Characterisation and Monitoring of Mangroves Using ALOS PALSAR Data

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***Abstract*—Methods for classifying mangrove communities from remote sensing data has primarily focused on extent, structure, biomass and/or dominant/species or genus. However, many algorithms have been developed on and applied to local regions but are not applicable at regional levels. For the tropical and subtropics, data from the Japanese Space Exploration Agency's (JAXA) Advanced Land Observing Satellite (ALOS) Phased Arrayed L-band Synthetic Aperture Radar (PALSAR) have been acquired routinely since 2006. As part of the JAXA Kyoto and Carbon (K&C) Initiative, regional mosaics of L-band HH and HV data have been generated for insular and mainland Southeast Asia, northern Australia, Belize and the Amazon-influenced coastline of South America. By using these data in conjunction with Shuttle Radar Topography Mission (SRTM)-derived estimates of mangrove canopy height, a classification of forest structural types was developed which could be applied regionally and potentially across the range of mangroves. Across the tropics and subtropics, mangroves are also subject to change in response to natural or anthropogenic drivers. Identifying such change requires, in many cases, the establishment of baseline datasets of mangrove extent although spatial information on the distribution of dominant species and both structure and biomass as a function of growth stage is desirable. For the same regions, comparison with existing baseline datasets established areas of significant change in French Guiana, Southeast Asia and northern Australia, with each attributable to different causes. The study highlighted the benefits of ALOS PALSAR for detecting change, particularly given the prevalence of cloud-cover in many regions. The utility of and requirements for the inclusion of PALSAR data within a global mangrove mapping and monitoring system are highlighted.**

***Index Terms*—ALOS PALSAR, K&C Initiative, Forest Theme, mangroves, structure, change.**

I. INTRODUCTION

A. Characterisation of mangroves

The mapping of mangrove extent and type in many regions 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 optical data is that mangroves are relatively distinct from non-mangrove areas, although confusion with adjoining tropical forests often leads to errors in the mapping of mangrove extent. Approaches to classification have varied and have included the use of standard classification supervised and unsupervised classification algorithms. However, typically only 2-3 mangrove classes have been mapped with these relating primarily to species, structure and/or biomass. Many of the classifications have also been developed and applied to local areas of mangroves and often cannot be applied more widely.

Whilst Synthetic Aperture Radar (SAR) have been used for characterising and mapping mangrove extent in some regions, most SAR have operated at higher frequency C-band (~ 2.6 cm wavelength) microwaves which interact primarily with the upper surface of the canopy. For this reason, separation between mangroves and other vegetation types and those with different structure and biomass has proved difficult, although some success has been obtained using combinations of SAR and optical data.

The launch of the Japanese Space Exploration Agency's (JAXA) Advanced Land Observing Satellite (ALOS) Phased Arrayed L-band SAR (PALSAR) in 2006 therefore represented a milestone in the global observation, characterisation, mapping and monitoring or mangroves, largely because these provide more information on the three-dimensional structure and biomass of woody vegetation and the presence and extent of (primarily tidal) inundation. As data can be day or night regardless of weather conditions, mangroves can be observed more frequently, even in regions with prevalent cloud cover.

B. *Detection of change*

Mangroves are dynamic ecosystems, responding to changes in the coastal environment by colonising areas where sediment has accumulated and facilitating further accretion [1]. Where changes are adverse (e.g., changes in tidal flow, flooding or storm damage), degradation or dieback of mangroves may occur with subsequent impacts on the distribution and state of the substrate. In the past, such changes have been the consequence of natural processes (e.g., sea level fluctuation) or events (e.g., cyclones or tsunamis). However, the trajectories of change are being altered by human-induced climate change which is manifesting itself as increases in the number and intensity of climate-related events (e.g., storms), longer term shifts in climate (e.g., temperature) and rises in sea level. Disaggregating the influence of climatic change on mangroves distributions and state from that associated with natural processes is therefore presenting a major challenge.

The situation is made more complex by the more direct impacts of human activity on mangroves. In many regions, extensive areas of mangrove have been cleared to support urban development, agriculture (e.g., rice production), mariculture (e.g., oyster and mussel fisheries) and pond culture (mainly shrimps) [2]. The influence of climate change processes on such mangroves is therefore often masked as such activities often lead to artificial changes in hydrological and tidal flows and recolonisation of mangroves is often prevented as the land previously available for expansion is otherwise designated for human use. Many mangroves areas, which might have been indicators of a changing climate, have been and continue to be cleared despite their importance (e.g., as a breeding ground for fish and sustainable source of natural materials). Even so, the role of mangroves in protecting coastlines is also becoming increasingly apparent, particularly since the 2004 Asian tsunami, and efforts are ongoing to ensure their long-term preservation in many regions.

C. *Research objectives*

Focusing on northern Australia, the Amazon-influenced coast of South America, central America (Belize) and southeast Asia, the research had two main objectives:

a) To establish the potential of the ALOS PALSAR, either singularly or in conjunction with other remotely sensed data, for consistent regional characterisation of mangroves. In particular, the research sought to provide better information for discriminating structural or biomass classes.

b) To investigate the use of these data for detecting changes in mangroves and to establish the causative factors.

These areas were primarily selected as they are supported extensive areas of mangrove and were subject to natural and human-induced influences, including that associated with climate changes.

II. BACKGROUND

L-band microwaves (wavelength approximating 25 cm) emitted by the ALOS PALSAR penetrate through the foliage and interact primarily with the woody components of vegetation [3]. Horizontally transmitted waves are either depolarised through volume scattering by branches in the canopy, with a proportion of vertically polarised microwaves returning to the sensor, or penetrate through the canopy and interact with the trunks, returning primarily through double bounce scattering, as a horizontally polarised wave However, where extensive prop root systems occur, as in the case of higher biomass mangroves dominated by *Rhizophora* and, to a certain extent, the sapling stage of *Brugeiria* and *Ceriops* species [2], multiple scattering results in little energy returning to the sensor, particularly in the HH polarisation [3,4]. This scattering behaviour is captured in the dual polarised L-band HV and HH data respectively.

Whilst these interactions are well known, the use of L-band HH and HV data for mapping and/or characterising mangroves is complicated by the following:

a) Similarities in the L-band response of mangroves and adjacent forest areas often prevent their discrimination and mapping.

b) Where mangroves with extensive prop root systems occur, these often exhibit a low L-band backscatter (particularly at HH polarisation), which leads to confusion with non-vegetated areas.

c) L-band backscatter is enhanced when mangroves are tidally-inundated.

For these reasons, additional information has to be referenced to assist their characterisation.

For global mapping of mangrove extent, optical remote sensing (e.g., Landsat sensor) reflectance data have been widely exploited. Derived products, such as the Landsat-derived Foliage Projected Cover (FPC; [5]) used for mapping the extent of woody and non-woody vegetation in Australia, have also shown promise. However, whilst the use of optical remote sensing data can assist the mapping of mangroves, these data are often difficult to use in combination with regional SAR data as the prevalence of cloud in many areas limits opportunities for acquisition. Nevertheless, many of the World's mangroves have been mapped using these data, and often in conjunction with aerial photography. Such data have been collated into regional to global reference datasets (e.g., the Global Atlas of Mangroves; [6]) and maintained and/or published by national and international organisations, such as the United Nations Environment Program (UNEP) World Conservation Monitoring Centre (WCMC). Whilst much of these data have come from different sources and been generated using a range of methods, they nevertheless provide a baseline of current knowledge. Within the mapped area, mangroves can then be characterised using, for example, SAR data, and variations from the baseline used to detect and describe change.

The characterisation and mapping of mangroves across their range requires consistent and systematically acquired global datasets, which necessarily obtained using satellite sensors. The ALOS PALSAR archive represents one of these datasets. Two other datasets are associated with the Geoscience Laser Altimeter System (GLAS) carried on the ICESat Mission; [7]) and the Shuttle Radar Topography Mission (SRTM; [8]). The ICESAT GLAS is a full waveform LiDAR that provides height profiles for footprints 70 m in dimension and with a post spacing of 14.5 km at the equator. These data have been shown to be sensitive to the heights of mangroves [9]. The SRTM took place in 2000 during which C-band SAR interferometric sensors onboard the Space Shuttle Endeavour acquired data that was used subsequently to generate a Digital Surface Model (DSM) for the majority of the Earth's surface. However, the dominant interaction of C-band microwaves with the leaves and small branches of the upper canopy [9] resulted in the overestimation of ground surface height for many forested areas. Whilst the potential for direct retrieval of forest height was recognized early on (e.g., [10], this required a reliable Digital Terrain Model (DTM) which was not always available. However, as mangroves occur at sea level, the height determined by the SRTM approximates the average stand height. The major limitation was that the SRTM data were distributed at 90 m spatial resolution, although finer (30 m) resolution data were or will be released for some regions. Using SRTM data, calibrated with both field and ICESat data, [9] reported that the crown weighted mean height (H_{CWM}) for mangroves was related to the SRTM height (H_{SRTM}) by:

$$H_{CWM} = 2.1 + 0.94\, H_{SRTM} \quad \text{(Equation 1)}$$

with the margin of error being +/- 1.9 m.

Individually, data from the ALOS PALSAR, optical sensors and the SRTM provide unique information on the extent and characteristics of mangrove ecosystems. However, when combined, considerable insight into the extent and structure of mangroves can be obtained which can be exploited to assist their classification. As these data are globally available, the potential exists for the development of a regionally-consistent algorithms for characterization and detection of change.

III. METHODS

A. Study areas

The method for characterising mangroves using the available datasets was developed initially for mangroves occurring in northern Australia, Belize and the Amazon-influenced coast of South America and is currently being applied to areas within southeast Asia. In all regions, the structural diversity of mangroves is similar in that canopy heights can 30 m in some areas, a closed canopy is commonplace, and the same types of rooting systems are evident. Levels of biomass are also similar although vary across the coastal environment as a function of environment and growth stage.

Mangroves in Australia are extensive (1.5 million ha in 2005; [2]), particularly along the northern and eastern coastlines. As with southeast Asia, the species diversity is high. Whilst urban expansion has been primarily responsible for the loss of mangroves in Australia, the majority remains relatively pristine and, as such, are useful barometers of environmental change

The mangroves of French Guiana and Brazil cover 55,000 and 1.0 million ha respectively (FAO, 2007). Those occurring along the 1600 km stretch of coastline north of the Amazon mouth are particularly dynamic because they receive vast amounts of sediment from the Amazon River. [10] describe this area as being under the influence of the Amazonian Dispersal System whereby alternate sequences of substantial accretion and erosion occur. Changes in mangroves are therefore associated primarily with these processes, although some human-disturbance is evident. Sediment delivery may also be affected by changes in climate within the Amazon region and also the amount and nature of deforestation activities over time. This low-lying area is vulnerable to sea level rise and also storm and wave damage.

The Southeast Asia region supports approximately 4.9 million ha of mangrove, with these distributed primarily in Indonesia, Malaysia and Myanmar (Table 1). 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 (e.g., for mariculture) and extensive logging [2].

Table 1. Area of mangroves, Southeast Asia (FAO, 2007)

Country	Area (ha)	Year[1]	Country	Area (ha)	Year[1]
Brunei Darussalam	18418	1996	Philippines	247,362	2003
Cambodia	72,835	1997	Singapore	500	1990
Indonesia	3,062,300	2003	Thailand	244,085	2000
Malaysia	564,971	2005	Vietnam	157,500	2000
Myanmar	518,646	1999	**TOTAL**	**4,886,617**	

[1]Year for which estimates were current

B. *Satellite and ground data*

For Australia, Belize and the Amazon-influenced coasts, 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 [12], 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 SRTM with ALOS PALSAR data and using ALOS orbital state vectors and ancillary information. However, 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. Cross-track correction and mosaicing of the orthorectified strips was undertaken using procedures within Gamma and also developed by the European Commission's Joint Research Centre (JRC). The procedures were developed to ensure a high level of geometric accuracy (geocoding errors were typically less than one pixel and better in northern Australia where the panchromatic data had been used in the orthorectification process; Figure 1). The cross track correction and mosaicing procedures allowed the provision of relatively seamless regional mosaics for most of the study regions and particularly for areas of homogeneous cover (e.g., forested areas in South America; Figure 2). Difficulties in obtaining seamless mosaics for northern Australia were encountered but was not limiting for characterising and mapping mangroves.

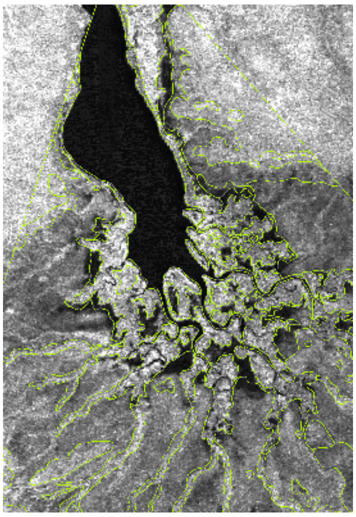


Figure 1. Extent of mangroves overlain onto orthorectified ALOS PALSAR HH mosaic (errors of registration < 50 m)

A number of existing spatial datasets were available to support the detection of change from the ALOS PALSAR. For all regions, the United Nations Environment Program (UNEP) World Conservation Monitoring Centre (WCMC) provided a global polygon dataset generated in collaboration with the International Society for Mangrove Ecosystems (ISME), 1997. A polygon dataset prepared for the forthcoming 2nd edition of the World Atlas of mangroves compiled by UNEP WCMC [13], and funded by ITTO, was also made available. Other datasets were also available for the study regions. For Australia, existing mangrove coverages provided by the Environmental Protection Agency (EPA) Queensland Herbarium (QH) were utilised. These provided a baseline map of mangroves, primarily for Queensland. For Belize, French Guiana and regions of Brazil (e.g., the Bragantina), nationally-generated datasets were available.

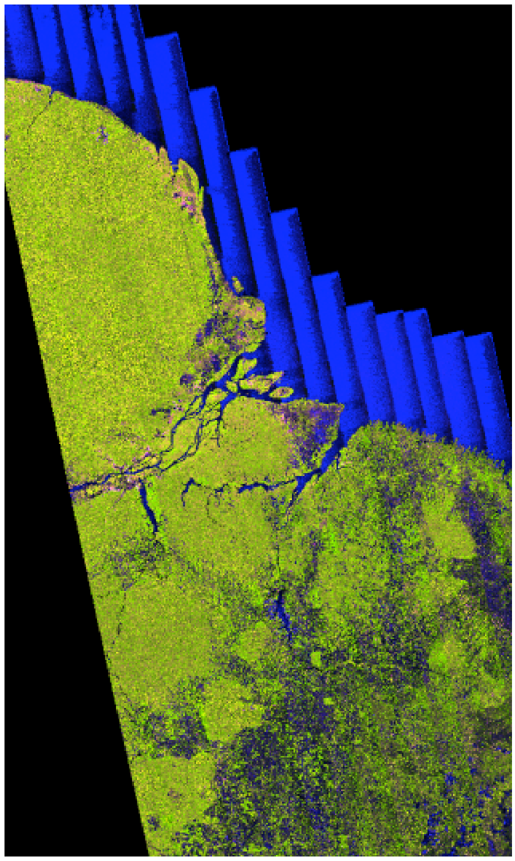


Figure 2. ALOS PALSAR mosaic of the Amazon influenced coast generated using Gamma SAR processing software (L-band HH, HV and HH/HV in RGB).

In establishing baselines of mangrove extent, information from countries in the tropics and subtropical regions was necessarily collated. However, the methods of mapping mangroves in each of the contributory countries varied as did the time-period over which the mapping was valid. Updating of estimates using, for example, Landsat sensor data was not possible because of issues relating to data availability and cloud cover [2], although these baselines could be adjusted to a common mid 1990s date using Japanese Earth Resources Satellite (JERS-1) SAR data (which were available for selected regions).

C. *Ancillary datasets*

For all regions, SRTM tiles at 90 m spatial resolution were combined to generate regional mosaics. As the SRTM mosaics were used in the orthorectification of the ALOS PALSAR data, errors in spatial registration were minimised. For northern Australia only, Landsat-derived FPC data were obtained from the Queensland Department of Natural Resources and Water (QDRNW).

For sites in northern Australia (Kakadu National Park in the Northern Territory and the Daintree River National Park in Queensland), a range of airborne data, including that acquired by polarimetric multifrequency airborne SAR and hyperspectral sensors, was available to support the interpretation of the ALOS PALSAR and other data. Products derived from these data included canopy height maps (generated from stereo aerial photography and SAR interferometry; [4,13,14] and species maps (classified from hyperspectral data; [15]). For Belize and French Guiana, interferometric and/or polarimetric SAR data were acquired for areas of mangrove along the coast.

D. Approach to classification

Based on previous studies using the available airborne datasets [3], the following observations were used to develop rules that could be used subsequently in the classification of mangroves. In particular:

a) With increases in the biomass of most mangrove communities, the radar backscatter was shown to increase to about 100-120 Mg ha^{-1} at which point, saturation of the signal was observed such that no further increases with biomass were observed. However, the exception was mangroves with extensive prop root systems where the L-band HH and HV backscatter was shown to progressively decrease with increases in biomass above 100-120 Mg ha^{-1} (Figure 3).

b) Mangroves with these high levels of biomass generally exceeded 10 – 15 m in height, as estimated from ground data and stereo aerial photographs.

c) Comparison of Digital Elevation Models (DEMs) determined from Intermap X-band SAR and SRTM C-band SAR acquired over mangroves in Belize suggested reliable retrieval of height by the SRTM where mangroves were greater than 10 m in height and the 90 m pixel was largely occupied by the mangrove canopy. Where the height was < ~10 m and the 90 m pixel area was only partially occupied by mangroves, height retrieval was less reliable.

Within all regions, mangroves could be mapped using ALOS PALSAR data alone when bordered by non-vegetated areas. However, when occurring adjacent to forests on the landward margins, discrimination was often difficult (Figure 4). For this reason, the extent of mangroves was defined on the basis of existing mapping which had primarily been generated using optical remote sensing data.

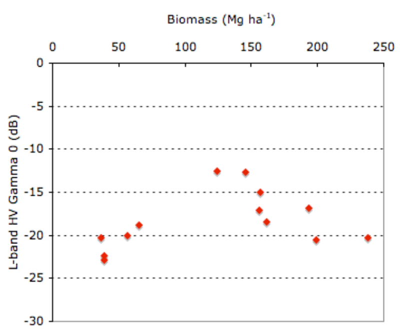


Figure 3. Observed relationships between SAR backscatter and biomass for Australian mangroves. Note the decline in backscatter above 100–120 Mg ha^{-1}

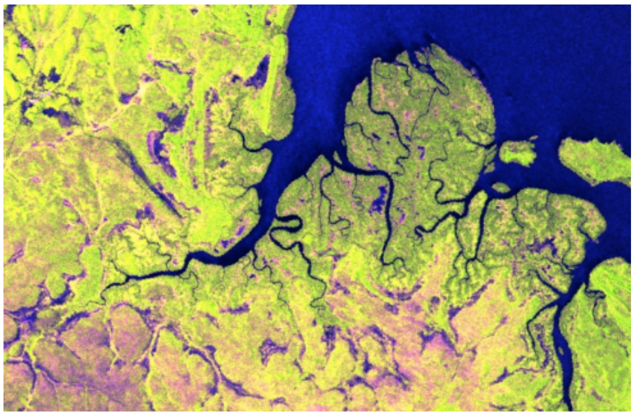


Figure 4. ALOS PALSAR image (L-band HH, HV and the ratio of HH and HV in RGB) illustrating the difficulty in discriminating mangroves from proximal rainforest and other vegetation covers.

Using Definiens Developer software [16], a segmentation of the imagery 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 in two stages to map three forest structural types. First, mangroves <= and > 10 m (as defined using the SRTM-derived H_{CWM}; Equation 1) were separated. Second, and for mangroves > 10 m in height, an L-band HH backscatter <= or > a specified threshold was used to separate higher biomass mangroves (> ~ 100 – 120 Mg ha^{-1}) with prop roots from those without. This latter category was associated with species with pneumatophores typical to the genera *Avicennia*, *Sonneratia* and *Laguncularia* [2]. A refinement to the segmentation was undertaken in Australia 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 < 12 % was used to define non- or sparsely vegetated areas.

E. The detection of change

For the detection of change, differences between the extent of mangroves mapped within the existing baseline datasets and that observed within 2007 ALOS PALSAR data mosaics was mapped. The change detection procedures were again developed within Definiens Developer software and focused primarily on the loss of mangroves from the existing baseline area and also on expansion of mangroves in the seaward direction. Inland extension of mangroves could be detected where expansion occurred into non- or sparsely vegetated areas but not into areas occupied previously by other forests or previously disturbed (e.g., tree plantations), because of similarities in backscatter at both L-band HH and HV polarisation. For several areas (e.g., French Guiana), regional mosaics of JERS-1 SAR data, acquired between 1992 and 1998) were available and could be used to adjust existing baselines to a common reference year. For Queensland, Landsat-derived Foliage Projected Cover (FPC) data (range 0 to 100 %) were available for 2006. Within these data, mangroves were particularly evident as their closed canopy led to FPC percentages of > 80 %, with lower values associated primarily with low and scattered mangroves. These data were used to confirm the extent of mangroves mapped within the baseline.

IV. Results

A. *Examples of mangrove classifications*

The rule-based classification was applied initially to sites for which a) ground data and/or airborne data and derived products were available or b) extensive tracts of mangrove with distinct zonations occurred. As an example, Figure 5 illustrates the distribution of the three main mangrove categories for Hinchenbrook Island, Queensland, Australia. The majority of tall mangroves with prop roots (primarily *R. stylosa*) are located on the seaward margins.

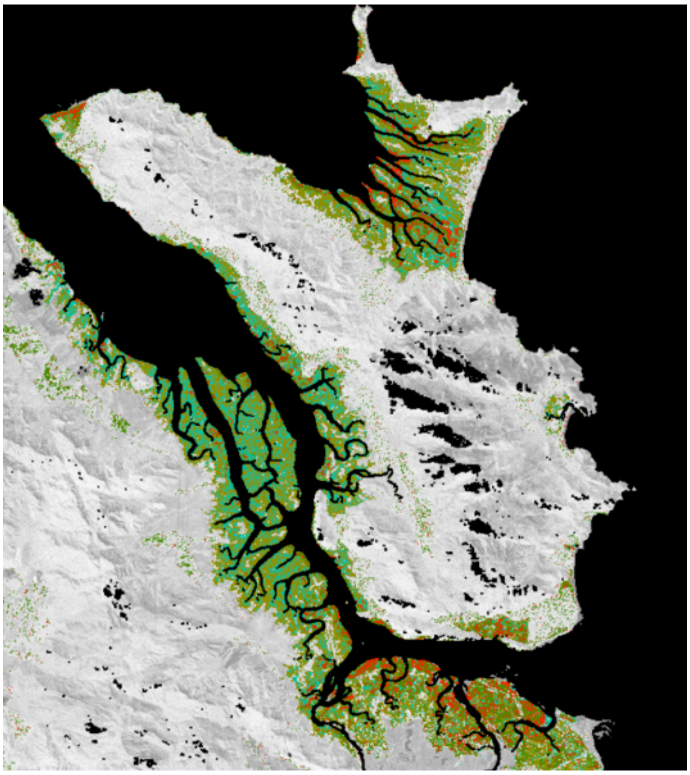


Figure 5. The distribution of mangroves < 10 m (green), > 10 m without prop roots (olive) and > 10 m with prop roots (red).

B. *Comparison with existing mapping*

Comparisons with existing classifications were undertaken, noting that the majority of these focused on the classification of species type or relative height classes. By contrast, the rule-based classification is primarily of structural classes although these can be associated with a broad species types. As an example, tall (> 10 m) mangroves with prop roots are typically dominated by *Rhizophora* or *Brugeira* species. An existing mangrove classification of species (Figure 6) is compared with the rule-based classification (Figure 7) for a coastal area near Aurukun on the Cape York Peninsula, Queensland, Australia. A general correspondence is observed between areas mapped previously as *R. stylosa* and those mapped as tall mangroves (with prop roots) using the rule-based classification is observed. Some areas dominated by *R. stylosa* are classified as low (< 10 m) mangroves, which is not incorrect but rather illustrates the complementary information these provide.

C. *Regional classifications*

For the study regions, the classification was applied to the areas mapped as mangrove. An example classification applied over Belize is presented in Figure 8, which illustrates the capacity for classifying mangroves at a regional level. Similar classifications were also generated for Australia and are to be applied to the Amazon-influenced coast and Southeast Asia.

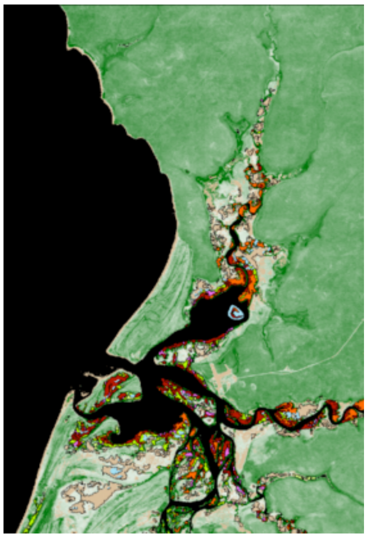


Figure 6. Classification of mangroves by species type [17].

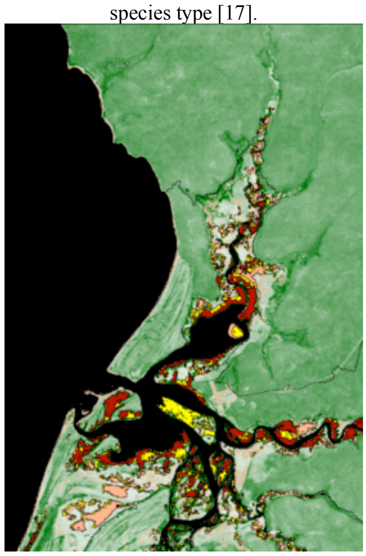


Figure 7 Distribution of mangrove classes mapped using a combination of ALOS PALSAR, SRTM and Landsat-derived FPC data.

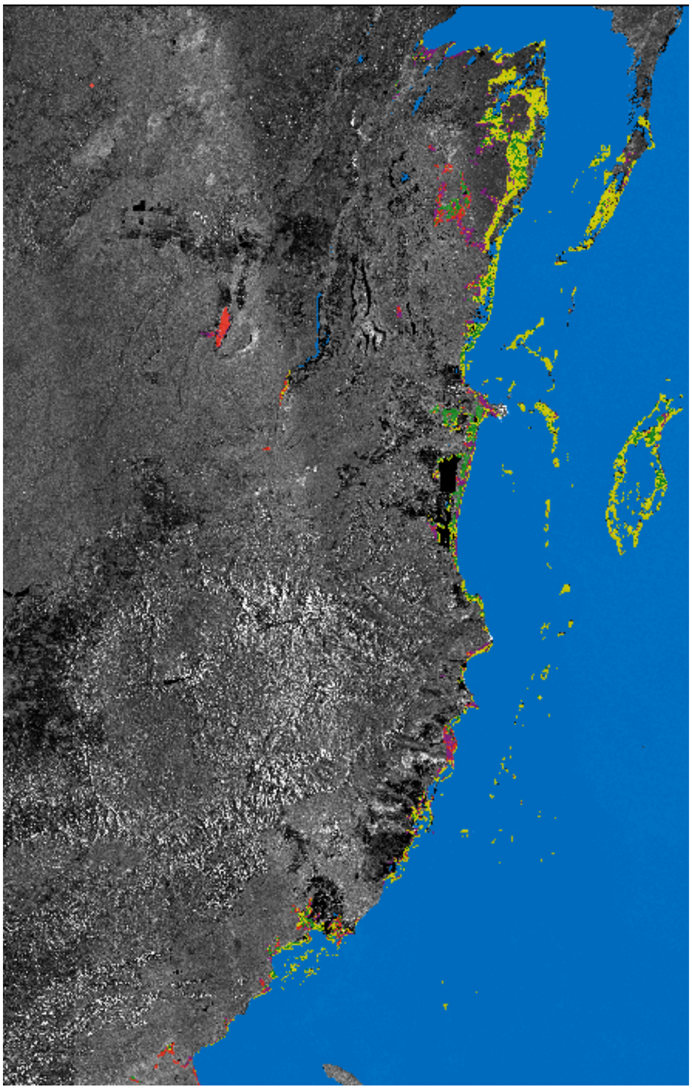


Figure 8. The distribution of mangrove classes, Belize.

Detection of change

For the north and east of Australia, and focusing primarily on Queensland, significant change away from the established baseline was not observed with the exception of the southern Gulf of Carpentaria. Here, seaward expansion of mangroves was noted along the length of the coastline (Figure 9). The cause of such change is likely to be increased sedimentation on the coastal fringe as a result of increases in rainfall and storm events. As an example, Figure 10a and b shows MODIS images of the region prior to and during the extensive flooding in 2009 [18]. The area of mangrove expansion corresponds with that influenced by the flood waters of the Flinders River.

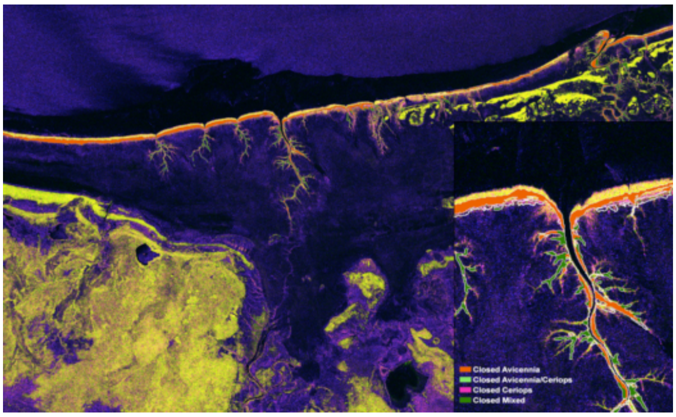


Figure 3. Seaward expansion of mangroves near Burkestown, Gulf of Carpentaria, Queensland, Australia.

Changes in the distribution of mangroves along the Amazon-influenced coast, as documented by [19], continued to be observed using ALOS PALSAR data. The baseline dataset of mangrove extent (Figure 11a), when overlain on the JERS-1 SAR image, revealed discrepancies which were adjusted for within Definiens Developer to establish a new baseline for 1995. When compared against the ALOS PALSAR data acquired in 2007 (Figure 11b), significant losses and gains in the area of mangroves relative to the 1995 baseline were mapped (Figure 11c). More stable areas of mangroves were observed, as were areas of mudflat, which exhibited a noticeably low L-band HH backscatter. These areas represented sites where future colonisation of mangroves might occur.

Within Belize, changes in mangroves from the national baseline were difficult to establish because of apparent discrepancies in definition and the mapped distribution. In particular, significant areas of mangrove savanna in the north of Belize were not mapped previously but were evident within the ALOS PALSAR mosaic (Figure 12).

Within Southeast Asia, comparison of the existing WCMC UNEP maps of mangrove extent with ALOS PALSAR mosaics (Figure 5a) indicated discrepancies in the mapped extent. These were largely associated with:

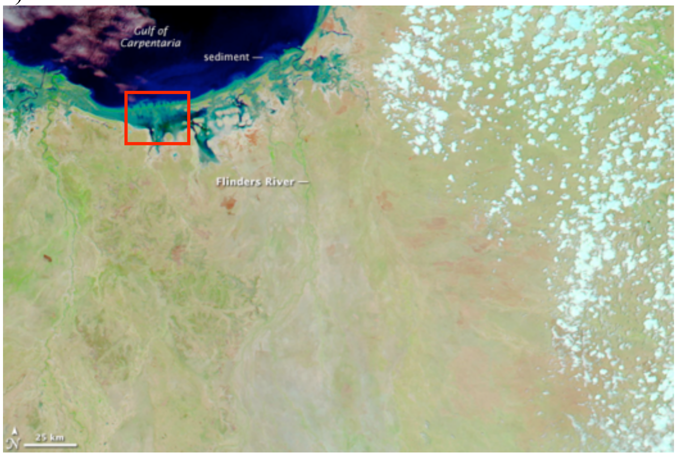
a) The resolution of the linework and the nature of digitising, which is variable between countries.

b) Registration errors between the two datasets, which led to difficulties in adjusting baselines (e.g., relative to the JERS-1 SAR mosaics) and mapping change.

c) Significant losses of mangrove with the mapped area with these associated primarily with expansion of urban areas, agriculture and fisheries.

d) Differences in the definition of mangroves.

a)



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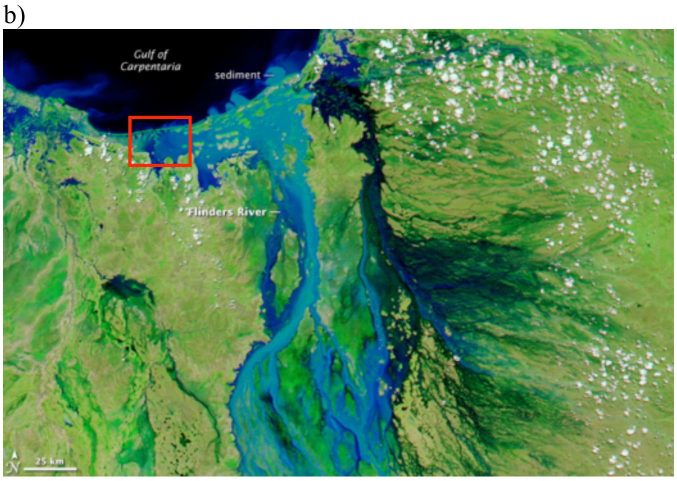
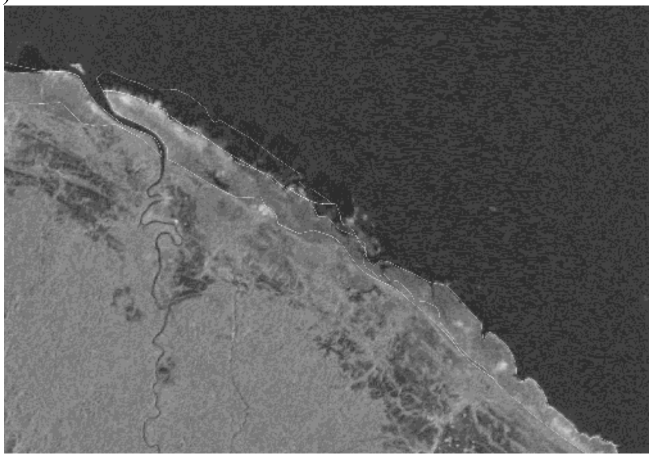


Figure 10. Changes in flooding of the Flinders River as observed from MODIS data (2009). Discharge of sediment into the Gulf of Carpentaria is evident [18]. The area corresponding to Figure 9 is shown in red.

As an example of these issues, Figure 12b illustrates the mapped extent of mangroves overlain onto the ALOS PALSAR data. The capacity for detecting change through comparison of multi-temporal JERS-1 SAR and ALOS PALSAR data is illustrated in Figure 13 [20] where the dynamics of clearance and regeneration of mangroves in Perak State, Malaysia, are evident.

a)



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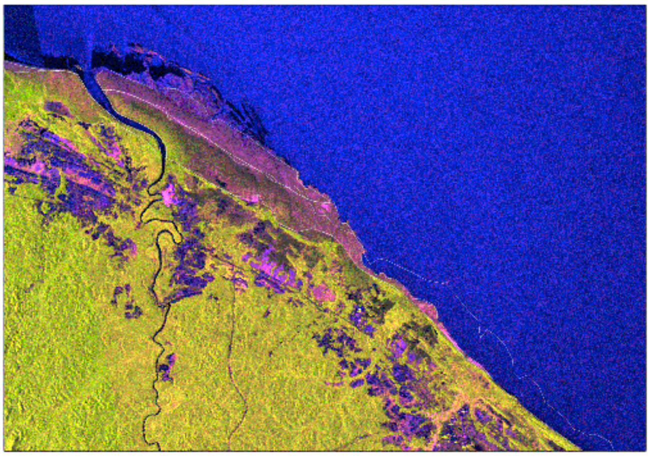


c)

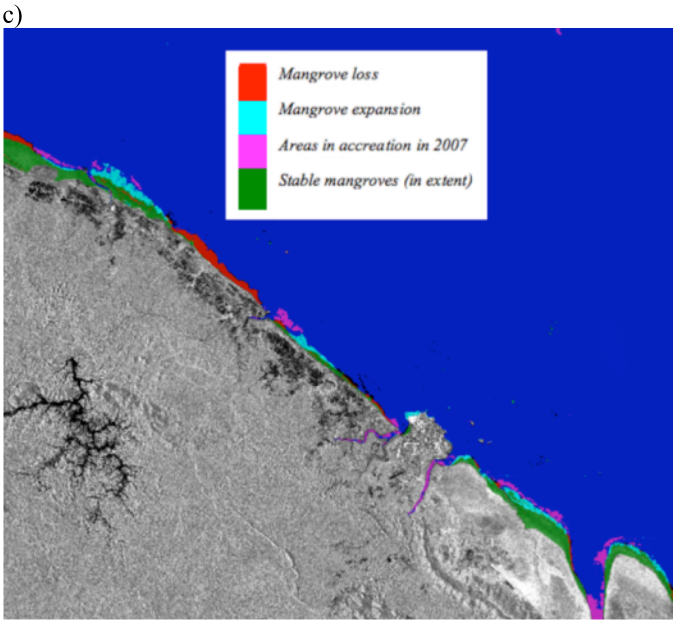


Figure 4. Mangroves along the coast of French Guiana, near Sinnamary as observed using a) JERS-1 SAR and b) ALOS PALSAR data acquired in 1995 and 2007. By comparing these datasets, areas of stable mangrove, mangrove colonisation and loss and mudflats along the French Guiana coast were identified.

Figure 5. ALOS PALSAR mosaic of Belize and baseline map of mangrove extent (white). Differences between mangroves and adjoining forests within the ALOS PALSAR data but discrepancies in the extent of mangroves are evident.

V. DISCUSSION

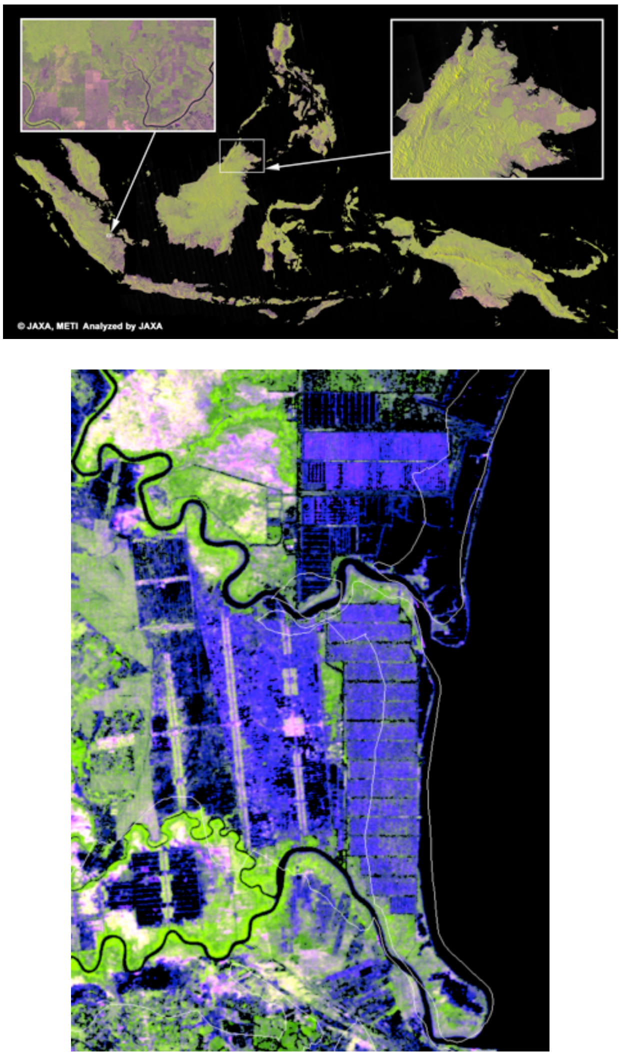
A. Relevance of mangrove classification

The majority of studies focusing on 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. The classification approach adopted in this study provides 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.

B. The detection of change

The study has highlighted the capacity of using ALOS PALSAR data in conjunction with existing mapping to detect changes in mangrove extent as a function of both natural and anthropogenically-induced change. However, only changes in a seaward direction and losses of mangroves within the known areas of mangroves were mapped. Inland or up-river extension of mangroves as a consequence of, for example, sea level rise, were not able to be mapped with confidence largely 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 many regions.

a)



b)

Figure 12. a) JAXA K&C mosaics available for Insular Malaysia and b) UNEP WCMC map of mangroves (white line) overlain onto a subset of the mosaic. Using these data, the establishment of change is difficult because of variations in digitising, registration and the process of change itself.

Whilst the ALOS PALSAR can provide information on changes in mangroves, the cause of change can also be better understood using these and other datasets. For example, within northern Australia, time-series of ALOS ScanSAR data provide unique information on the dynamics of flooding in relation to changing rainfall patterns and runoff, factors which may explain the longer-term changes in dynamics within the Gulf of Carpentaria.

A number of limitations in the detection of change were highlighted which related to the georeferencing, digitising resolution and mangrove definitions. The relative coarse (50 m) spatial resolution of the K&C mosaics also resulted in only major changes in mangroves being identified whereas many may be extensive but associated with only a small change in terms of distance from the pre-occurring mangroves. Longer-time series, focus on areas of change using finer spatial resolution datasets, and better development of consistent retrieval algorithms is therefore required.

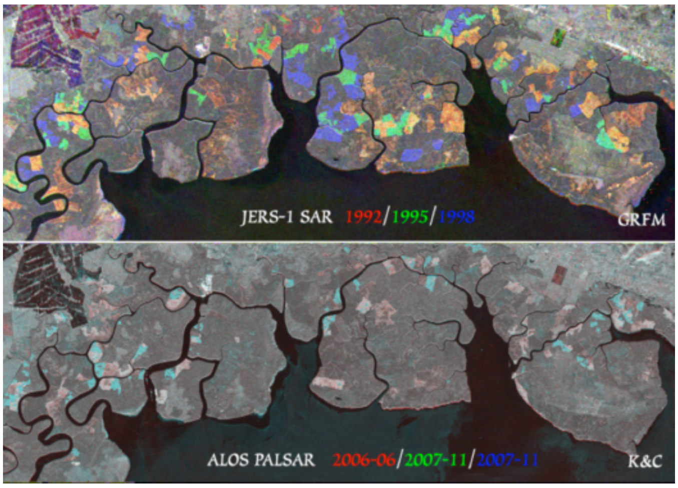


Figure 13. The Matang Mangrove Forest Reserve in Perak, Malaysia [20]. Top: JERS-1 SAR time series from 1992, 1995 and 1998. Areas logged in the period appear in blue and green, while areas of regrowth appear in orange. Bottom. ALOS PALSAR composite from 2006-2007. Red indicates regrowth in areas logged recently prior to the 2006 observation. Blue shows recent crearings. Only the HH channel has been used, as the increased double-bounce scattering from the water surface and remaining tree stumps is the key signal for the detection of logged mangroves.

C. Overview of approach

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 provides opportunities for detecting change, as illustrated in Figure 13. The use of multi-temporal ALOS PALSAR data is advocated as errors associated with classification of other remote sensing data or digitising are largely overcome. The primary objective should therefore be to establish a consistent baseline dataset for a single year (e.g., 2007/2008) against which change can be assessed.

The use of the SRTM data is adequate for retrieving the height (within certain error bounds) of extensive areas of relatively closed-canopy mangroves, the 90 m spatial resolution does limit retrieval. Therefore, the integration of finer spatial resolution DEMs (e.g., 30 m SRTM data or 10 m NextMap Intermap is advocated). The reliability and consistency of height retrieval across regions and for a range of mangrove structural types therefore needs to be quantified in order to give confidence in the 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 cause 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.

VI. CONCLUSIONS, RECOMMENDATIONS AND FUTURE STUDY

Using ALOS PALSAR in conjunction with SRTM data, extensive areas of mangrove can be categorised into a minimum of three broad classes, with these relating to relative biomass and structure. 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 rule-based and can be applied between regions.

The detection of change using ALOS PALSAR data currently requires reference to existing baselines of mangrove extent although it is anticipated that after adjustment to a single year, the ALOS PALSAR can form part of an ongoing mangrove monitoring system. The main benefit of the ALOS is that cloud-free observations of regions can be guaranteed.

Within the study region, both human-induced and natural change has been observed through comparison of ALOS PALSAR data against existing baselines. Key outcomes from the research include:

a) Detection of ongoing change in mangrove colonisation and loss along the Amazon-influenced coast of South America.

b) Significant seaward expansion of mangroves in the Gulf of Carpentaria in northern Australia, which is linked to increased rainfall and extreme flooding within the catchments.

c) Loss of mangrove areas in south-east Asia which have previously been reported as intact.

For several study areas, the existing baseline datasets appear to not reliablely depict the extent of mangroves, either due to issues arising during their generation or because of change occurring in the interim periods. Within Phase 2, continued development of the mangrove mapping and change detection for the study regions will be undertaken together with the development of algorithms that can be applied to other regions when regional mosaics become available.

APPENDUM: WETLANDS CLASSIFICATION, QUEENSLAND

In addition to establishing the potential of ALOS PALSAR for mangrove characterisation and mapping, the role of these data for supporting classification of wetlands in Queensland is being investigated. Across the State, regional mapping of wetlands has been undertaken previously by the Queensland Environmental Protection Agency (EPA) through reference to aerial photography and optical (primarily Landsat but also SPOT and IKONOS) sensor data supported by ground survey. The ALOS PALSAR provides complementary and often new information on wetlands, particularly in relation to inundated (woody) vegetation (Figure 14) and open water. These data are being integrated within a rule-based classification (e.g,. Figure 15; based on Definiens Developer software) with a view to refining or advancing the classification of wetlands occurring from the coastal margins to the inland semi-arid regions of the south-west of the State. These classifications makes use of the Landsat FPC and ALOS PALSAR mosaics generated for the State. These classifications will be supplemented using ScanSAR data acquired by the ALOS during Phase 2.

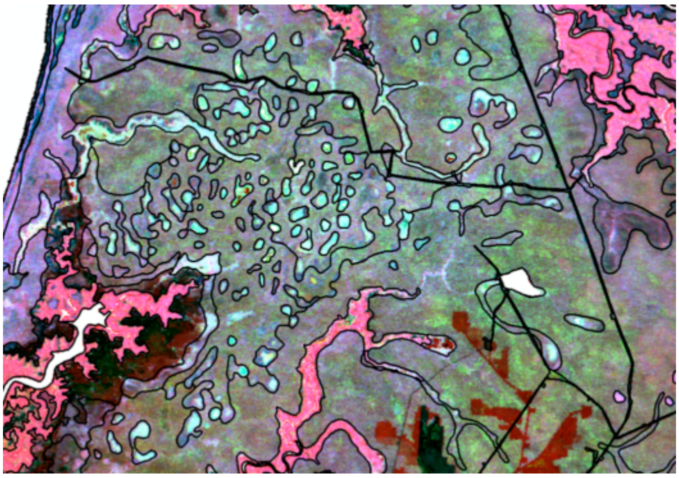


Figure 14. Composite image of Landsat-derived FPC (in red), L-band HH (green) and L-band HV (blue) showing areas of inundated vegetation (primarily paperbark swamps) in the north-west Cape York Bioregion. Queensland Regional Ecosystem mapping is overlain.

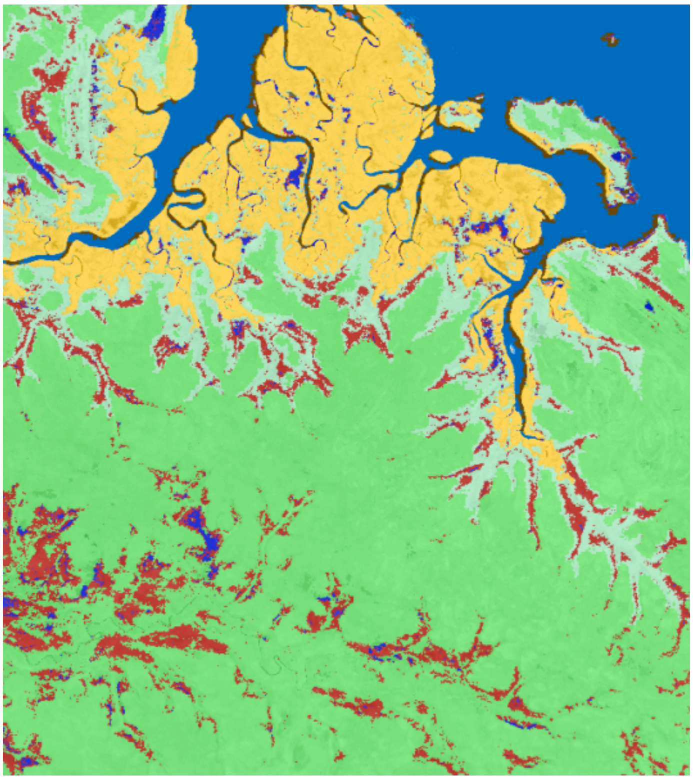


Figure 15. Preliminary classification of estuarine (including mangroves; orange), and palustrine (red) systems and open water (blue), north-east Cape York Bioregion.

ACKNOWLEDGEMENTS AND IMAGE COPYRIGHTS

This work has been undertaken within the framework of the JAXA Kyoto & Carbon Initiative. ALOS PALSAR data have been provided by JAXA EORC. All PALSAR images and derived products illustrated in this paper are copyright to the ALOS K&C © *JAXA/METI*. The authors would also like to thank the UNEP World Conservation Monitoring Centre (WCMC).

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