K&C Science Report – Phase 2

Characterisation and Monitoring of Mangroves Using ALOS PALSAR Data

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Abstract—**As part of the Japan Aerospace Exploration Agency's (JAXA) Kyoto and Carbon (K&C) Initiative, Advanced Land Observing Satellite (ALOS) Phased Arrayed L-band Synthetic Aperture Radar (PALSAR) dual polarization (L-band HH and HV) mosaics have been generated for several regions, including insular and mainland Southeast Asia, Australia and South/Central America. This research aimed to evaluate and demonstrate the use of these mosaics for mapping, characterising and monitoring mangroves within these regions.**

Whilst the extent of mangroves could be discerned in some cases (e.g., when interfacing with estuarine areas), ALOS PALSAR data were generally limited for mapping. For this reason, existing regional (e.g., Queensland Herbarium Regional Ecosystem Mapping) or global data (e.g., those available through the World Conservation Monitoring Centre (WCMC) or USGS/NASA) were used to define the extent of mangroves. Within this defined area, three classes of mangrove (low biomass and high biomass, with and without prop root systems) could be differentiated by integrating estimates of canopy height derived from Shuttle Radar Topography Mission (SRTM) data with L-band HH data. Maps of these structural classes were generated for several regions (northern Queensland, Australia, and Belize) where sufficient validation (ground or airborne) data were available.

Throughout the tropics and subtropics, mangroves are subject to change in response to natural or anthropogenic drivers. By using existing datasets (namely the USGS/NASA global mangrove dataset) as a baseline of mangrove extent, changes in mangroves were mapped for the Atlantic coast of South America, southeast and mainland Asia, northern Australia and Belize. Significant changes in the extent of mangroves were identified in northern Queensland (Gulf of Carpentaria, French Guiana and Sumatra), with these attributed to increased accretion or erosion of sediments and sea level fluctuation. Hotspots of mangrove loss were identified in southeast Asia, including the northern Tawa Islands and northeast Borneo, with these primarily associated with human disturbance. The study highlights the benefits of using ALOS PALSAR for detecting change, particularly given the prevalence of cloud-cover in many coastal regions and concludes by conveying the utility of and requirements for the inclusion of these data within a global mangrove mapping and monitoring system.

***Index Terms*—ALOS PALSAR, K&C Initiative, Wetlands Theme, mangroves, Asia, Australia, South and Central America.**

I. Introduction

A. Approaches to discriminating and mapping growth stage

For many regions, the classification of mangroves has focused largely on the use of optical remote sensing data and especially that acquired by Landsat, SPOT and ASTER sensors. A particular advantage of using these data is that mangroves are relatively distinct from non-mangrove areas, although confusion with adjoining closed forests often leads to errors in the mapping of mangrove extent. The use of Synthetic Aperture Radar (SAR) for characterising and mapping mangroves has been comparatively limited, with most focusing on data collected by sensors operating at C-band (~ 2.6 cm wavelength). As C microwaves interact largely with the upper surface of canopies, information on the structure and biomass of the woody components has not been discerned, although some success has been obtained using combinations of SAR and optical data (e.g., [1]).

The launch of the Japanese Space Exploration Agency's (JAXA) Advanced Land Observing Satellite (ALOS) Phased Arrayed L-band SAR (PALSAR) in 2006 provided new opportunities for characterising, mapping and monitoring mangroves at regional to global levels. From the Fine Beam Dual (FBD; HH and HV polarisation) data, regional mosaics have been generated as part of the JAXA Kyoto and Carbon (K&C) initiative, including for Southeast Asia, Australia and the Atlantic coast of South America. A particular advantage of using these L-band data is that microwaves (~ 25 cm wavelength) penetrate the canopy and interact with the woody components, thereby allowing retrieval of structural attributes and above ground biomass (AGB) and better detection of inundation. Comparison of data acquired by the ALOS PALSAR with archival optical or SAR data as well as existing mapping can also be used to quantify changes in mangroves which arise from both natural events (e.g., cyclones or tsunamis) or processes (e.g., sea level rise) and human disturbance (e.g., for logging or agriculture and mariculture). A particular advantage of the SAR is that they provide regular observations regardless of illumination conditions and cloud cover, which is often frequent in tropical coastal regions.

Using mosaics generated by JAXA and also the Institute of Geography and Earth Sciences (IGES), Aberystwth University, the use of ALOS PALSAR for characterizing, mapping and monitoring mangroves was investigated. The research was undertaken as part of the JAXA Kyoto and

Carbon (K&C) initiative and sought to provide better information on the state of mangroves to assist in their conservation. More specifically, the research aimed:

a) To establish the utility of ALOS PALSAR data, either singularly or in combination with other remote sensing data, for consistent regional characterisation of mangroves.

b) To investigate the use of time-series datasets for detecting changes in mangroves and to establish causative factors.

As illustration, examples are taken from Australia, Belize, the Atlantic coast of South America and Southeast Asia where extensive tracts of mangrove have been subject to natural and/or human-induced influences, including those associated with climate change.

II. DATA PREPROCESSING

A. *Pre-processing of strip data*

For all regions (with the exception of southeast Asia), ALOS PALSAR strip mosaic data (Level 1.0) at a reduced spatial resolution of 50 m were provided by JAXA. Using Gamma SAR processing software ([2][3]), these data were calibrated and orthorectified to standard regional coordinate systems. For all areas, orthorectification was undertaken by cross correlating a SAR image simulated from either 30 or 90 m spatial resolution SRTM data with ALOS PALSAR data and using ALOS orbital state vectors and ancillary information. For the Australian strips, the process was refined through cross-correlation with Landsat panchromatic mosaics, largely because of the lack of significant relief in many northern regions. Mosaicing of the orthorectified strips was undertaken using procedures available within ENVI and in-house software. The procedures were developed to ensure a high level of geometric accuracy (geocoding errors were typically less than one pixel, particularly in northern Australia where the panchromatic data were used in the orthorectification process). The cross track correction and mosaicing procedures resulted in the generation of relatively seamless regional mosaics for these study regions. For Australia, image strips acquired during periods of relatively low ground moisture were used to generate a data mosaic for 2007. For mainland (Indochina) and insular (Borneo, Sumatra, Sulawesi, Tawa Islands, the Philippines and New Guinea) Southeast Asia, ALOS PALSAR mosaics generated by JAXA were used.

III. APPROACHES TO MAPPING MANGROVES

When mapping the extent of mangroves, the nature of the land cover adjoining the mangroves presented different challenges, with the difficulty of separation being greatest where these were bordered by dense forest (Figure 1). However, where mangroves were bordered by expanses of mudflats or low vegetation (e.g., samphire flats), better delineation of the mangrove area was achieved although this was inconsistent within and between regions.

Two approaches to defining the extent of mangroves were considered. In the first, existing datasets were integrated to locate areas associated with mangrove. These included the Belize Ecosystem Mapping and the Regional Ecosystem Mapping of Queensland ([4]). For Southeast Asia and the Atlantic coast of South America, WCMC global mangrove datasets were considered initially for defining the extent of the mangroves. However, as these were generated over various time-frames and using different source data, the accuracy of mapping was inconsistent across these regions. For this reason, the more recent USGS/NASA global mangrove dataset ([5]) was substituted. In all cases, a high level of registration accuracy between the JAXA PALSAR mosaics and the USGS/NASA datasets was evident.

Figure 1. ALOS PALSAR image (L-band HH, HV and the ratio of HH and HV in RGB) of the Jardine River National Park, Cape York, Queensland, Australia. Discrimination of coastal mangroves (darker green) and proximal forest and other vegetation covers is difficult because of similarities in L-band backscatter).

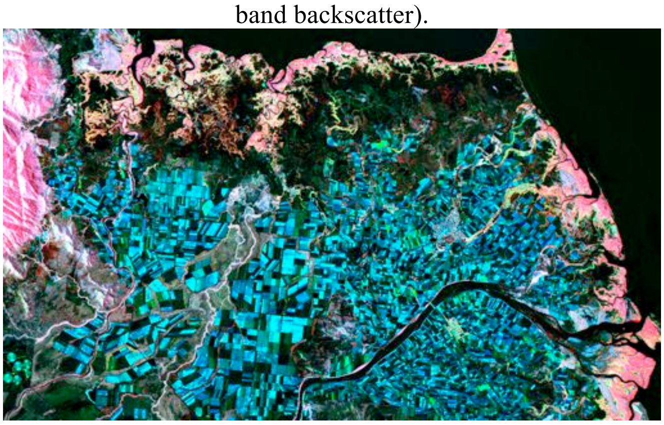


Figure 2. ALOS PALSAR image (Landsat FPC, L-band HH and HV in RGB of mangroves and sugar cane fields in northern Queensland.

A second approach was to include data or derived products from optical remote sensing data. In Queensland, Australia, Landsat-derived Foliage Projected Cover (FPC) data ([6]) were used to guide or confirm the mapping of mangrove extent, as mangroves typically exhibited a higher FPC compared to other vegetation types, including rainforest. This is highlighted in Figure 2, wherein mangroves are distinct from other vegetation and surface types in the composites of Landsat FPC and ALOS PALSAR L-band HH and HV (in RGB). In Belize, 10 m spatial resolution SPOT-5 High Resolution Geometric (HRG) imagery were integrated to assist the mapping of mangrove extent. For other areas (e.g., French Guiana), and depending upon the age of the existing baseline datasets, other optical and also Japanese Earth Resources Satellite (JERS-1) SAR data were used to refine maps of the historical distribution of mangroves. However, these were superseded by the USGS/NASA dataset, which was considered to provide a more consistent and reliable baseline.

IV. CHARACTERISATION OF MANGROVES

Within the mapped area of mangroves, three classes relating to structure (height) and relative biomass were discriminated and mapped using a rule-based approach developed within eCognition, with this based on ALOS PALSAR strip mosaic and Shuttle Radar Topographic Mission (SRTM) data.

[5] demonstrated the potential of using SRTM data for retrieving the height of mangrove canopies. Using SRTM data, calibrated with both field and ICESat data, the crown weighted mean height of the canopy surface (HCWM) for mangroves was related to the SRTM height, with the margin of error being +/- 1.9 m. As mangroves occur at sea level, the requirement for a digital terrain model (DTM) was largely avoided. The reliability of mangrove canopy height retrieval is, however, optimal where mangroves are expansive and contiguous in cover over an area exceeding the spatial resolution of the digital surface model (DSM). To evaluate the use of the SRTM for retrieving mangrove height, DSMs determined from Intermap X-band SAR and SRTM C-band SAR acquired over mangroves in Belize were compared. Retrieval using the SRTM was more reliable where mangroves were greater than ~10 m in height and the SRTM pixel area was entirely occupied by the mangrove canopy. Where the height was < ~10 m and the pixel area was only partially occupied by mangroves, height retrieval was less successful. This was attributed in part to the lower stature and non-contiguous nature of mangroves (e.g., on the landward and seaward margins of more expansive stands). On this basis, the SRTM was considered appropriate for approximating the height of mangroves, with 30 m spatial resolution data available for Australia and 90 m for all other regions, although adjustments for variations in mean sea level are needed. However, a limitation is that the SRTM data were acquired in 2000 and hence significant changes may have occurred in the subsequent period. For this reason, the use of DSMs generated from more recent sensors (e.g., Tandem-X) is advocated, particularly as these will be provided at finer spatial resolutions.

The ALOS PALSAR data were used largely to identify communities dominated by species with an extensive prop root system, including *Rhizophora stylosa* and *Ceriops tagal*. Previous studies utilising NASA airborne SAR (AIRSAR) acquired over Kakadu National Park in Australia's Northern Territory ([8]) and the Daintree National Park in Queensland ([9]) established that high biomass mangroves dominated by *R. stylosa* exhibited an L-band HH and to a lesser extent HV backscatter which was similar in magnitude to that observed for non-forest. Such observations were supported by field visits to both Belize (in 2010) and northern Australia (2009). Furthermore, with increases in AGB, L-band backscatter HH and HV backscatter declined after ~ 100-120 Mg ha^{-1}. By comparison, mangroves species lacking a root system (e.g., *Avicennia, Sonneratia* and *Laguncularia*) tended to support an L-band HH and HV backscatter equivalent to non-mangrove forests of similar AGB, with no decline recorded with further increases in AGB.

On the basis of these observations, the following classification of ALOS PALSAR and SRTM data was developed and implemented within eCognition. First, a segmentation of the SAR data was undertaken whereby objects (one or several pixels in size) were generated within the pre-defined area of mangrove. A rule-based classification was then applied to map three forest structural types, with these being:

a) Low mangroves (HCWM < 10 m)

b) High mangroves with prop root systems (HCWM ≥ 10 m; L-band HH gamma0 (γ^o) below a specified threshold, with this determined as the lowest value for contiguous mangroves with a HCWM approximating 10 m).

c) High mangroves with prop root systems (all remaining mangroves > 10 m with L-band HH above the threshold defined for b).

The 10 m threshold of the HCWM was used as, in Belize, the correspondence between airborne-derived DEMs and the SRTM was greatest above this threshold. Furthermore, the reduction in L-band HH backscatter was observed to occur at approximately this height level in Kakadu NP, northern Australia, which corresponded to an AGB of ~ 100-120 Mg ha^{-1}. An example of the classification for Belize is given in the previous Phase 1 report to JAXA.

A refinement to the segmentation was investigated for Queensland, where mangroves with a mean and standard deviation of Landsat-derived FPC above specified thresholds were mapped initially with these assumed to support a closed canopy and the same rules outlined above were applied. Below this threshold, mangroves were assumed to be of limited spatial extent and/or fragmented and a separate class was defined, particularly as the height estimates were then considered to be less reliable. An FPC threshold of < 11 % was used to separate mangroves from non- or sparsely vegetated areas. The classification scheme was supported by field and airborne (including SAR) observations at sites in Australia (e.g., Kakadu and Daintree National Parks) and Central/South America (e.g., Belize) and with reference to published studies (e.g., [6][8][9]).

For Queensland, statewide mosaics of Landsat-derived FPC were available and can provide an additional layer to describe the structure of mangroves. The Landsat FPC relates indirectly to canopy cover and estimates are generated for the state of Queensland on an annual basis ([4]). Within these mosaics, the FPC for mangroves can vary from 11 % (equivalent to ~20 % canopy cover and hence defined as forests; [10]) to 100 %, with the majority supporting an FPC towards this higher end. When combined with information on mangrove height from the SRTM, classes can be defined on the basis of height and cover. As Landsat FPC data are only produced for Queensland and New South Wales, this approach to mapping was not applicable to other regions and hence is not reported further in this paper.

V. Detection of Change

For the detection of change, differences between the existing baseline datasets of mangrove extent and the ALOS PALSAR data mosaics were highlighted. A loss of mangroves by 2007 (when the first PALSAR observations occurred) was associated either with a low or elevated L-band HH backscatter compared to proximal mangroves. Higher L-band HH was associated with recently cut areas and was attributed to scattering from woody debris and cut stumps left following the clearance event. The lower L-band HH was attributed to specular scattering from cleared and comparatively smooth surfaces (including from mariculture ponds or inundated areas). Thresholds were identified through reference to known areas of change. For Southeast Asia, further change was identified by comparing L-band HH and HV backscatter obtained in 2007 with that observed in 2008 and 2009, depending upon the availability of mosaics. The expansion of mangroves in the seaward direction was identified using a sea mask generated from SRTM data and assuming that all areas with an elevated L-band HH backscatter represented colonizing mangrove systems.

For Southeast Asia, the Atlantic coast of South America and Belize, the USGS/NASA mangrove and 2000 SRTM datasets were used as reference, with the latter used specifically for detecting seaward expansion. For northern Australia, the Regional Ecosystem maps of mangrove extent provided the necessary baseline. The change detection procedures were developed within eCognition and focused primarily on the loss of mangroves from within the previously mapped extent and on seaward expansion.

A. Changes in Australian mangroves

Mangroves in Australia are extensive (1.5 million ha in 2005; [11]) particularly along the northern and eastern coastlines, and support a large diversity of species. Whilst urban expansion has resulted in the loss of mangroves in more populated areas, the majority remains relatively pristine and, as such, are useful barometers of coastal environmental change (e.g., sea level rise). For the north and east of Australia, and focusing primarily on Queensland, significant change away from the established baseline was not detected with the exception of the southern Gulf of Carpentaria. Here, seaward expansion of mangroves was observed within the ALOS PALSAR data, with this confirmed through subsequent comparison of time-series of Landsat data (Figure 4).

Comparison of MODIS images prior to and during extensive flooding in 2009 suggested that seaward expansion may be attributed to increased sedimentation on the coastal fringe as a result of increases in rainfall and storm events, particularly as the area of mangrove expansion corresponded with that influenced by the flood waters of the Flinders River. However, landward expansion was also evident, which may be attributed to inland intrusion of seawater. Whilst time-series of Landsat sensor data allows areas of change to be identified, the ALOS PALSAR data can indicate the relative structural development of the forests and also provide information over periods when cloud cover limits acquisition of optical sensor data.

a) 1987
b) 1995
c) 2001
d) 2008

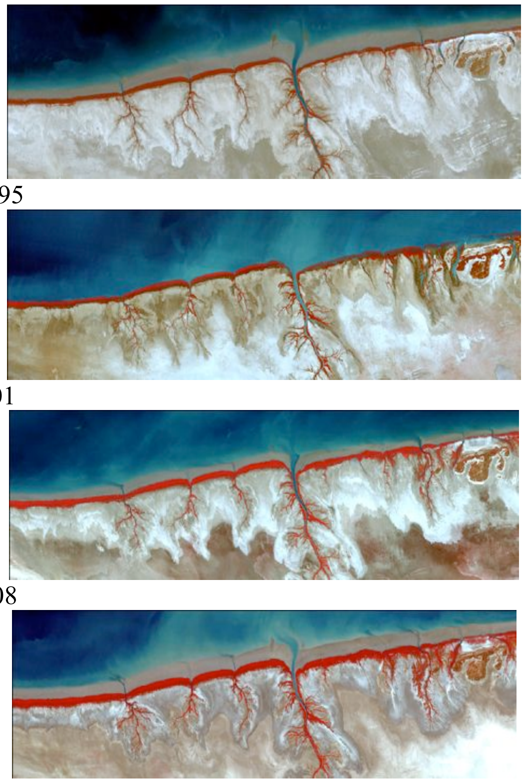


Figure 4. The expansion of mangroves in the Gulf of Carpentaria, Queensland, observed through (a-d) time-series comparison of Landsat sensor data.

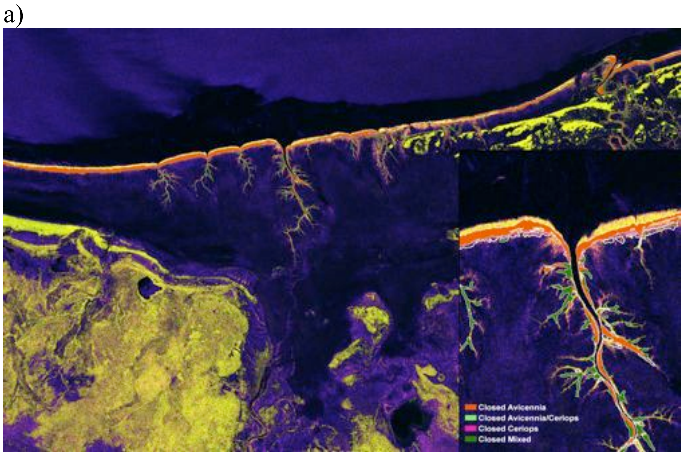
B. Changes in South American mangroves, Atlantic coast.

Along the Atlantic coast of South America, the loss and also expansion of mangroves was significant. In French Guiana (Figure 6), widespread accretion and erosion of sediments [12] resulted in alternate expansion and loss of mangroves, with this being typical of region. Similar changes were observed in the northern coastal sections of Brazil but a more consistent seaward expansion was observed in the Bragantino region [1] of northeast Brazil (Figure 7). Many areas within the Amazon River had also silted up, with a corresponding increase in the extent of vegetation although establishing whether this was associated with mangroves or riverine forests was difficult.

C. Changes in Belizean mangroves

Within Belize, the loss of mangroves has been largely associated with urban expansion. A field visit to the Belize region was undertaken to support characterization and the detection of change in mangroves, with this focusing on the Placencia lagoon area in the south of the country. Most areas cleared were for the development of tourism facilities and coastal resorts, with these being readily detectable within the fine beam dual (FBD) data but less so the 50 m resolution strip mosaic data. The study highlighted the requirement for finer spatial resolution datasets within a global mangrove monitoring system.

a)



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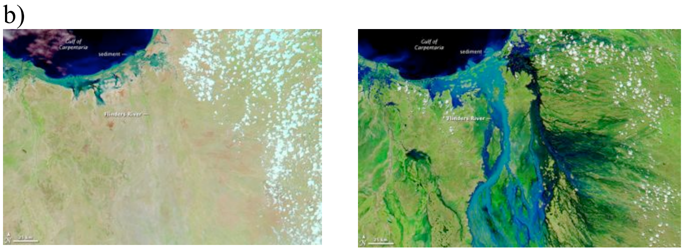


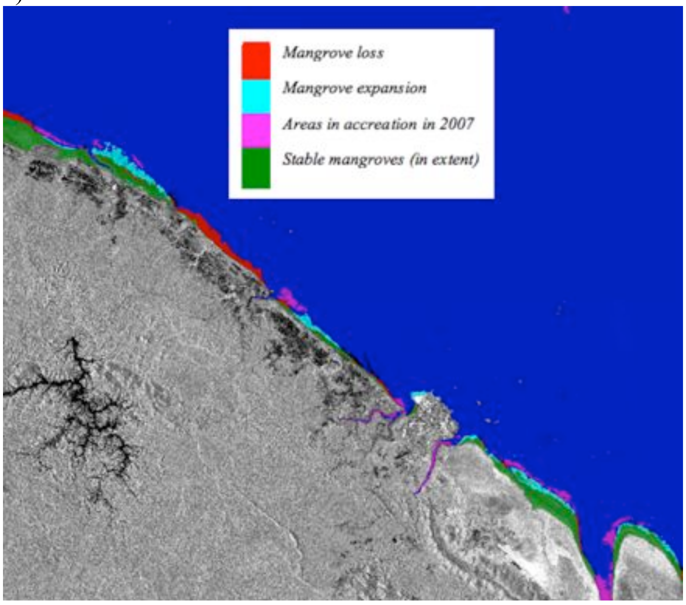
Figure 5. a) The seaward and landward expansion of mangroves in the Gulf of Carpentaria, northern Australia, as observed by comparing ALOS PALSAR data with existing regional baseline data. The changing extent of surface water under b) dry and c) flooded conditions within the Flinders River catchment, as observed by MODIS, is also highlighted.

D. Changes in Southeast Asian mangroves

The Southeast Asia region supports approximately 4.9 million ha of mangrove, with these distributed primarily in Indonesia, Malaysia and Myanmar. Whilst rates of change have generally been reported as < 1 % for many regions, this translates to significant losses for Indonesia and Malaysia in particular with most associated with land use change ([11]).

Maps of mangrove change were generated for the majority of Southeast Asia (Figure 8). Significant areas of seaward expansion were noted in south-east Sumatra, with this attributed to increased erosion as a consequence of increases in deforestation in the region.In several areas, including north-

a)



b) c)

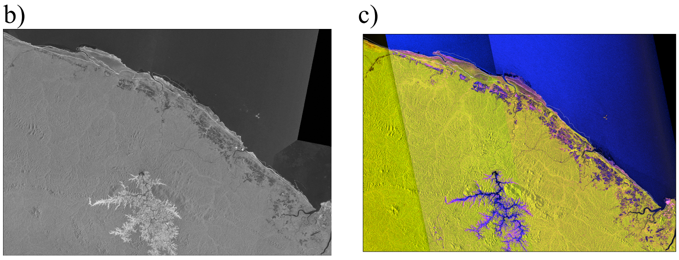


Figure 6). a) JERS-1 SAR and b) ALOS PALSAR data of French Guiana acquired in the mid 1990s and 2007 respectively. c) The extent of change mapped over the same period.

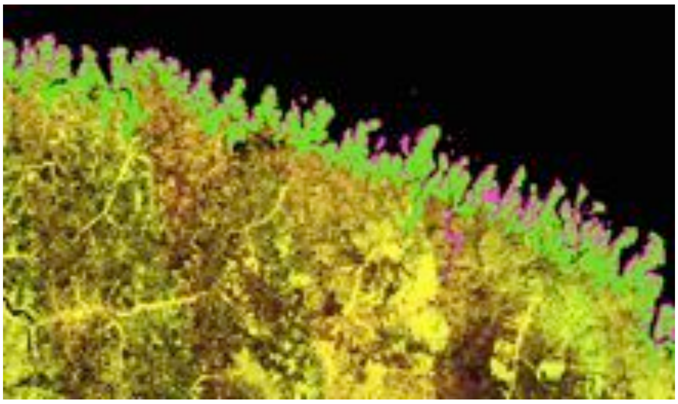


Figure 7. Expansion (magenta) and losses (blue) of a) coastal/estuarine mangroves and riverine forest along the Atlantic coast of South America and b) the Bragantina zone of northeast Brazil. Areas of no change are highlighted in green.

east Borneo (Figure 9) and the north of the Tawa Islands, hotspots of change were identified. A limitation of the approach was that variations in inundation conditions often led to a decrease or increase in L-band backscatter, and gave a false alarm in terms of mangrove loss. However, many areas of significant change had often previously experienced extensive deforestation and fragmentation of the mangrove systems and were therefore more vulnerable to further deforestation and degradation. Few areas that were previously regarded as intact were subject to new deforestation and, within some regions (e.g., Irian Jaya), extensive areas of mangrove remained intact (Figure 10).

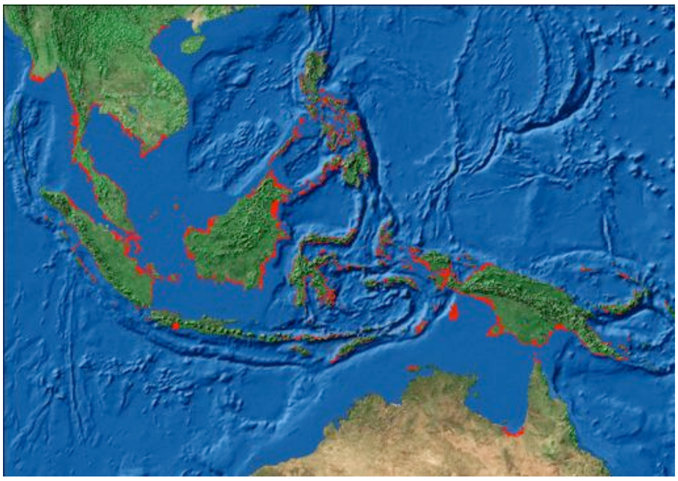


Figure 8. Mangrove areas (red) where change datasets have been generated by detecting losses of mangrove based on L-band HH and HV anomalies in ALOS PALSAR data acquired in 2007, 2008 and 2009 mosaics where available.

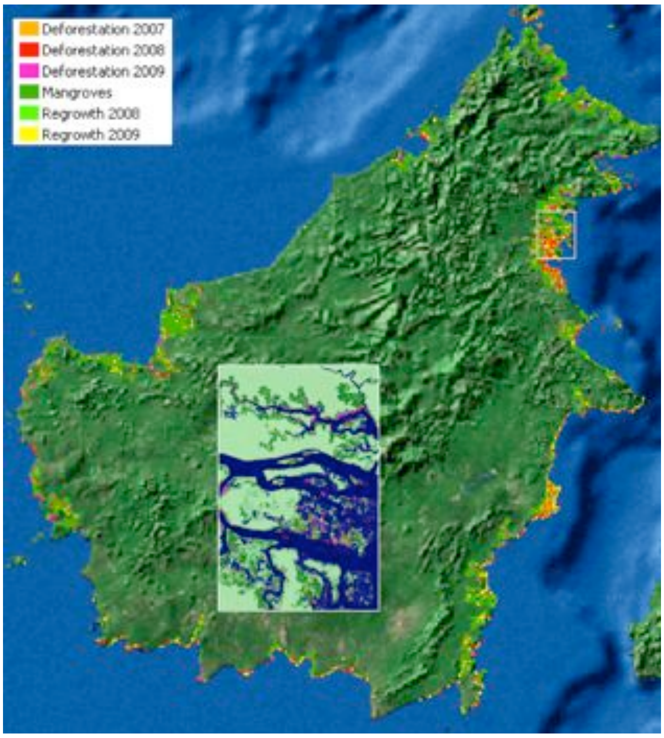


Figure 9. Areas of change (deforestation and regrowth) in Borneo detected through comparison of ALOS PALSAR data with the USGS/NASA global mangrove dataset.

a)

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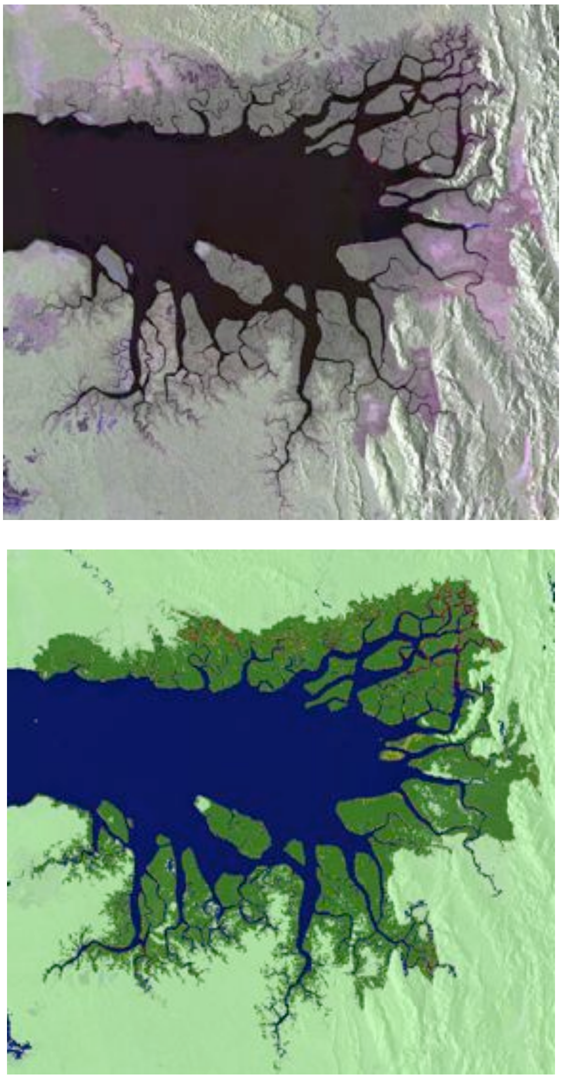

Figure 10. Mangroves in western Irian Jaya a) observed within ALOS PALSAR data. b) Time-series comparison of mosaics from 2007 and 2008 indicated minimal change.

VIII. Discussion

A. Overview

The majority of studies classifying mangroves have largely only mapped a few classes, with most of these being specific to the area of interest and focusing primarily on species or relative height or cover. The classification adopted in this study suggests a more consistent approach that utilises globally available datasets (i.e., the ALOS PALSAR and SRTM) and which can be applied within and between regions. Refinements to the classification can also be made using optical data where available. The scheme has been applied to northern Australian and Belize.

The study has highlighted the capacity of using ALOS PALSAR data in conjunction with existing mapping to detect changes in mangrove extent in response to both natural and anthropogenically-induced events and processes. However, only changes in a seaward direction and losses of vegetation amount within the known areas of mangroves were mapped with confidence. Inland or up-river extension of mangroves as a consequence of, for example, sea level rise, was less reliably mapped because of similarities in the backscatter of the vegetation covers being replaced. Even so, such changes were evident within some regions (e.g., northern Australia) and are important to identify, particularly given predictions of sea level rise in some regions.

The primary benefit of using ALOS PALSAR data was the provision of cloud-free observations for entire regions over a relative short (1 - 4 month) time period during any annual cycle. The consistent provision of data over consecutive years also provided opportunities for detecting change. However, change away from a baseline established using data other than ALOS PALSAR is considered essential as a first step, with the USGS/NASA dataset regarded as the most consistent globally. Subsequent changes can then be identified through time-series co-registered multi-temporal ALOS PALSAR data.

Within the mapped area of mangroves, the use of the SRTM data is adequate for retrieving the height (within certain error bounds), but only for extensive areas of relatively closed-canopy mangroves. However, the 90 m spatial resolution does limit retrieval and the integration of finer spatial resolution DEMs (e.g., 30 m SRTM data, 10 m NextMap Intermap or Tandem-X) is therefore advocated. The reliability and consistency of height retrieval across regions and for a range of mangrove structural types and spatial configurations needs to be quantified in order to give greater confidence in the inclusion of these data in the classification approach.

Whilst maps have been generated for all or part of the study regions, the validation of these remains a challenge, particularly in relation to the detection of change, the causes and magnitudes of which vary considerably between regions. This needs to be achieved by strengthening collaboration with existing mapping agencies in the countries involved, at both the national and international level.

II. Conclusions

The mapping of mangrove extent using ALOS PALSAR data is problematic in many regions because of the similarities in L-band backscatter with adjacent land covers, particularly those that are forested. (In some regions (e.g., Southeast Asia), differentiation can be achieved where mangroves with extensive root systems adjoin tropical forests because of their comparatively lower L-band HH backscatter). Therefore, for subsequent classification, an existing baseline map of mangrove extent is needed, with that generated by the USGS/NASA considered to be the most robust because of its consistency in generation (i.e., primarily from Landast sensor data).

Using ALOS PALSAR in conjunction with SRTM data, extensive areas of mangrove were categorised into a minimum of three broad classes, with these relating to relative differences in biomass and structure (including the presence or otherwise of prop root systems). A benefit of the classification approach is that the datasets used are available globally. The classification is supported by observations using airborne SAR data at sites in Australia and Belize. A particular advantage of the technique is that the classification is simple and can be applied between regions. However, further validation of the resulting classifications based on reference sites needs to be undertaken if the approach is to be routinely adopted.

The detection of change using ALOS PALSAR data again requires reference to existing baselines of mangrove extent. Whilst these baselines exist for many regions, they can be refined and/or updated using PALSAR data. From these, ongoing monitoring using PALSAR data, either singularly or in combination, can be undertaken.

Acknowledgements and Image Copyrights

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