RESEARCH FRONT

CSIRO PUBLISHING

Marine and Freshwater Research, 2014, **65**, 589–603
http://dx.doi.org/10.1071/MF13177

Contribution of L-band SAR to systematic global mangrove monitoring

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Abstract. Information on the status of and changes in mangroves is required for national and international policy development, implementation and evaluation. To support these requirements, a component of the Japan Aerospace Exploration Agency's (JAXA) Kyoto and Carbon (K&C) initiative has been to design and develop capability for a Global Mangrove Watch (GMW) that routinely monitors and reports on local to global changes in the extent of mangroves, primarily on the basis of observations by Japanese L-band synthetic aperture radar (SAR). The GMW aims are as follows: (1) to map progression of change within or from existing (e.g. Landsat-derived) global baselines of the extent of mangroves by comparing advanced land-observing satellite 2 (ALOS-2) phased array L-band SAR 2 (PALSAR-2) data from 2014 with that acquired by the Japanese earth resources satellite (JERS-1) SAR (1992–1998) and ALOS PALSAR (2006–2011); (2) to quantify changes in the structure and associated losses and gains of carbon on the basis of canopy height and above-ground biomass (AGB) estimated from the shuttle radar topographic mission (SRTM; acquired 2000), the ice, cloud and land-elevation satellite (ICESAT) geoscience laser altimeter system (GLAS; 2003–2010) and L-band backscatter data; (3) to determine likely losses and gains of tree species diversity through reference to International Union for the Conservation of Nature (IUCN) global thematic layers on the distribution of mangrove species; and (4) to validate maps of changes in the extent of mangroves, primarily through comparison with dense time-series of Landsat sensor data and to use these same data to describe the causes and consequences of change. The paper outlines and justifies the techniques being implemented and the role that the GMW might play in supporting national and international policies that relate specifically to the long-term conservation of mangrove ecosystems and the services they provide to society.

Additional keywords: climate change, forest dynamics, international conventions, remote sensing.

Received 5 July 2013, accepted 23 January 2014, published online 20 June 2014

Introduction

Mangroves are located primarily in the intertidal zones of the tropics and subtropics where they provide valuable resources for local populations, harbour a diverse fauna and flora, offer coastal protection and store substantive amounts of carbon (Glaser 2003; Mumby 2006; Alongi 2008; Donato *et al.* 2011). Despite their importance in ecosystem service provision, extensive areas have been cleared to support commercial ventures such as aquaculture, annual crops (e.g. swamp rice) and tree crops, with annual rates of loss averaging 0.8% since 1970 (Butchart *et al.* 2010). Mangroves are also responding to coastal change that is human-induced, natural and/or influenced by climatic fluctuation. However, the extent of these different events and processes and their causes and consequences remain largely unknown at a global level because no systematic mapping depicting changes in mangroves has historically, or is currently, taking place.

For several decades, remote-sensing data from both airborne and spaceborne sensors have been available to provide some capacity for observing and quantifying changes in mangroves across the required range of scales, although their use for monitoring has been limited. At the local and site level, aerial photography and very high-resolution (VHR) optical spaceborne (e.g. Quickbird, Worldview) data provide a large amount of detail for establishing baseline maps of the extent of mangroves, but spatial coverage is limited and acquisitions are often not repeated (Proisy *et al.* 2007; Neukermans *et al.* 2008; Wang *et al.* 2004, 2008). For regional-scale assessments, the moderate spatial resolution optical (e.g. Landsat, SPOT, ASTER) data are better placed (Spalding *et al.* 1997, 2010; Giri *et al.* 2011). However, routine detection of change has proved difficult in many tropical and subtropical regions where mangroves occur, largely because the persistence of cloud cover prevents regular observations. Increasingly, this restriction is being overcome by exploiting the dense Landsat sensor time series, which has led to a plethora of techniques (e.g. pixel mining; Zhu and Woodcock 2012) for increasing the number of cloud-free observations and, hence, mapping capability. Others (e.g. Souza-Filho and Paradella 2003; Nascimento *et al.* 2013) have instead exploited synthetic aperture radar (SAR) acquired at various frequencies and polarisations, either singularly or in combination with optical data, because these allow observations regardless of weather and illumination conditions.

Spaceborne SAR with capability for monitoring at global levels and with historical archives are the European Space Agency's (ESA) European remote-sensing (ERS) satellite-1 (1991–2000) and -2 (1995–2011) advanced microwave instrument (AMI) and ENVISAT advanced SAR (2002–2012) and the Canadian Space Agency's (CSA) RADARSAT-1 (1995–2013) and -2 (2007–present), all of which operated at C-band. ESA's Sentinel-1 SAR will continue observations at C-band from 2014. The German Space Agency (DLR) successfully instigated the Tandem-X mission (in 2010; encompassing the TerraSAR-X; launched 2007) and the Italian COSMO-SkyMed (a constellation of four satellites, with the last launched in 2010) is also providing X-band SAR data. The limitation of using the X- and C-band data from sensors operating in the past, however, has been that the global acquisitions have not been systematic over the period of operation; access has, until recently, been limited by availability and cost, and retrieval of the three-dimensional structure of forests (through polarimetry and interferometry) is generally restricted to the upper canopy. The most useful of these sensors for mangrove monitoring is arguably the TanDEM-X mission, because the global DEMs derived from these data (without the canopy removed) are anticipated to provide information on mangrove canopy height across their range. By comparing canopy heights from the TanDEM-X mission (following release in 2014) with those generated using the 2000 shuttle radar topographic mission (SRTM), changes in height should reflect changes in mangrove structure.

The primary L-band sensors operating at a global level have been the Japan Aerospace Exploration Agency's (JAXA) Japanese earth resources satellite (JERS-1) SAR and the advanced land-observing satellite (ALOS) phased array L-band SAR (PALSAR), which were in operations from 1992 to 1998 and from 2006 to 2011, respectively (Shimada and Ohtaki 2010; Shimada *et al.* 2010). Both JERS-1 SAR and ALOS PALSAR featured systematic acquisition strategies that provided consistent pantropical (JERS-1) and global (ALOS) L-band SAR coverages on an annual basis (Rosenqvist *et al.* 2000, 2007*a*). The ALOS-2 PALSAR-2 is their successor and was launched in 2014, from which observations of the coastal tropics and subtropics will continue on from those obtained during the previous two decades. The benefits of these sensors for mangrove monitoring are (1) that consistent, systematic and cloud-free observations across their geographical range will be continued over three decades and (2) their greater sensitivity to the three-dimensional woody components of mangroves, which allows the above-ground biomass (AGB) and structure to be retrieved (Lucas *et al.* 2007).

Given the known capabilities of Japanese SAR for mangrove monitoring (Lucas *et al.* 2007), a component of JAXA's Kyoto and Carbon (K&C) initiative (Rosenqvist *et al.* 2010) has been to develop capability for a Global Mangrove Watch (GMW; JAXA 2013), primarily using Japanese L-band SAR data. During early activities within the GMW, historical JERS-1 SAR and ALOS PALSAR data have been used to update Landsat-based baseline maps (by e.g. Giri *et al.* 2011 of the extent of mangroves for several years (mid-1990s, 2007, 2008, 2009 and 2010) against which future change observed by the ALOS-2 PALSAR-2 can be quantified. Furthermore, within the mapped areas, baseline measures of structure and AGB generated using historical interferometric radar and lidar data, such as those provided by the SRTM (11 February 2000, for 10 days) and/or the ice, cloud and land-elevation satellite (ICESAT; 12 January 2003 for 7 years) geoscience laser altimeter system

(GLAS), respectively (Simard *et al.* 2006, 2008; Fatoyinbo and Simard 2013), are being referenced. The global datasets of mangrove tree species composition compiled by the International Union for the Conservation of Nature (IUCN; www.iucnredlist.org) are being used to indicate species losses and gains. The L-band SAR data themselves can also be used to distinguish taller (>~10 m) mangroves with prop root systems (e.g. *Rhizophora* and *Ceriops* species) from those without because of their comparatively lower L-band HH backscatter (Lucas *et al.* 2007). The combination of these remote-sensing datasets, therefore, allows changes in the extent and structure and losses and gains in both carbon and tree species diversity to be quantified.

A necessary component of the GMW is to provide validation of these biophysical attributes (including extent) as well as observed change. One approach is to use local- to regional-scale reference sites distributed across the tropics and subtropics for which field data and observations (including crowd-sourced) and also airborne/spaceborne VHR remote-sensing data are available. However, this is difficult to coordinate, particularly given the infrequency of access to mangrove areas, the historical nature of the SAR datasets, and also the timeliness of field and remote-sensing data collection. Therefore, an alternative, complementary and global source of validation data is the dense time series of Landsat sensor data, which have been released recently by the United States Geological Survey (USGS), and the interpretation of these.

The present paper provides an overview of the GMW and its components but also focuses on policy needs that can be addressed through the provision of GMW outputs relating to extent and biophysical attributes and changes in these. Justification is provided for the use of L-band SAR within the GMW. The integration of these data with complementary optical remote-sensing data within the framework of the GMW is demonstrated for the purposes of providing information needed for policy development, implementation and evaluation. The validation of output products is also considered.

The importance of mangroves

Across their geographical range, mangroves are a main contributor to near-shore productivity, offer coastal protection, provide shelter for commercially important fish species and crustaceans and filter pollutants (Mumby 2006). Mangroves are also important to local communities because the timber is used for construction of dwellings, furniture and boats, the manufacture of charcoal, and firewood. Beyond the mangrove trunk, the branches are used to make fishing poles and traps, the bark provides tannins and fodder for animals, and the sap has commercial value in that it can be used for producing medicines, sugars, alcohol, insecticides and pesticides (Bandaranayake 1998; Rasolofoharinoro *et al.* 1998; Hogarth 1999).

Despite their importance, human activities beyond local exploitation are leading to the alteration and loss of mangrove forests across their geographical range. Large and often contiguous areas of mangroves are cleared for aquaculture and agriculture, saltpan creation, commercial forestry and timber harvesting, urban expansion and maritime development (Barbier and Cox 2004). In many regions, such changes have gone unnoticed by the wider community or have been inadequately quantified, largely because of the lack of spatial observations of sufficient extent, detail and temporal frequency. However, there is an increasing need for timely information on their changing distribution and condition at scales ranging from the local to global, for several reasons.

(1) Mangroves provide a substantial reservoir (Fatoyinbo and Simard 2013) and a potentially large sink for carbon (Dittmar *et al.* 2006; Donato *et al.* 2011; Hutchison *et al.* 2013), particularly given their high growth rates and ability to rapidly colonise. As such, they can contribute to reductions in net greenhouse gas (GHG) emissions and potentially provide 'carbon' income to local populations and governments. Continued destruction and degradation of mangroves is, however, contributing carbon emissions from the land use, land-use change and forestry (LULUCF) sector (Siikamäki *et al.* 2012).
(2) Mangroves are increasingly seen as barometers of regional to global climate change, responding to fluctuations in sea level and also to anomalous rainfall and temperature regimes (Beaumont *et al.* 2011). In many regions, mangroves have been shown to offer protection against storm surges and tsunamis (Alongi 2008), attenuating the destructive nature of the extreme events and offering options for their future mitigation.
(3) Mangroves support high levels of floral and faunal diversity and associated provisioning services (Vo *et al.* 2012), many of which are critical to local livelihoods and of importance to both local and regional economies.

Examples of the importance of mangrove, human impacts and their role in providing ecosystem services are provided in Table 1.

The needs of policy

The Ramsar Convention

Contracting Parties to the Ramsar Convention, which was adopted in 1971, have committed to 'the conservation and wise use of all wetlands by local and national actions and international cooperation, as a contribution towards achieving sustainable development throughout the world'. Mangroves are designated as Marine/Coastal Wetlands: I (intertidal forested wetlands) under the Ramsar Convention and, globally, 262 sites are designated, covering an area of 27 million hectares (Ramsar 2012. Under this Convention, the Parties have committed themselves to 'undertake national wetland inventories to support national policy initiatives and site management that ensure the wise use of wetlands in their territories'. However, major weaknesses in the techniques used and management of information (Finlayson 1999; MEA 2005; Rosenqvist *et al.* 2007*b*) led to a further Ramsar resolution in 2005 that aimed to improve wetland inventory, assessment and monitoring through the use of multi-scale approaches that integrated remote-sensing data (Ramsar 2005). To evaluate the ecological outcomes resulting from implementation of the Ramsar Convention, eight indicators of effectiveness are used, of which the indicator of effectiveness 'A', on the status and trends in wetland ecosystem extent, is the most relevant in this context.

Table 1. Indicative facts, highlighting the role of mangroves, the impacts of losses

Global area	Varied estimates spatially and temporally. [6]In 1990, 161 000 km^2, [1]In 2000, 137 760 km^2 in 118 countries with 75% in 15 countries. [5]In 2005, 152 000 km^2. In 2010, 156 000 km^2; 47% of mangroves in Indonesia, Brazil, Nigeria, Australia and Mexico.
Total economic value	[3]Up to US$10 million ha per year, depending on site and concomitant management regimes. [7]US$1.6 billion per year worldwide.
Level of protection	[1]6.9% within the existing protected areas network.
Biodiversity	[8]90% of marine organisms spend part of their life in mangroves. [7]70 species of mangrove across the tropics and subtropics, with highest diversity in Indo-Malesia and Australasia.
Food provisioning	[7,8]Almost 80% of global fish catches are dependent to some extent on mangroves.
Carbon storage	[2]In the tropics, an average of 1023 Mg C ha^{-1} and up to 20 Pg C. Approximately five times more C per unit area compared with other forest ecosystems because of long-term C burial in sediments.
Deforestation rates	[3,4]Between 1% and 2% per year. Global loss of 30–50% over the past half century, with [5]20% (3.6 million ha) lost since 1980, primarily through aquaculture development, deforestation, and freshwater diversion.
Contribution to global anthropogenic CO_2 emissions	[3]Estimated at 0.02–0.12 Pg C $year^{-1}$; second only to fossil-fuel combustion equivalent to 10% of annual emissions from deforestation.
Species loss	[7]Almost 40% of mangrove-dependent animal species considered to be at a higher risk of extinction. Majority of declines in Indo-Malesia and Australasia, with these being centres of diversity.

Sources: [1]Giri *et al.* (2011), [2]Donato *et al.* (2011), [3]Siikamäki *et al.* (2012), [3]World Mangrove Network (2013), [4]MEA (2005), [5]FAO (2007), [6]FAO (2010), [7]Daru *et al.* (2013), [8]Sandilyan and Kathiresan (2012)

The key data requirements to support the Ramsar Convention include maps showing the extent and condition of wetlands (including mangroves), with these addressing the commitments of contracting parties to achieve a 'coherent and comprehensive national and international network' of wetland types. Information on levels of inundation and disturbance within the defined wetland areas is needed, with this also specified as a contribution to a global wetlands inventory by JAXA's K&C initiative. In addition, data on how wetlands are changing as a result of previous policy or management responses are required to assess their effectiveness in relation to the 'conservation and wise use of wetlands'. Such information can then support the ongoing development and adaptation of policy responses (MacKay *et al.* 2009) and also ensure the representation of wetland types within the Ramsar listings.

The Convention on Biological Diversity

The Convention on Biological Diversity (CBD), which came into force in 1993, obliged signatory nations to ensure 'conservation of biological diversity, the sustainable use of its components and the fair and equitable sharing of the benefits arising out of the utilisation of generic resources.' In 2010 in Nagoya, Japan, governments agreed to the Strategic Plan for Biodiversity (2011–2020) and the Aichi Biodiversity Targets as a basis for halting and eventually reversing the loss of biodiversity, with this supported by a joint Ramsar workplan with the CBD (Rosenqvist *et al.* 2007*b*; Ramsar 2012). The CBD also endorsed (through Decision XI/3) the development of a set of essential biodiversity variables (EBVs) (Convention on Biological Diversity 2010) relevant to the derivation of biodiversity indicators, with these designed to harmonise monitoring (Pereira *et al.* 2013). The Biodiversity Indicators Partnership (BIP) is charged with assessing and reporting on the Aichi Target achievement through its suite of indicators for each target.

The Aichi Targets most relevant to mangroves are 5, 7, 10, 11, 12, 14 and 15 (Table 2), with these requiring information on the rate of habitat loss, degradation and fragmentation, actual and future impacts including those associated with climatic change, the extent and condition of mangroves of particular importance for biodiversity and ecosystem services (e.g. for inclusion within protected areas), extinction risk and provision of ecosystem services. The EBVs that require measurement include species populations (abundance and distributions), community composition (taxonomic diversity) and ecosystem structure (Pereira *et al.* 2013). In the latter case, remotely sensed estimates of cover by height and biomass were explicitly stated as a requirement for measurement and scalability. A particular benefit of the use of the JERS-1 SAR, ALOS PALSAR and ALOS-2 PALSAR-2 is that the observations taken in the mid-1990s, late 2000s and mid-2010s respectively and derived layers relating to the EBVs, as generated by the GMW, can assist in reporting on and meeting the Aichi Targets.

The United Nations Framework Convention on Climate Change (UNFCCC)

The UNFCCC is an international treaty signed in 1992 that sought to limit the average global temperature increases and the resulting climate change and to cope with these impacts. The Kyoto Protocol was signed in 1997, which legally bound signatory countries to emission-reduction targets over two commitment periods, namely 2008–2012 and 2013–2020. Within this Treaty, the Clean Development Mechanism (CDM) is one of three operational, flexible and financial mechanisms that were created under the UNFCCC Kyoto Protocol and was developed as a carbon standard in 1997. Under the CDM, credits are generated through emission-reduction projects in the developing world to assist countries with caps on emissions meet their targets. The verified carbon standard (VCS) is a

Table 2. Convention on Biological Diversity (CBD) Aichi Targets of relevance to mangrove ecosystems

No.	Target
Strategic goal B: reduce the direct pressures on biodiversity and promote sustainable use	
5	By 2020, the rate of loss of all natural habitats, including forests, is at least halved and, where feasible, brought close to zero, and degradation and fragmentation are significantly reduced.
7	By 2020, areas under agriculture, aquaculture and forestry are managed sustainably, ensuring conservation of biodiversity.
10	By 2015, the multiple anthropogenic pressure on coral reefs and other vulnerable ecosystems affected by climate change or ocean acidification are minimised, so as to maintain their integrity and functioning.
Strategic goal C: improve the status of biodiversity by safeguarding ecosystems, species and genetic diversity	
11	By 2020, at least 17% of terrestrial and inland water and 10% of coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem services, are conserved through effectively and equitably managed, ecologically representative and well connected systems of protected areas and other effective area-based conservation measures, and integrated into the wider landscapes and seascapes.
12	By 2020, the extinction of known threatened species has been prevented and their conservation status, particularly of those most in decline, has been improved and sustained.
Strategic goal D: enhance the benefits to all from biodiversity and ecosystem services	
14	By 2020, ecosystems that provide essential services, including services related to water, and contribute to health, livelihoods and well being, are restored and safeguarded, taking into account the needs of women, indigenous and location communities, and the poor and vulnerable.
15	By 2020, ecosystem resilience and the contribution of biodiversity to carbon stocks has been enhanced, through conservation and restoration, including restoration of at least 15% of degraded ecosystems, thereby contributing to climate change mitigation and adaption and to combating desertification.

voluntary GHG-reduction program that ensures that carbon credits are real, measurable, additional, permanent, independently verified and traceable, with all projects being listed in an online registry. The UN Reducing Emissions from Deforestation and forest Degradation (REDD+) was also launched in 2008, to assist developing countries build their capacity for reducing emissions through conservation, sustainable use and enhancement of forest carbon stocks. As part of this process, a monitoring, reporting and verification (MRV) system was introduced, which requires countries to respond to a set of requisites to ensure access to international financial mechanisms (Lawrence 2012).

Discussions within the UNFCCC and other international organisations have led to the introduction of Intergovernmental Panel on Climate Change (IPCC) guidelines for quantifying carbon, including within wetland forests and other wetlands. This has arisen out of recognition that ecosystems such as mangroves, and also sea grasses and saltmarshes, represent large reservoirs for carbon, with a significant proportion stored in the organic soil beneath. Indeed, regional studies in the Indo-Pacific region have confirmed that mangrove forests are among the most carbon (C)-rich ecosystems on the planet (Donato *et al.*, 2011) with total (above, below and soil) C density reaching 1000 Mg ha^{-1}.

The rationale behind initiatives such as REDD+ is that, given adequate C prices in the market, the C contained in standing mangroves would provide higher financial returns than the profits foregone by destroying or degrading mangroves for alternatives uses (Murray *et al.* 2012). This idea is particularly applicable in developing countries where opportunity costs are low and the mangrove C-mitigation potential is high. This is the case in several tropical countries where alternative uses to mangroves are mostly related to agriculture or wood collection. Through win–win financial mechanisms such as REDD+, tropical countries have the opportunity to contribute to the conservation of ecologically valuable mangrove ecosystems, thus keeping the benefit of their present and future ecological services, while promoting clean development and contributing to the international effort of curbing human-driven climatic changes. REDD+ also acknowledges the importance of creating social and economic safeguards against factors that might jeopardise food security in developing countries, whose populations mainly rely on natural resources for their subsistence. Presently, REDD+ projects are generating only C credits on the voluntary market, although some important decisions and key milestones have been made at the 19th Conference of Parties (COP), including that 'the framework for results-based payments for REDD+ is now in place' and that 'countries that have the required elements for REDD+ (i.e. a national REDD+ strategy, a national forest monitoring system, a forest reference emission level and/or forest reference level) can begin to access financing from various sources on the basis of an agreed metric: tonnes of CO_2-equivalent'.

The Intergovernmental science-policy Platform on Biodiversity and Ecosystem Services (IPBES)

IPBES is an intergovernmental body, with 115 member states, which was established in 2012. The IPBES aims to bridge the gap between science and policy in the fields of biodiversity and related ecosystem services. The initial work program was adopted at the December 2013 plenary session, and Objective 4, for the period 2014–2018 seeks to 'strengthen the knowledge–policy interface on the global dimensions of changes in biodiversity and ecosystem services'. As a contribution

to this objective, maps of the status and trends of mangroves and the identification of drivers and pressures are needed, thereby enabling the effectiveness of policy response to be monitored.

Convention on the Conservation of Migratory Species of Wild Animals (CMS)

The CMS is an intergovernmental treaty dedicated to the conservation of migratory species, their habitats and migration routes. It was signed in 1979 and currently has 199 member states. To tailor to specific needs of species or habitat conservation, the CMS uses several instruments for implementation, such as legally binding agreements (e.g. the Africa–Eurasian Waterbird Agreement; AEWA), and less formal Memoranda of Understanding (MoU) (e.g. the Dugong MoU and Western African Aquatic Mammals MoU). Within the context of the CMS, information on changes in the extent and biophysical properties of mangroves is essential, given the dependence of the species covered under these on mangroves during all or part of their lifecycle (Heinsohn *et al.* 1979; Martin and Finch 1995).

Regional, national and corporate examples

On regional and national levels, there is a wide range of needs relating to mangroves that involve a wide range of authorities. These include up-to-date and standardised outputs on the extent, status and change of mangroves, which would benefit the following:

(1) The MRV element of a country's 'Readiness Preparation Plan' to engage in the UN-REDD+ process, among other multilateral programs (e.g. the Forest Carbon Partnership Facility (FCPF) and the Forest Investment Program (FIP)).
(2) The Regional Partnership For Marine And Coastal Conservation In West Africa (PRCM) strategic line of Action 3 'analysis, prevention and management of risks and challenges in the coastal and marine area' of the 2012–2016 strategy (PRCM 2012).
(3) Indonesia's 'One Map' initiative, streamlining the use of geospatial data across all government agencies and supporting the National Forest Monitoring System.
(4) Global Monitoring for Environment and Security (GMES) & Africa, an ongoing initiative that aims to extend the GMES (now Copernicus) services and products in Africa. In particular, the Marine and Coastal Areas thematic component clearly identifies the need for comprehensive monitoring of mangrove areas in the African continent.
(5) National mangrove-based coastal defence strategies.
(6) Wetland inventories that need to be established and maintained in countries where mangroves occur.

The Global Aquaculture Alliance (GAA) is a corporative example where information on mangroves and their replacement land covers is also needed. The GAA was established in 1997 as a non-profit NGO and it develops the 'best aquaculture practices' (BAP) performance standards addressing corporate social and environmental responsibility in a voluntary certification program for aquaculture facilities. The Finfish and Crustacean Farms BAP standards address mangroves in 'BAP Standard 4: Mangrove and Wetlands Conservation'. To monitor and report on this implementation for BAP-certified shrimp farms, the GAA requires regular and up-to-date information on the status and extent of mangroves.

To address the requirements of the diversity of initiatives and projects underway, information on the extent of intact, regenerating and degraded mangrove forests is required, together with estimates of their biomass (C) and changes in these measures over time, with associated measures of uncertainty. Knowledge of the causes and consequence of change and the capacity to protect, restore and sustainably manage mangrove forests is also needed. For these purposes, a reliable and consistent monitoring system becomes essential.

Addressing the needs

In recognising the urgency for more information on mangroves globally, several initiatives have been forthcoming over the past two decades. Improving knowledge of the extent of mangroves for reference years has been the focus of several international efforts. Spalding *et al.* (1997) produced the first global product by using a combination of existing maps, ground surveys and remotely sensed data; UNEP–WCMC released an updated 'World Atlas of Mangroves' in 2010, developed from a wide range of sources ranging from point-based measurements to maps (Spalding *et al.* 2010); and Giri *et al.* (2011) generated an updated global mangrove baseline of the extent, with this based primarily on the Landsat sensor-data archive.

The generation of these baseline maps of the extent provides a critical tool for conservation efforts and management of mangroves and could be used to quantitatively assess some of the ecosystem services they provide (Table 3). However, several initiatives have recently sought to obtain and use more specific information about mangrove services. In particular, BirdLife International initiated the 'Mangrove Conservation Alliance' in 2011, which is aimed at conserving and sustainably managing mangrove ecosystems; Wetlands International conceived the 'Mangrove Capital' program, which aims to bring the values of mangroves to the fore and provide the knowledge and tools necessary for the improved management of mangrove forests; the International Tropical Timber Organization (ITTO) funded the establishment of an international network for the conservation and sustainable use of mangrove genetic resources and established a Global Mangrove Database and Information System (GLOMIS), a searchable database of scientific literature relating to mangroves and institutions and scientists working on all aspects of mangroves.

The United Nations Environment Program (UNEP) Blue Carbon Initiative, a coordinated global partnership program, was created in response to the need of coordinated efforts to address issues relating to climate-change impacts on coastal ecosystems and also their values, including in relation to C sequestration. The Initiative seeks to further research and develop financial and policy platforms for restoring and conserving coastal ecosystems (e.g. mangroves, seagrasses and saltmarshes). These platforms include internationally applicable and acceptable measurement standards to support financial platforms (e.g. MRV). For this purpose, a reliable and consistent monitoring system becomes essential.

Despite these efforts, there is still no system that routinely and consistently provides timely and accurate information on

Table 3. Common information requirement on mangroves that can be addressed using remote-sensing technologies and spatial-analysis techniques

Information requirements	Primary users	Primary reasons
Extent	Policy Land holders	Define areas for conservation and exploitation
Quantitative summaries of economic, social, cultural and environmental values	Policy	Ensure maintenance or enhancement for general well being
Food quantity (actual and predicted; fish, game, fruits, grain)	Local populations Commercial Local/national government	Ensure continued provision of food for populations
Fibre and fuel amounts	Local populations Commercial	Determine potential resource and/or ensure sustainable use of mangrove habitats
Biochemical and genetic material	Commercial Policy	Ensure maintenance of habitat condition and floral and faunal species diversity
Habitat structure and floristic composition	Conservation Science community	Evaluate condition of breeding sites for faunal species (invertebrates, fish, birds) and pollinators
Extent and rates of mangrove removal	Conservation Policy Science community	Quantify area, trends in area loss, causes and consequences
Regeneration and restoration rates	Conservation Commercial Science community	Highlight expansion, areas of potential exploitation, causes and areas used sustainably
Areas capable of supporting mangroves	Conservation Policy	Identify potential areas for restoration
Extent and arrangement of mangrove zones	Conservation	Evaluate role and potential for coastal protection (e.g. in areas vulnerable to storm surges or tsunamis)
Response to sea level fluctuations	Policy Science community	Understand implications of global climate change
Erosion and accretion	Land managers	Indicate sites of mangrove loss and actual or potential colonisation
Changes in water and soil quality (e.g. salinity, sediment loads, pollutants, acid sulfate)	Land managers Local government	Indicate degradation state and allow ameliorative action to be taken before long-term damage is inflicted
Volume, biomass, carbon stocks and cycling	Policy Science community Commercial	Quantify existing resource and identify current and potential carbon accumulation capacity of mangroves

the status and trends of mangroves at regional to global scales. Realistic quantitative measures of the economic values of mangroves are also needed as is a commitment to ensure that these are not undervalued in both private and public decision making in relation to their use. Agreement on definitions and more consistent use of methods in space and over time is essential to ensure objective and reliable estimates of the extent, tree species diversity and C losses and gains within and among regions.

The contribution of L-band SAR

Mangrove extent

Although global maps of the extent of mangroves have been generated from optical remote-sensing data, a limitation is that several (e.g. Spalding *et al.* 1997, 2010) used data gathered by a range of organisations and from a variety of sources, of which many had limited or no repeatability. Furthermore, mapping was often necessarily undertaken using data from different years because cloud cover often prevented observations within a single period. The map of Giri *et al.* (2011) incorporated an element of repeatability by using freely available satellite sensor data but the reliance on optical data prevented routine monitoring because of gaps in coverage. For these reasons, such products cannot be easily updated for the purpose of consistent and regular monitoring.

Despite these limitations, baseline maps of the extent of mangroves generated from optical remote-sensing data need to be integrated because of the difficulty in generating these from the L-band SAR data themselves, even though the issues surrounding cloud cover are overcome. In particular, the generation of baseline maps of the extent of mangroves from L-band SAR data alone is limited where mangroves adjoin forests (including plantations) and shrublands because of similarities in backscatter (Fig. 1). Where mangroves are backed by non- or sparsely vegetated surfaces (e.g. sand or mud flats, samphires) on their landward margins, these can generally be discriminated and mapped because of their higher backscatter at both L-band HH and HV polarisation, although confusion with high-biomass mangroves with extensive prop root systems may also occur because of the low backscatter from these forests (Held *et al.* 2003; Lucas *et al.* 2007). One solution is to confine the mapping of mangroves to areas where they have a higher probability of occurrence. For example, mangroves are unlikely to occur on sloping ground, close to saline water or at elevations above sea level exceeding 10 m. The existing baseline maps of the extent of mangroves can be used to determine, at a subregion level, statistics on their distribution relative to environmental

variables and, hence, the probability of occurrence. Therefore, the approach adopted in the GMW is to use these existing baselines to initially establish where mangroves occur within a reference year and then refine these baselines based on changes within the areas they are most likely to occur and as observed and quantified using temporal L-band SAR.

AGB and structure

Once a baseline of the extent of mangroves is established, estimates of mangrove canopy height, AGB and BGB (e.g. derived from allometric equations that use tree size or ratios describing the relationship between AGB and BGB components and, subsequently, C storage) can be generated within the mapped area (e.g. Comley and McGuinness 2005). These estimates of AGB are already available for several regions (see Fig. 2), including Africa (Fatoyinbo and Simard 2013; Fatoyinbo *et al.* 2008), Florida in the United States (Simard *et al.* 2006) and Colombia (Simard *et al.* 2008). Most have been generated using SRTM data acquired in 2000 and, hence, the estimates are compatible with the baseline estimate of the extent of mangroves generated by Giri *et al.* (2011), primarily on the basis of Landsat sensor data from 2000.

The estimates of AGB can be improved further by integrating ALOS PALSAR data. For example, Omar *et al.* (2014) observed an asymptotic increase in L-band HV backscatter with AGB in commercial mangrove forests in Malaysia, although saturation in the relationship was evident. Focusing on Australian mangroves, Lucas *et al.* (2007) and Held *et al.*

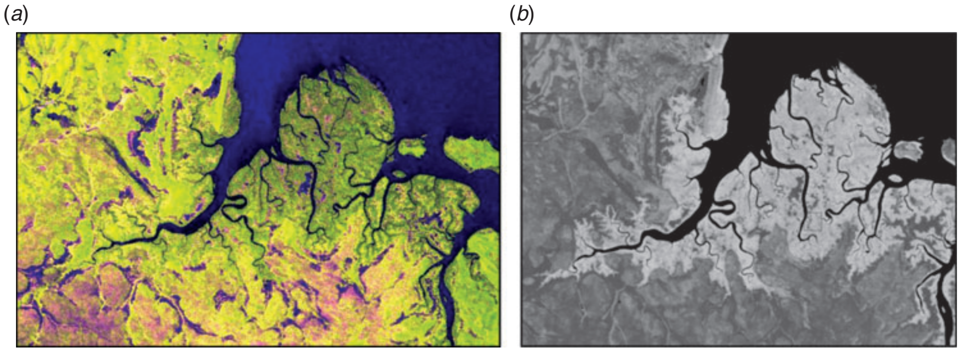

Fig. 1. Mangroves in Cape York, Australia, observed by (*a*) the ALOS PALSAR, with HH, HV and the ratio of HH to HV displayed in RGB. (*b*) The same mangroves can be discriminated from adjoining forests by the higher Landsat-derived foliage projective cover (FPC; often >90%).

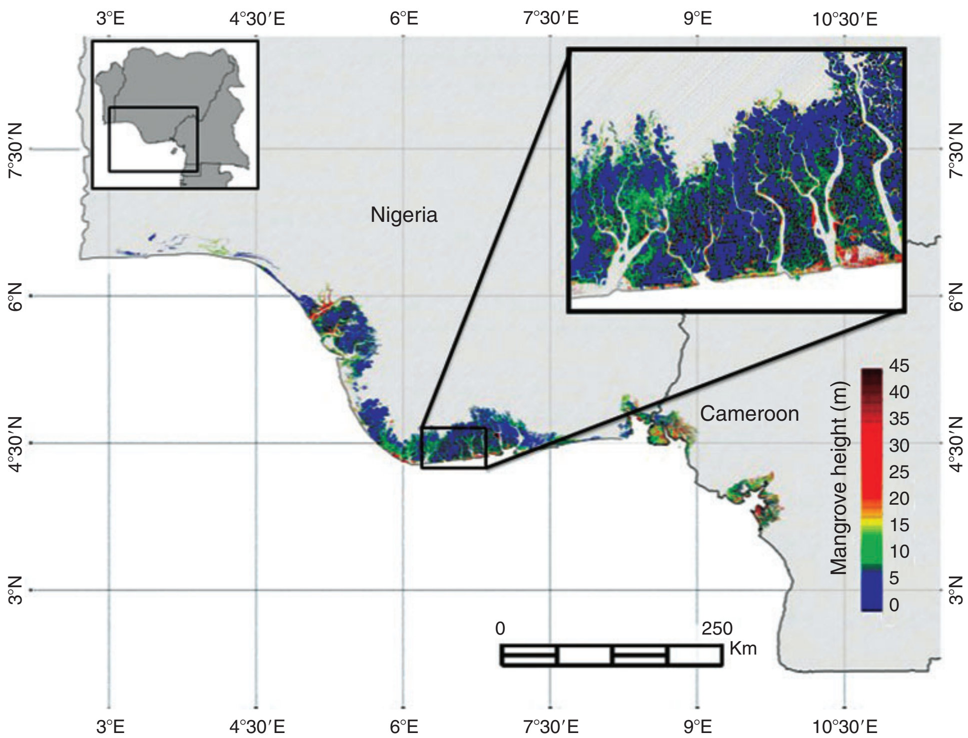

Fig. 2. Map of mangrove canopy height, derived from shuttle radar topographic mission (SRTM) data.

(2003) noted, however, that where extensive prop root systems occurred, the 'typical' asymptotic increase in L-band backscatter with AGB was disrupted at ~120 Mg ha^{-1} (approximating to ~8–12 m in height), with the backscatter then decreasing in proportion to increasing AGB to over 400 Mg ha^{-1} (Lucas *et al.* 2007). By exploiting these backscatter characteristics of mangroves, new mapping techniques have been developed that exploit mangrove canopy-height models (CHMs) and L-band SAR backscatter to differentiate between mangroves with and those without prop root systems (Fig. 3; Lucas *et al.* 2007). Because information on mangrove structure is also obtained, these data can be used to measure relative stages of regeneration and colonisation. The broad species composition can be inferred because only a few species (e.g. *Rhizophora*) support such structures. However, an approach adopted here is to also use the range-map data from the IUCN Red List database, with this indicating where the different mangrove species are distributed globally on a quarter-degree square basis (Fig. 4).

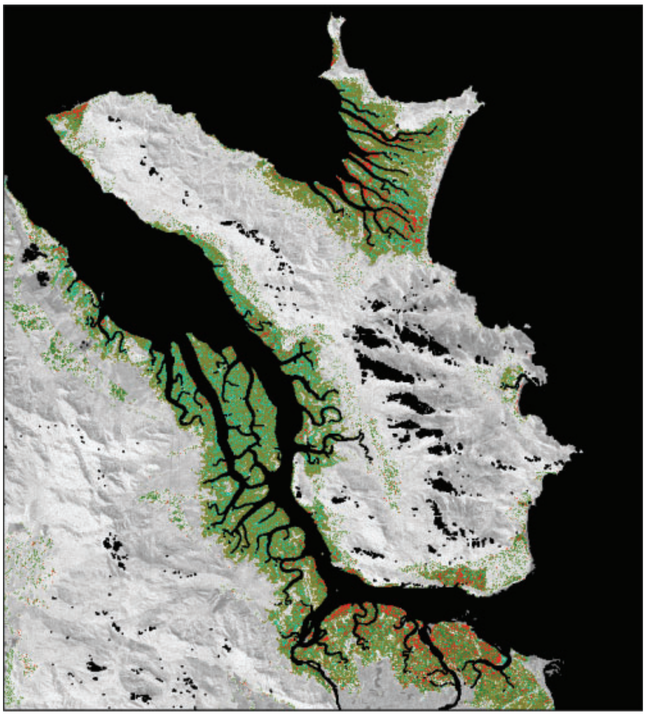

Fig. 3. Classification of mangroves, Hinchinbrook Island, Queensland, Australia showing areas of low (pale green) and high (olive green) biomass forests without prop roots, and high biomass forests with prop roots (red).

Detection of change

On the basis that the global map of Giri *et al.* (2011) from 2000 is used because of its time compatibility with the SRTM, changes within and from the mapped area can be quantified using the available L-band SAR data. Through this process, revised baselines of the extent of mangroves can be generated for each year of observation on the basis of observed expansion into sea areas and, where detectable, inland colonisation, although the latter is more difficult because of similarities in backscatter with forest vegetation. Because coverage of the L-band SAR data is systematic and global, wall-to-wall mapping within selected years (e.g. 1995, 2007, 2010) and change detection is also achieved, overcoming the difficulties experienced by the FAO (2007) in compiling spatial and statistical datasets from disparate sources and from different years. Within the baseline area, changes associated with deforestation or degradation, whether natural or anthropogenic, can be detected on the basis of

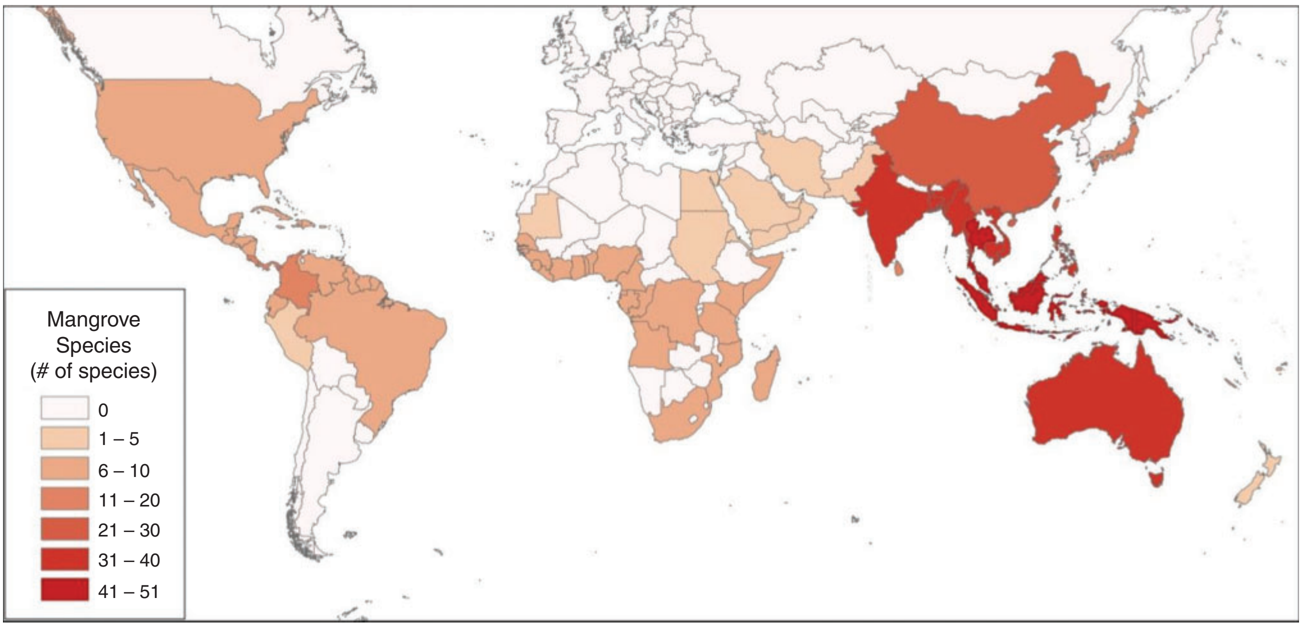

Fig. 4. Mangrove species richness by country (IUCN 2010).

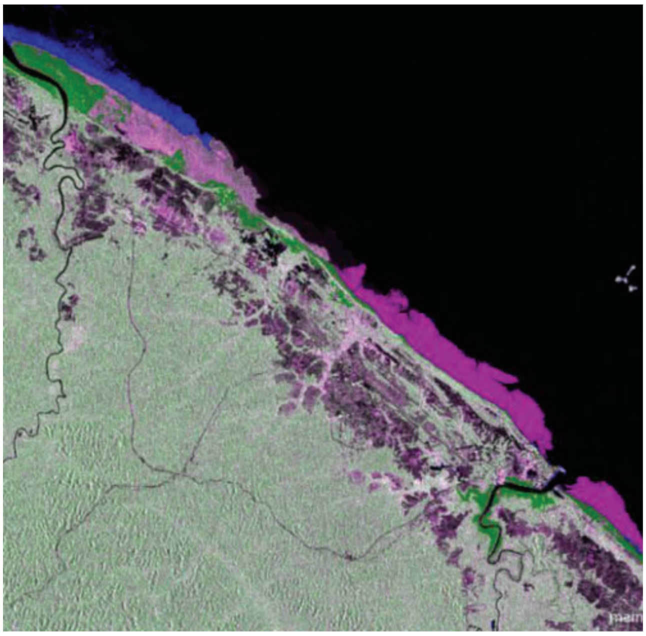

Fig. 5. Changes in the extent of mangroves in French Guiana observed through time-series comparison of Japanese earth resources (JERS-1) SAR and the advanced land-observing satellite (ALOS) phased array L-band SAR (PALSAR) data from 1996 to 2010, showing areas of loss (magenta) and colonisation (blue). The areas of stable mangroves (dark green) were mapped by Giri *et al.* (2011).

knowledge of the characteristics of changed areas (e.g. low backscatter in areas deforested) or comparison of backscatter values over the period of the time-series. A useful approach is to focus monitoring only on areas into which mangroves can potentially grow into on the basis of maps of suitable ecosystems (e.g. mudflat) or areas defined on the basis of, for example, altitude, slope and distance to the sea. By referencing the JERS-1 SAR data, baselines of extent can potentially be backdated to the mid-1990s.

The ability to detect change in the extent of mangroves depends on the nature of the change processes occurring. In many regions, mangroves have remained relatively undisturbed for decades either because of their inaccessibility or stringent protection (e.g. within national parks), which is well implemented in countries such as the USA and Australia. Mangroves in these regions can nevertheless be used as reference to assess changes associated with climatic and sea-level fluctuations. Such processes often take place over long periods of time and, hence, decadal observations are needed, with these being able to be obtained using the L-band data archive. Natural events rather than processes can also lead to significant change, with extensive tracts of mangroves often lost through damage by tsunamis (e.g. Indonesia) or tropical storms (e.g. the Gulf of Mexico). Lightning strikes are also prevalent in many regions, particularly where mangroves are dominated by *Rhizophora* species, and can temporarily alter the structure.

In other regions, events and processes occurring on the land areas can exacerbate natural changes in the extent and dynamics of mangroves. This is observed in French Guiana where vast water flows and heavy sediment loads discharged from the Amazon (partly through deforestation activities) lead to highly variable changes in the patterns of accretion and erosion (Allison and Lee 2004). The deposition of sediment provides new land to be colonised by mangroves, spurring a subsequent advance in the extent of mangroves, whereas the erosion of sediment removes soft substrate and causes a retreat. This is exemplified in Fig. 5, where the comparison of JERS-1 SAR L-band HH data acquired in 1996 and ALOS PALSAR HH data acquired in 2007 and 2010, respectively, showed substantial losses and gains in mangrove cover along the coastline. The classification of change is with respect to the baseline of the extent of mangroves mapped by Giri *et al.* (2011).

In many developed and developing countries, extensive tracts of mangroves have or are being transformed for both commercial and, to a lesser extent, subsistence agriculture and fisheries, with this leading to complete and often largely irreversible loss (Giri *et al.* 2008; Polidoro *et al.* 2010; Guimarães *et al.* 2010). Losses associated with aquaculture have been spurred by a global demand for fish and shellfish that has more than doubled in the past 15 years, with such practices now accounting for the production of over 25% of all fish for human consumption (Naylor *et al.* 2000). This practice has been particularly prevalent in South-east Asia and is exemplified in eastern Kalimantan (Fig. 6) where vast areas of mangrove have been converted to aquaculture. The losses have been exacerbated by the development of the coastline to accommodate offshore oil exploration. In this example, most of the mangroves were relatively intact in the mid-1990s when observed by the JERS-1 SAR, whereas they were largely cleared by 2006, at the time of the first ALOS PALSAR acquisitions. In many regions, clearance of mangroves for marine, urban and infrastructure development (e.g. to support tourism) can be observed within the colour composite images of L-band SAR, with this also being evident when dense time-series of Landsat sensor data are compared.

The changes in mangroves are highly diverse but, in many cases and as indicated, can be observed within the time-series of Japanese L-band SAR data, largely because of cloud-free observations over extended time periods. Many of the changes are most notable when JERS-1 SAR data from the mid-1990s are included within the time-series. The patterns of expansion and retreat, including within previously established baselines of the extent of mangroves, can also be interpreted to provide a unique insight into the causes and consequences of change.

Validation

In any system for monitoring, past and ongoing validation of extent and change is essential. Given the difficulty in obtaining field data of sufficient coverage, historical or current very high-resolution (VHR) airborne or space-borne remote-sensing data are best suited for this purpose. In the validation of change, the main variables to consider are the extent, structure and AGB of mangrove plants, recognising that the biomass of the below-ground components is also significant, but cannot be mapped directly. Observations or classifications of VHR data from sensors operating in most modes (multispectral, LIDAR, SAR) can be utilised for validation. Mangroves can generally be

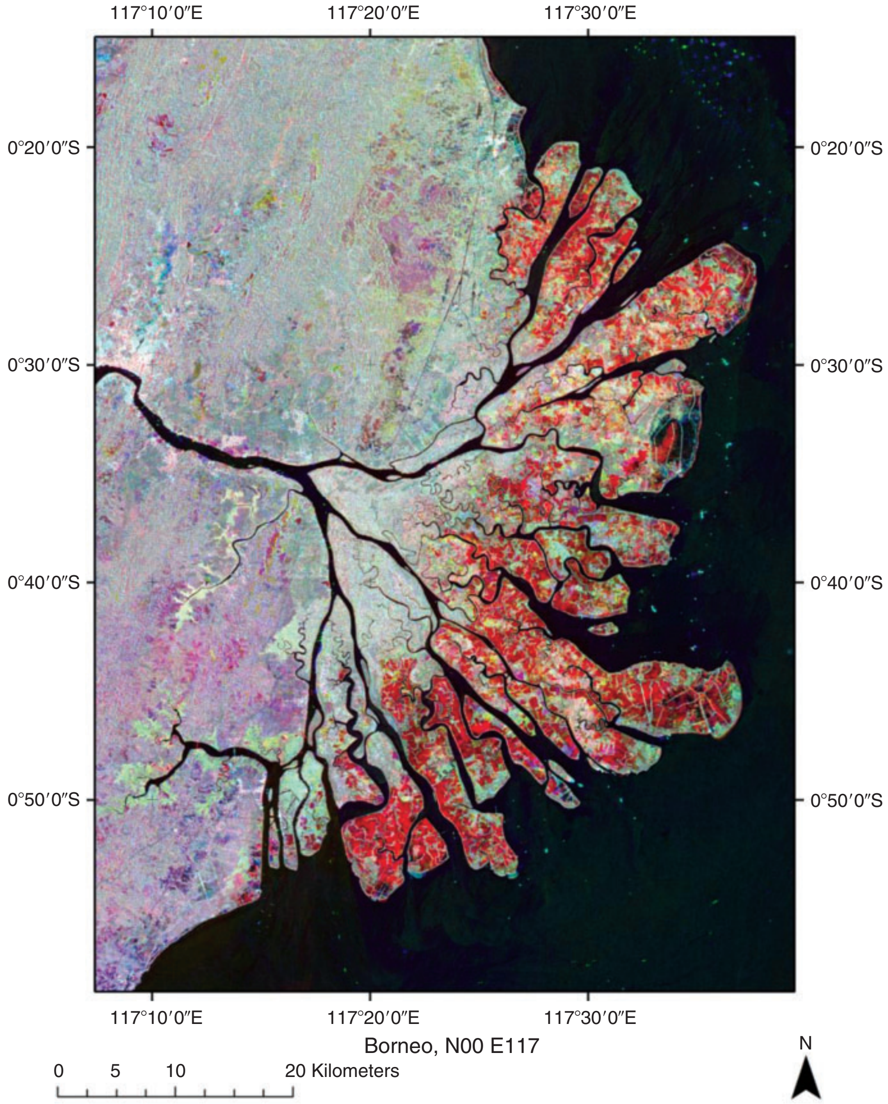

Fig. 6. Japanese earth resources (JERS-1) SAR (1996) and the advanced land-observing satellite (ALOS) phased array L-band SAR (PALSAR) (2007, 2010) L-band HH colour composite (1996, 2007 and 2010 in RGB), showing extensive loss of mangroves as a consequence of aquaculture and oil exploitation in East Kalimantan. Reductions in the extent of mangroves are indicated in red, whereas gains (relatively minor) are indicated in green and blue.

better discriminated from adjoining vegetation covers and non-vegetated surfaces within VHR data on the basis of spectral (spectral reflectance, SAR backscatter) or height differences. Texture measures can also be exploited, given the homogeneity of mangrove canopies relative to many other forest types. Even when the extent of mangrove forest remains constant, its structure and biomass may change. For this reason, estimates of canopy cover, height and AGB of mangroves obtained primarily from stereo imagery (Lucas *et al.* 2002; Mitchell *et al.* 2007), lidar and/or InSAR are required. Validation of change also needs to be achievable, particularly if undertaken at a global level. Hence, approaches such as systematic stratified sampling within and among regions and according to distributions of mangroves (e.g. by type) are needed. In the future, validation activities need to take place at the same time or close to observations by the ALOS-2 PALSAR-2 to assess performance within a mangrove monitoring system. In this regard, considerable potential exists for using the additional resource of crowd-sourced information for validation, particularly given that the local populations often cause ongoing changes in mangroves through their activities, or are affected by these.

A complementary approach to validating change is to use the dense time-series of Landsat sensor data, which have recently been released by the United States Geological Survey (USGS). This is exemplified by Fig. 7, which highlights how the changes in French Guiana observed by comparing the JERS-1 SAR and ALOS PALSAR data are also evident within the Landsat time-series. A particular benefit of using both

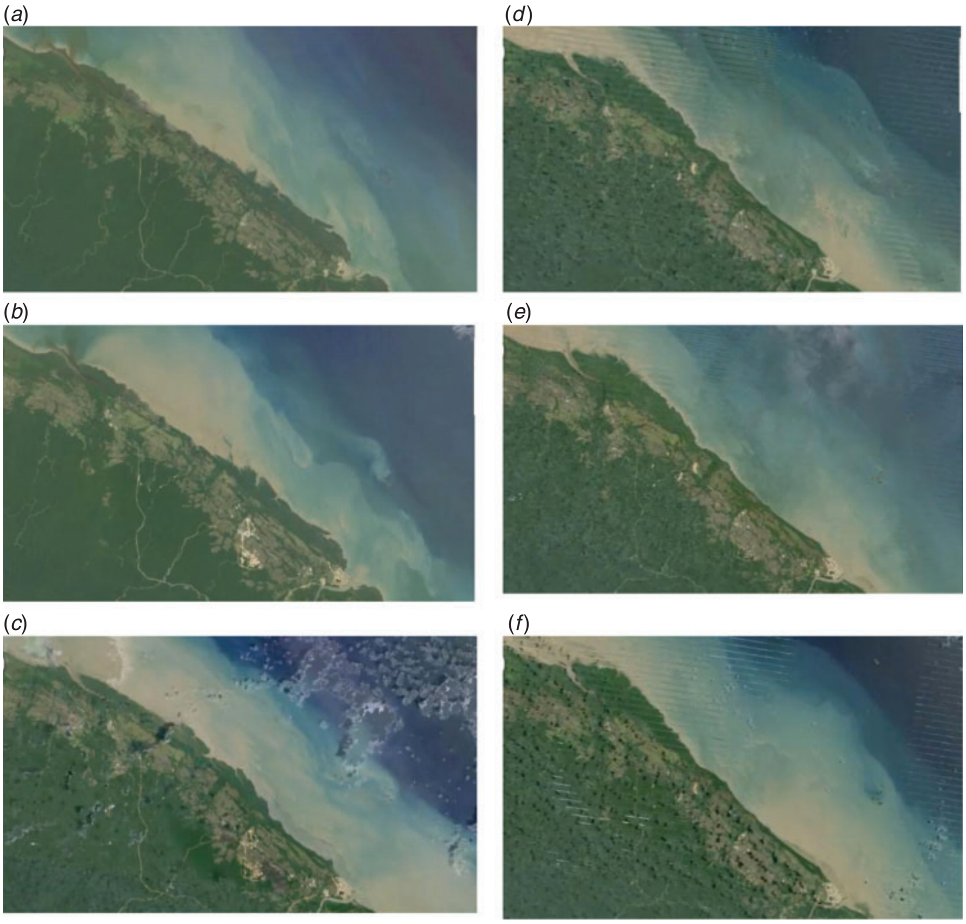

Fig. 7. The changing extent of mangroves observed in French Guiana in (*a*) 1984, (*b*) 1990, (*c*) 1998), (*d*) 2007, (*e*) 2008 and (*f*) 2010. The patterns observed correspond to those mapped in Fig. 5.

time-series is that the potential causes (e.g. deforestation within catchments upstream or clearing for aquaculture or saltpans) can be suggested and consequences (e.g. losses, increased accretion of sediments or forest dieback) observed. Using dense time-series datasets of Landsat sensor data, the overall accuracy of classification of change exceeded 90% (losses and gains in the seaward direction) for nine sites, including French Guiana (N. Thomas, R. Lucas and T. Itoh, unpubl. data), although losses and colonisation at the landward margins were more difficult to quantify.

Discussion and conclusions

The GMW conducted as part of JAXA's K&C initiative aims to support global monitoring of mangroves by using time-series of JERS-1 SAR, ALOS PALSAR and ALOS-2 PALSAR-2. For this, the use of existing baselines of the extent of mangroves generated from other data sources (e.g. Landsat) is essential because of the difficulty in discriminating mangroves from adjoining land covers (particularly forests) by using the L-band SAR data themselves. The global maps of Giri *et al.* (2011) are preferred because of time-compatibility with the SRTM global-elevation dataset. The baseline mapping can also be continually refined and updated using the available SAR data. The primary benefits of using Japanese L-band SAR with the GMW are as follows:

(1) systematic, temporally consistent and cloud-free observations of mangroves across their global range over several decades are available and will continue to be provided on at least an annual basis; as such, these data provide capacity for a wall-to-wall rather than sample-based approach for mapping and monitoring;
(2) these data are sensitive to the three-dimensional structure and AGB of vegetation and changes in these; and
(3) the historical data have been combined by JAXA into global and regional L-band HH mosaics for the mid-1990s (1994–1998) and HH and HV mosaics for 2007, 2008, 2009 and 2010, which can be augmented using data to be acquired by the ALOS-2 PALSAR-2 from 2014; as a consequence, wall-to-wall rather than sample-based monitoring can take place and global baselines of extent can be refined for specific years.

Although other sensors (e.g. X- and C-band or optical) have provided and continue to provide data that can contribute observations of mangroves, the L-band SAR fulfils more of the requirements for ongoing and routine monitoring at a global level (Table 4).

Table 4. Strengths and weaknesses of global observing satellite for mangrove characterisation, mapping and monitoring
See text for explanation of the abbreviations

	L-band SAR			C-band SAR	X-band SAR	Optical sensor	
	JERS-1 SAR	ALOS PALSAR	ALOS-2 PALSAR-2			Landsat	SPOT/ASTER
Cloud-free observations	•	•	•	•	•		
Sensitivity to foliage components				•	•	•	•
Sensitivity to larger woody components	•	•	•				
Sensitivity to woody biomass	•	•	•				
Global acquisitions	•	•	•	•	•	•	•
Systematic acquisitions	•	•	•			•	
Archival data	•	•		•		•	•

Within the baselines of the extent of mangroves established, spatial estimates of structural attributes and AGB have already been established for some regions (Simard *et al.* 2006, 2008; Fatoyinbo and Simard 2013) and can be extended globally and also refined using the ALOS PALSAR data themselves (e.g. by distinguishing between high-biomass mangroves with and those without prop root systems). Using these data, estimates of C and structural change can be quantified for areas where change is detected by using the Japanese SAR data. The tree species composition of affected mangroves can also be discerned through reference to the IUCN mapping.

A key requirement of the GMW is the provision of data, both historical and current, for validating maps of the extent, retrieved biophysical properties and the change of mangroves. For this purpose, airborne SAR and LIDAR data should be exploited where possible because of the ability of the former to penetrate cloud and the capacity to retrieve structure and AGB from both. Consideration should also be given to the use of crowd-sourced information during the period of the ALOS-2 PALSAR acquisitions. However, the use of the dense time-series of Landsat sensor data is advocated for validation at a regional to global scale, given the complementarity and consistency of information provided.

The GMW is intended to support the range of activities that are ongoing to ensure conservation and sustainable use of mangroves, including through policy development, implementation and assessment. For most policies, maps of the extent, structure, species composition and biomass are required and the GMW can contribute to such provision, particularly following launch of the ALOS-2 PALSAR-2 where the intention is provide up-to-date change mapping as and when data are acquired. Information to assess the impacts of past and current policies and inform the likely consequences of future actions can also be provided. A previous limitation of using Japanese SAR data has been the availability and cost. In the GMW, the intention is to make the baseline and change maps available to the wider community such that these can be used to determine past extents but also increase awareness of current changes associated with specific events (e.g. deforestation) or processes (e.g. erosion or colonisation following accretion).

In many of the regions where mangroves occur, wetlands are also prevalent and, although a larger area would need to be imaged in some cases, the GMW can act as demonstrator and also precursor to the Ramsar Global Wetland Observing System (GWOS). Such a system would also benefit from the use of the time-series of Japanese SAR data and particularly the wide swath coarser-resolution (100 m) ScanSAR data, which will be observing at both HH and HV polarisation when the ALOS-2 PALSAR-2 is launched. These same data would also benefit the monitoring of forest and non-forest areas, particularly in tropical regions.

Mangroves form an integral but often poorly recognised component of coastal ecosystems; however, in the long-term, the environmental, social and economic benefits of retaining mangroves far outweigh those associated with replacement land covers. Hence, the implementation of the GMW will inform on the changing extent and dynamics of mangroves and their contribution to, for example, ecosystem services. However, such as system requires a high level of coordination and investment through a range of mechanisms agreed by national and international governments, businesses and organisations.

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