic aperture radar (SAR) is capable of observing scenarios independent of sunlight and under most weather conditions, providing the potential for a more effective deforestation monitoring in the Amazon rainforest. In this study Envisat ScanSAR data from the European Space Agency (ESA) were used for deforestation mapping and change detection in the Amazon River estuary, providing a demonstration of enhanced effectiveness in comparison to the use of optical data. A trade-off between spatial coverage and satellite image resolution capacity was made; multi-temporal observations for the 2002 to 2006 time frame were made using amplitude Envisat ScanSAR data of tracks 174, 360 and 447.

2. Study area and data

2.1 Amazon rainforest

Amazon, the world largest rainforest extending over 5,500,000 square kilometers, covers most of the Amazon Basin of South America. This region includes territory belonging to nine nations; 60 per cent of the rainforest is within Brazil, followed by Peru with 13 per cent and Colombia with 10 per cent; the remaining 17 per cent are part of Venezuela, Ecuador, Bolivia, Guyana, Suriname and French Guyana [3]. The Amazon comprises the largest and most biodiverse tract of tropical rainforest in the world. One in ten known species of the planet has been recorded there, including 2.5 million insect species, tens of thousands of plants and 2,000 birds and mammal species [4].

Conservation and sustainable development of the Amazon rainforest are facing challenges, particularly from the negative impacts of deforestation. More than 20per cent of the rainforest has been irreversibly destroyed. Land is being cleared for cattle ranching, mining, logging and subsistence agriculture, or being burned to make charcoal to power industrial plants [5]. The estuary of the Amazon River is a representative area for the evaluation of anthropogenic activities, because there are several cities or towns along the river, such as Macapa, Santana and Santarem, connected by national-provincial roads or river channels. The study area covered by the multi-track, multi-temporal Envisat ScanSAR data is shown as a red rectangle in figure 1 and extends over 458,000 square kilometers.

Figure 1. Location of the study area (red rectangle) in the Amazon River estuary region, shown on a composite MODIS image of South America (Source: NASA).

2.2 Envisat ScanSAR and SRTM DEM data
Given the large study area, Envisat ScanSAR data were used for deforestation monitoring and change detection. A total of 15 multi-temporal scenes were acquired by the European Space Agency in Envisat ScanSAR imaging mode during the 2002 to 2006 time frame, over multiple tracks (174, 360 and 447). The C-band ScanSAR data with HH polarization and ascending orbit characteristics cover a 405 km wide swath. Data acquisition details are summarized in table 1.

Table 1. Multi-temporal, multi-track Envisat ScanSAR data used in this study.

Acquisition (yyyymmdd)	Track
20021222	174
20030302	174
20030406	174
20031011	360
20041017	174
20041030	360
20050724	174
20050806	360
20051119	360
20060115	174
20060901	447
20060917	174

For the slope analysis of regional topographic terrain, eight tiles of 3 arc-second (~90 m resolution) Shuttle Radar Topography Mission (SRTM) DEM data were downloaded from the United States Geological Survey (USGS) web site and then mosaicked into a single DEM. The spatial coverage of SRTM DEM data was chosen to be larger larger than the SAR data in order to accommodate the SAR coverage. The void values in SRTM DEM data have been replaced by zero values in the ocean area or interpolated by surrounding valid height-values in other terrains.

3. Methodology and data processing

3.1 Principle of deforestation mapping using SAR data
Generally, forest land cover in the Amazon region showed moderate radar backscatter on C-band Envisat ScanSAR data, mainly influenced by multiple scattering mechanisms of the vegetation cover; a deforested region is characterized by low amount of backscatter and specular reflection. Hence it appears dark on the image. This is the principle for the deforestation detection in this study. Deforestation in the Amazon rainforest is dominated by human activities, e.g., logging and agricultural expansion. Consequently, the occurrence of regular topology within a forest neighborhood can be another important indicator of deforestation. Nevertheless, our results indicated that false alarms were commonly induced by water bodies, as these also tend to appear dark on the radar images; their radar signature is characterized by wind- and wavelet-induced Bragg scattering, as well as specular reflection. Given the frequent occurrences of water bodies and slope aspects (either in E-W or N-S direction), a three-step deforestation mapping solution was adopted taking advantage of the phenomena of the backscattering anomaly and topological forest-neighborhood characteristic referred to above, as well as the SRTM DEM-derived slopes. Accordingly, suspected deforested regions were

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detected based on the reduction of backscatter; detected regions without forest neighborhood were discarded; and false alarms were further mitigated using the shape threshold of object-oriented slope aspects for the removal of water bodies.

3.2 Data processing

The processing of Envisat ScanSAR data for deforestation mapping and change detection was carried out according to the procedure illustrated in figure 2, as follows:

- *Geocoding*. In order to extend the spatial coverage of the observed scenario as well as for the purpose of change detection, the 15 scenes of multi-track, multi-temporal ScanSAR data (table 1) were geocoded using the SRTM DEM data in the latitude and longitude coordinates system. The simulated SAR image of each acquisition was first generated using the SAR imaging mechanism and the terrain in DEM by means of geometric and backscattering simulation [6]; then each pair of simulated and real SAR images were co-registered using the correlation-maximum approach [7]. Projection functions between SAR and SRTM DEM data were calculated for the SAR data geocoding. Visual inspection demonstrated a high accuracy within one to three to pixels. Speckle noise in the SAR images was reduced by applying an Enhanced Lee filter [8].
- *Generation of mask for water bodies*. In this procedure, two slope maps in E-W and N-S direction were derived using the SRTM DEM data. Initial flat-slope pixel objects were then generated using a threshold of 3-degrees. For the purpose of masking out water bodies, an object-oriented approach was applied by analyzing the shape parameter of flat-slopes identified previously. Unlike regions impacted by anthropogenic deforestation activities, the shape of natural water bodies tends to be more irregular and heterogeneous. A smoothness heterogeneity t_m, which is the ratio of the flat-slope border length l and the border length b given by the bounding box of the slope extracted [9], was applied for generating the mask (equation 1):

$$t_m = \frac{l}{b} \quad (1)$$

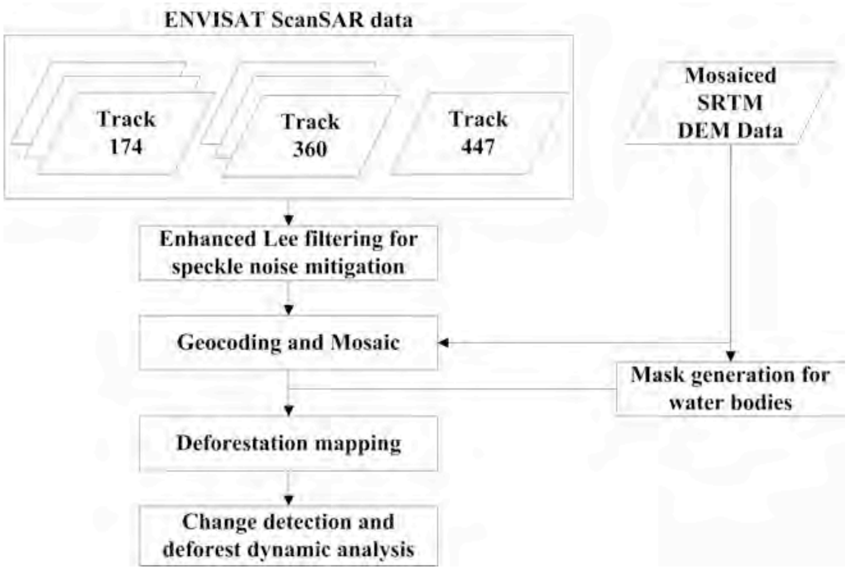

Figure 2. Flow diagram outlining the step-wise procedure for processing multi-temporal, multi-track ENVISAT ScanSAR data for deforestation mapping and change detection.

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- *Deforestation mapping*. Using the backscatter threshold, regions with dark tones were firstly detected as suspected areas in each acquisition of ScanSAR images (small patches with irregular shapes were removed manually). Then, regions without neighbouring forests (dominated by non-forest regions, e.g., natural grass land) were identified for removal by visual inspection. Finally, false alarms linked to water bodies were further discarded using the smooth heterogeneity $t_m > 2.5$ (the derived optimal value after several treatments of the data). In order to extend the spatial coverage, the multi-temporal, multi-track SAR images were mosaicked together. The most recent SAR data acquisition for each track and frame was used in the mosaic procedure. Deforestation mapping for the purpose of generating geographic information system (GIS) compatible layers was carried out manually.
- *Change detection*. For multi-temporal ScanSAR data with uniform tracks, the dynamic evolution of deforestation could be evaluated by the comparison of the data layers, particularly for track 174 which included seven different acquisition dates from 2002 to 2006. In such a way, the deforestation rates during the four-year time interval were quantitatively estimated.

4. Results and validation

4.1 Results

Using our deforestation mapping method and data procedures in Section 3, a deforestation map based on the ScanSAR data mosaic was derived (figure 3a). This map reflects the deforestation status up to 2006 considering the most recent acquisition applied in the mosaic procedure. Three indicators, including the backscattering anomalies on amplitude SAR images, the neighbouring forest constraint

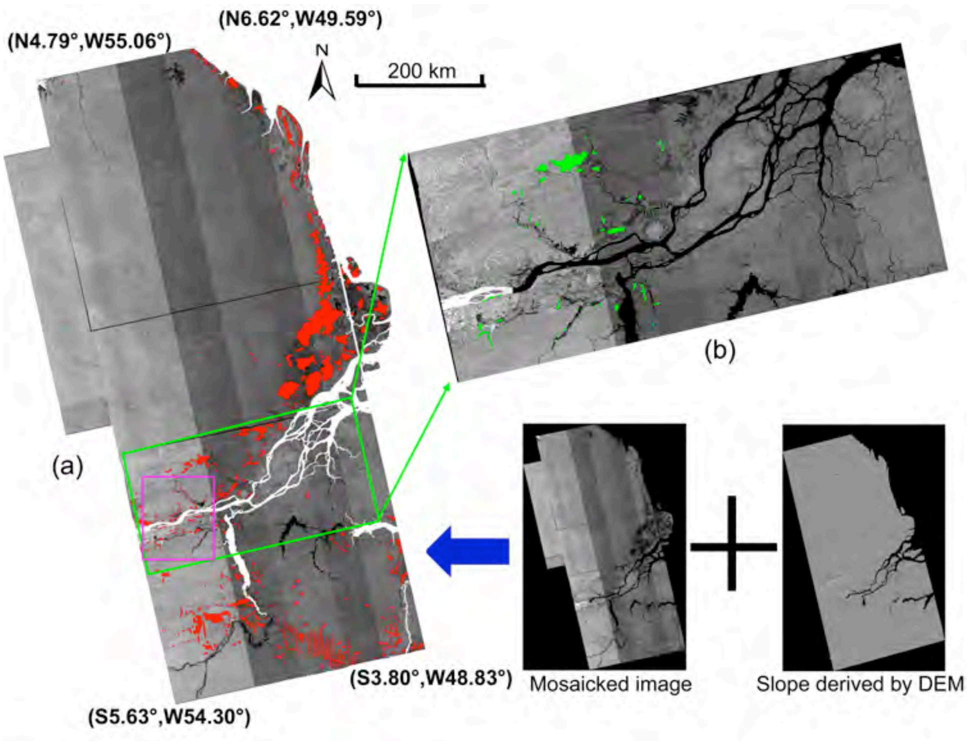

Figure 3. (a) Deforestation map (up to the year 2006) derived by multi-temporal, multi-track Envisat ScanSAR and slope data; (b) the dynamics of deforestation in a subset of the study area (highlighted by the green rectangle in) through the comparison of track 174 SAR images acquired in 2002 and 2006. (Source of SAR imagery: ESA)

and the regular shape of SRTM DEM calculated slope aspects, were jointly used for the deforestation mapping. Experimental results demonstrated that deforestation in the region of Amazon River estuary is a serious problem, particularly along rivers, streams or roads, which are more susceptible to anthropogenic activities than other locations. Quantitative analysis revealed that 4.6 per cent (3,096,000 pixels) of the entire study area of approximately 458,000 square kilometres (67,320,000 pixels) was impacted by deforestation up to the year of 2006. In figure 3b we illustrate the results of change detection on a subset of the image in figure 3(a), as highlighted by the green rectangle, by comparing the SAR images of track 174 acquired in 2002 and 2006. These results also point to on-going deforestation despite several counter-measures put in place by the National Government.

Rivers, streams or roads are locations that provide easy access for settlers who become dependent on the surrounding forests for timber, agricultural land and other needs. In the Amazon considerable traffic of timber and other forest goods and products occurs along rivers and streams [10, 11]. Campaigns to reduce deforestation can make a significant impact if they are targeted around these ecosystem features that serve as natural attractors of anthropogenic activities.

4.2 Validation and discussion

Landsat-derived deforestation results [12] around the city of Almeirim were used for validating the Envisat ScanSAR results, as illustrated in figure 4. Figure 4a is a deforestation map of 2008 using Landsat images and historical vegetation data dating from the 1970s. Figure 4b shows the deforestation mapping of 2006 using Envisat ScanSAR data without reference to an inventory map. A consistent spatial deforestation trend was evident in the two maps. Spatial details were naturally less clear in the Envisat ScanSAR result because of the coarser resolution of 150 meters for the SAR used in this study when compared to the 30 m resolution of Landsat TM data that was used to obtain the

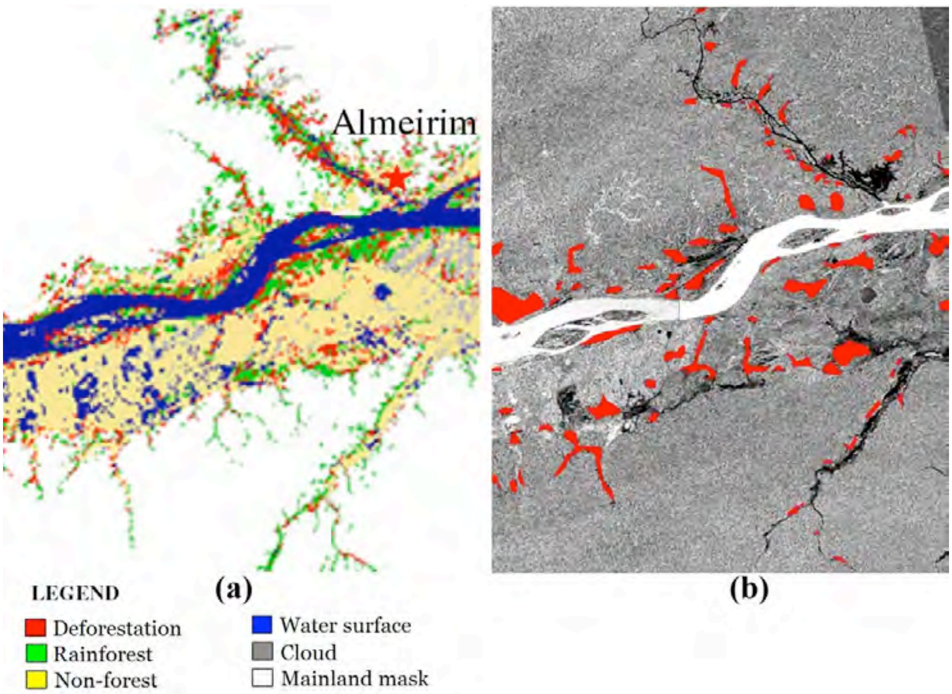

Figure 4. Comparison of deforestation results of Landsat and Envisat ScanSAR data; (a) Landsat by Reno et al.[12], (b) image subset of Envisat ScanSAR marked by the purple rectangle in Figure 3a. Over-estimation in SAR analysis results are interpreted by the lack of the temporal calibration (e.g., comparison with historical inventories), misclassified non-forest regions, as well as coarser spatial resolution of the SAR images. (Source of SAR imagery: ESA)

2008 deforestation map. It appears that ScanSAR data over-estimated deforestation due to the several reasons, as follows. Firstly, coarse spatial resolution of SAR data probably amplified some features of deforestation detected. Several non-forest regions (e.g., grasslands or areas deforested before 1970s when the historical vegetation data for the Landsat-derived 2008 deforestation map was obtained) could have been misclassified as deforestation in figure 4b) despite the application of the neighbouring forest constraint. However, deforestation change detection (figure 3b), as presented in this study, could be recommended for the dynamic analysis over time. The deforestation map (figure 3a) was derived by mosaicking the newest acquisitions of multi-temporal, multi-track SAR images; there were errors linked to the time difference between the different tracks; there is a 10-month difference between track 360 acquired on October 19, 2005 and track 174 acquired on September 17, 2006. Yet, Figure 3(a) allows for the estimation of deforestation changes between 2002 and 2006, which is about 4.6% (21,068 square kilometres) of the study area of 458,000 square kilometres. Overall Amazon deforestation rates rose dramatically in the early 2000s, peaking at 27,000 square kilometres in 2004 and then fell sharply to about 5,000 square kilometres in 2011 [13]. The estimation for the four to five year period in this study for the Amazon River estuary region alone is between 4,213 and 5,267 square kilometres. The total area of the Amazon is about 12 times the size of this study area. Deforestation in other parts of the Amazon is unlikely to have been as high as in the estuary region of the river that is exposed to much more anthropogenic impacts (e.g., soybean planting and cattle ranching) than the interior of the rainforest [14, 15].

The study area – a combination of floodplain and upland rainforest bordering the Amazon River – constitutes a rich ecosystem of significant ecological, economic and social importance [12]. In this area, deforestation impacts not only the terrestrial ecosystems, but also the aquatic system biodiversity [16-17], fishery production, water quality and the health of riparian population [18]. Deforestation monitoring by multi-temporal SAR (e.g., ESA's Sentinel-1) overcomes the acquisition limitation of optical data in tropical regions, and consequently represents an effective tool for Amazon rainforest monitoring, particularly in the evaluation of deforestation over time.

INPE's DETER system is based on optical imagery and is currently used to identify locations of potential deforestation that could be the focus for law enforcement officials on the ground. Nevertheless, as pointed out by Assunção and co-workers [13], "DETER is incapable of detecting land cover patterns in areas covered by clouds, so no deforestation is captured and no deforestation alerts are issued in these areas. Ultimately, this reduces the probability of monitoring personnel being allocated to such areas." The use of SAR imagery, as suggested in this paper, could complement and improve detection of land cover changes and targeting law enforcement on the ground in all areas, irrespective of cloud cover. It may also be worth considering pilot areas other than the present study area that have considerably higher levels of anthropogenic activity compared to the interior of the Amazon rainforest. Further studies could estimate the cost-benefit advantages of multi-temporal SAR for improved monitoring and law enforcement to prevent deforestation in the Amazon.

5. Summary

In this study, the deforestation process over the Amazon River estuary was mapped and analyzed using multi-temporal, multi-track Envisat ScanSAR data. A deforestation mapping approach was adopted that combines information from the SAR backscattering anomalies, the neighbouring forest constraint and flat DEM-derived slopes with regular shapes. The validation demonstrated that SAR-derived results produced an over-estimation when compared with Landsat data. This may be due to the combination of misclassified non-forest regions as well as the coarser spatial resolution of Envisat ScanSAR data. Nevertheless, the use of satellite SAR systems could overcome constraints introduced by intense and regular cloud cover in the Amazon and enable continuous and near-real time deforestation monitoring to guide law enforcement on the ground. Future studies will be focused on the calibration of deforestation maps as well as deforestation process monitoring using high resolution SAR data.

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