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RESEARCH PAPER

Status and distribution of mangrove forests of the world using earth observation satellite data

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ABSTRACT

Aim Our scientific understanding of the extent and distribution of mangrove forests of the world is inadequate. The available global mangrove databases, compiled using disparate geospatial data sources and national statistics, need to be improved. Here, we mapped the status and distributions of global mangroves using recently available Global Land Survey (GLS) data and the Landsat archive.

Methods We interpreted approximately 1000 Landsat scenes using hybrid supervised and unsupervised digital image classification techniques. Each image was normalized for variation in solar angle and earth–sun distance by converting the digital number values to the top-of-the-atmosphere reflectance. Ground truth data and existing maps and databases were used to select training samples and also for iterative labelling. Results were validated using existing GIS data and the published literature to map 'true mangroves'.

Results The total area of mangroves in the year 2000 was 137,760 km^2 in 118 countries and territories in the tropical and subtropical regions of the world. Approximately 75% of world's mangroves are found in just 15 countries, and only 6.9% are protected under the existing protected areas network (IUCN I-IV). Our study confirms earlier findings that the biogeographic distribution of mangroves is generally confined to the tropical and subtropical regions and the largest percentage of mangroves is found between 5° N and 5° S latitude.

Main conclusions We report that the remaining area of mangrove forest in the world is less than previously thought. Our estimate is 12.3% smaller than the most recent estimate by the Food and Agriculture Organization (FAO) of the United Nations. We present the most comprehensive, globally consistent and highest resolution (30 m) global mangrove database ever created. We developed and used better mapping techniques and data sources and mapped mangroves with better spatial and thematic details than previous studies.

Keywords

Global distributions, image processing, Landsat, mangrove, mapping, remote sensing.

INTRODUCTION

Mangrove forests are distributed in the inter-tidal region between the sea and the land in the tropical and subtropical regions of the world between approximately 30° N and 30° S latitude. Their global distribution is believed to be delimited by major ocean currents and the 20° C isotherm of seawater in winter (Alongi, 2009). The forests are typically distributed from mean sea level to highest spring tide (Alongi, 2009). They grow in harsh environmental settings such as high salinity, high temperature, extreme tides, high sedimentation and muddy anaerobic soils. The current estimate of mangrove forests of the world is less than half of what it once was (Spalding *et al.*, 1997; Spiers, 1999) and much of what remains is in a degraded condition

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(UNEP, 2004; MAP, 2005). Coastal habitats across the world are under heavy population and development pressures, and are subjected to frequent storms.

The continued decline of the forests is caused by conversion to agriculture, aquaculture, tourism, urban development and overexploitation (Alongi, 2002; Giri *et al*., 2008). About 35% of mangroves were lost from 1980 to 2000 (MA, 2005), and the forests have been declining at a faster rate than inland tropical forests and coral reefs (Duke *et al*., 2007). Relative sea-level rise could be the greatest threat to mangroves (Gilman *et al*., 2008). Predictions suggest that 30–40% of coastal wetlands (IPCC, 2007) and 100% of mangrove forests (Duke *et al*., 2007) could be lost in the next 100 years if the present rate of loss continues. As a consequence, important ecosystem goods and services (e.g. natural barrier, carbon sequestration, biodiversity) provided by mangrove forests will be diminished or lost (Duke *et al*., 2007).

Mangrove forests are among of the most productive and biologically important ecosystems of the world because they provide important and unique ecosystem goods and services to human society and coastal and marine systems. The forests help stabilize shorelines and reduce the devastating impact of natural disasters such as tsunamis and hurricanes. They also provide breeding and nursing grounds for marine and pelagic species, and food, medicine, fuel and building materials for local communities. Mangroves, including associated soils, could sequester approximately 22.8 million metric tons of carbon each year. Covering only 0.1% of the earth's continental surface, the forests account for 11% of the total input of terrestrial carbon into the ocean (Jennerjahn & Ittekot, 2002) and 10% of the terrestrial dissolved organic carbon (DOC) exported to the ocean (Dittmar *et al*., 2006). The rapid disappearance and degradation of mangroves could have negative consequences for transfer of materials into the marine systems and influence the atmospheric composition and climate.

Research need and objectives

Despite their importance and significance, our understanding of the present status and distributions of mangrove forests of the world is inadequate. Current estimates of the total area of global mangroves ranges from 110,000 to 240,000 km^2 (Wilkie and Fortune, 2003; FAO, 2007). Earlier global land-cover initiatives failed to map mangrove areas with sufficient detail because satellite data with coarse spatial resolution (e.g. 1 km) were used (Giri *et al*., 2007). The estimate of the Food and Agriculture Organization (FAO) of the United Nations is based on a compilation of disparate and incompatible geospatial and statistical data sources and does not provide spatial information with sufficient detail (Wilkie and Fortune, 2003; FAO, 2007). Global estimates are also computed using published literature (Alongi, 2002). These estimates are inconsistent across space and time. While local studies to map mangroves are abundant, they do not cover the entire world and use different data sources, classification approaches and classification systems.

Even with the availability of > 35 years of moderate-resolution satellite data (i.e. Landsat) and with a distinct signature of mangrove forests in the visible and near-infrared portion of the electromagnetic spectrum, mapping of mangrove forests at this resolution at the global scale has never been attempted. Cost and computing facilities have been the primary limitations to using Landsat data for global studies. With the availability of free Global Land Survey (GLS) data, the opening of the Landsat archive and improvements in computing facilities, global mapping is now possible. Global data on the extent and conditions of mangrove forests could provide critical information needed for policy-making and resource management. The main objective of this research is to use state-of-the-art remote sensing to prepare a global map of the mangrove forests of the world at 30-m resolution.

MATERIALS AND METHODS

We used the GLS data for 2000 supplemented by Landsat imagery available from the US Geological Survey (USGS) archive to prepare the first global map of the mangrove forests of the world. The GLS is a global dataset of Landsat 30-m resolution satellite imagery prepared in partnership between the USGS and the National Aeronautics and Space Administration (NASA) in support of the US Climate Change Science Program (CCSP), Group on Earth Observations (GEO) and the NASA Land-Cover and Land-Use Change (LCLUC) Program (Gutman *et al*., 2008). The GLS 2000 mosaics were prepared using images acquired from 1997 to 2000. We used Landsat imagery from the USGS archive if GLS data were cloudy. The entire Landsat archive from 1972 is now freely available at http://glovis.usgs.gov. Secondary data such as the global mangrove database (FAO, 2007) and national and local mangrove database were also collected.

We interpreted about a thousand Landsat scenes using hybrid supervised and unsupervised digital image classification techniques. Geometric correction was performed to improve the geolocation to a root mean square error of half a pixel, an accuracy needed for subsequent change analysis. Each image was normalized for variation in solar angle and earth–sun distance by converting the digital number values to top-of-atmosphere reflectance (Chander & Markham, 2003). The images were not enhanced prior to unsupervised classification, and the thermal band (band 6) was excluded.

Prior to classification, satellite images were subsetted to include only areas where mangrove forest is likely to occur (i.e. low-lying coastal areas and inter-tidal zones) and to exclude large areas where mangrove forests are not located (i.e. far inland, highlands and open ocean). Subsetting an area of interest should increase overall classification accuracy by reducing the number of land-cover types and spectral variation. In addition, subsetting substantially reduces data size, which is an important factor when mapping at a global scale.

Water bodies were mapped with a supervised classification. We then used an ISODATA clustering algorithm within ERDAS IMAGINE to generate 50–150 spectral clusters at the 99% convergence level. Through iterative labelling, mangrove classes were identified and labelled with reference to field data and high-resolution QuickBird and IKONOS imagery, and then merged into a single mangrove category. The entire analysis was performed on a scene-by-scene basis involving more than 30 student interns and visiting scientists from Africa, South America and Asia. Four land-cover classes were generated: mangrove, non-mangrove, barren lands and water bodies. Post-classification editing such as 'recoding' was performed to remove obvious errors.

It would be desirable to provide a statistically rigorous validation for this product. However, a statistically robust global validation dataset is not available to measure the accuracy of this global mangrove database. Nonetheless, we evaluated our database with other existing global, regional and local datasets. We also performed qualitative validation with the help of local experts and high-resolution satellite data such as QuickBird and IKONOS available within the enhanced version of Google Earth. We divided the entire area into 500 × 500 grids and checked each grid visually to identify and correct gross errors inherent in the classified maps. This measure helped characterize the map qualitatively.

We mapped 'true mangroves', defined as trees, shrubs and palms that grow exclusively in the tidal and inter-tidal zones of the tropical and subtropical regions (Tomlinson, 1986). The minimum mapping unit used in this study was 0.08 ha.

RESULTS AND DISCUSSION

Based on the first full assessment of all mangrove forests of the world (Fig. 1), we estimated that the total mangrove forest area of the world in 2000 was 137,760 km^2 in 118 countries and territories. The total mangrove area accounts for 0.7% of total tropical forests of the world. This areal estimate does not provide information about the quality of the forests.

The largest extent of mangroves is found in Asia (42%) followed by Africa (20%), North and Central America (15%), Oceania (12%) and South America (11%). Approximately 75% of mangroves are concentrated in just 15 countries (Table 1). The mangroves grow in river deltas, lagoons and estuarine complexes (Thom, 1984); they also occur on colonized shorelines and islands in sheltered coastal areas with locally variable topography and hydrology (Lugo & Snedaker, 1974).

Our estimate is approximately 12% smaller than the most recent estimate by the FAO (Fig. 2). We improved upon the global estimate by using coherent data sources, better mapping techniques, wall-to-wall coverage, consistent methodology and ancillary data (high-resolution satellite data, Google Earth and GIS data) needed for image classification. In contrast to previous studies, we mapped mangrove vegetation only and did not include water bodies and barren lands. Thus, our estimates will help improve estimates of carbon stocks in mangrove vegetation. Similarly, smaller patches (0.08 ha) of mangroves were mapped, which was not possible with coarser spatial resolution data. Earlier studies produced a global map with variable data quality, depending on the technological advancement and availability of mapping resources in the country. Continental products for selected regions are also available (Blasco *et al.*, 2001).

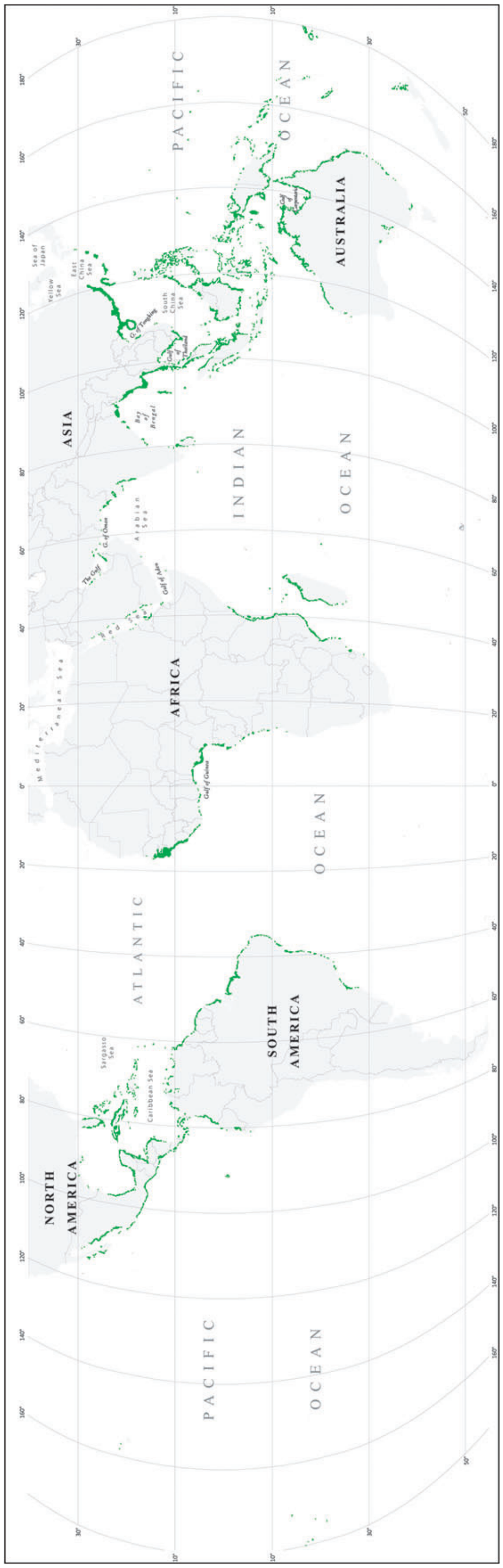

Figure 1 Mangrove forests distributions of the world – 2000.

Table 1 The 15 most mangrove-rich countries and their cumulative percentages. [Correction added on 3 September 2010, after first online publication: Table 1 column heading "Area (m^2)" corrected to "Area (ha)".]

SN	Country	Area (ha)	% of global total	Cumulative %	Region
1	Indonesia	3,112,989	22.6	22.6	Asia
2	Australia	977,975	7.1	29.7	Oceania
3	Brazil	962,683	7.0	36.7	South America
4	Mexico	741,917	5.4	42.1	North and Central America
5	Nigeria	653,669	4.7	46.8	Africa
6	Malaysia	505,386	3.7	50.5	Asia
7	Myanmar (Burma)	494,584	3.6	54.1	Asia
8	Papua New Guinea	480,121	3.5	57.6	Oceania
9	Bangladesh	436,570	3.2	60.8	Asia
10	Cuba	421,538	3.1	63.9	North and Central America
11	India	368,276	2.7	66.6	Asia
12	Guinea Bissau	338,652	2.5	69.1	Africa
13	Mozambique	318,851	2.3	71.4	Africa
14	Madagascar	278,078	2.0	73.4	Africa
15	Philippines	263,137	1.9	75.3	Asia

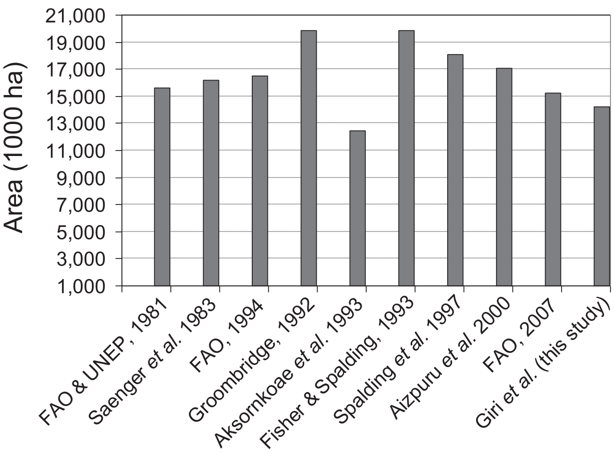

Figure 2 Comparison of aerial estimates of global mangroves.

Better data were available for some countries and regions than others. We produced consistent data products across the globe.

Of the total mangrove area, approximately 6.9% is protected under the existing protected areas network (IUCN protected areas categories I–VI). This percentage is slightly lower than the total forest area currently being protected (7.7%) and less than the 10% target by 2010, as agreed under the Convention on Biodiversity (CBD).

Our study confirms earlier findings that mangroves are generally confined to the tropical and subtropical regions of the world, with a few exceptions. Mangroves extend to 31°22′ N in Japan and 32°20′ N in Bermuda, and to 38°45′ S in Australia, 38°59′ S New Zealand and 32°59′ S on the eastern coast of South Africa (Spalding *et al.*, 1997).

Mangrove area decreases with the increase in latitude, except between 20 and 25° N latitude (Fig. 3), which is where the Sundarbans are located, the largest tract of mangrove forests in the world. Despite the highest population density in the world in its immediate vicinity, the mangrove forests of the Sundarbans have not changed in the last 30 years (Giri *et al.*, 2007). World-wide, species diversity, height and biomass are the lowest in the northern and southern extremes and increase toward the tropics. The best developed mangroves can be found in the Sundarbans, Mekong Delta, Amazon, Madagascar, Papua New Guinea and Southeast Asia. The Indo-Malesian region has 48 mangrove species (Duke *et al.*, 1998), the highest species diversity anywhere in the world. Although the exact reasons for species diversity can be debated, the conservation and sustainable management of this diversity are critical.

Caveats

Moderate-resolution satellite data such as Landsat contain enough detail to capture mangrove forest distribution and dynamics. However, very small patches (< 900–2700 m^2) of mangrove forests along the coast and canals will not be identified from these data. High-resolution satellite data (e.g. IKONOS, QuickBird) or aerial photographs are needed to assess and monitor those areas. However, those very small areas will not make a substantial difference in the global total (Wilkie and Fortune, 2003).

The use of multitemporal Landsat satellite data at a global scale poses a number of challenges, such as data availability, cloudy pixels and noisy pixels. Ideally, it is better to use the data acquired in the same year or season. However, GLS 2000 data used in this study were acquired from 1997 to 2000. The use of multiyear data for global land-use/land-cover assessment and monitoring is not uncommon (Achard *et al.*, 2002; Loveland & DeFries, 2004). The data are relatively cloud free and noise free. However, when cloud and shadow pixels were present, we used additional Landsat or ASTER images to derive information on those areas.

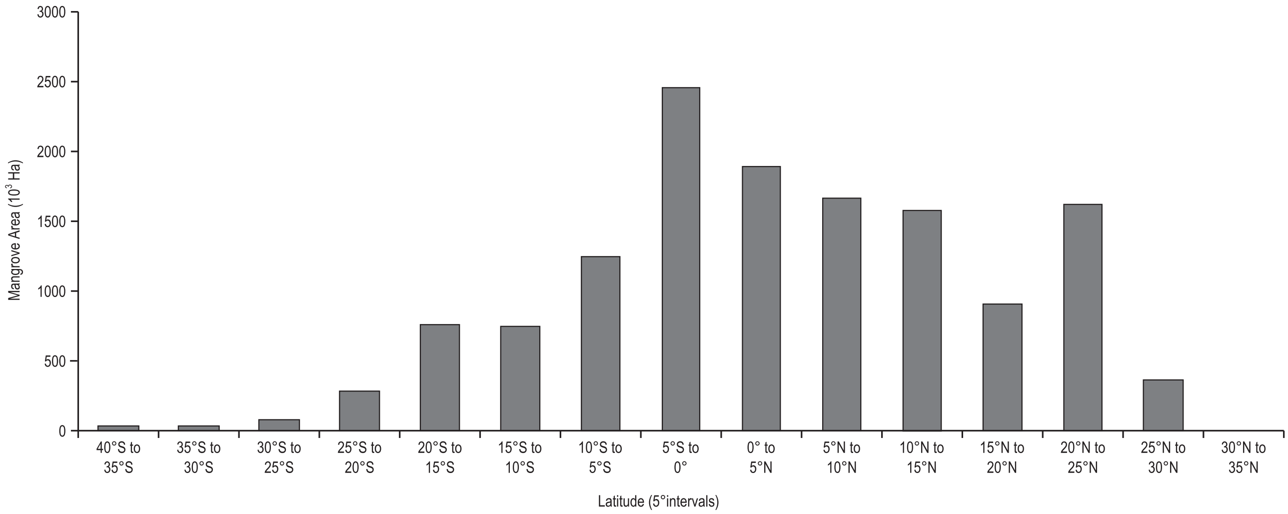

Figure 3 Latitudinal distribution of mangrove forest of the world.

CONCLUSIONS

The present study is the most comprehensive mapping of mangrove forests ever attempted at 30-m spatial resolution. The database provides an up-to-date and consistent overview of the extent and distribution of mangrove forests with better spatial and thematic details than previous datasets. This assessment provides the first wall-to-wall map of the world providing information on the total area and spatial distribution. Earlier studies provided the total area but failed to provide spatial information with sufficient details.

Mangroves are under constant flux due to both natural (e.g. erosion, aggradations) and anthropogenic forces. In the last three decades, forest losses because of anthropogenic factors have increased significantly. The remaining mangrove forests are under immense pressure from clear-cutting, land-use change, hydrological alterations, chemical spill and climate change (Blasco *et al*., 2001). In the future, sea-level rise could be the biggest threat to mangrove ecosystems. The information generated from this study will serve as a baseline to develop adaptive management strategies in anticipation of sea-level rise, set conservation priorities, monitor deforestation and forest degradation, improve terrestrial carbon accounting and quantify the role of mangrove forests in saving lives and property from natural disasters such as tsunamis.

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