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Decadal stability of Red Sea mangroves

Hanan Almahasheer [a, b], Abdulaziz Aljowair [c], Carlos M. Duarte [a], Xabier Irigoien [a, *]

[a] King Abdullah University of Science and Technology (KAUST), Red Sea Research Center, Thuwal 23955-6900, Saudi Arabia
[b] Biology Department, University of Dammam (UOD), Dammam 31441-1982, Saudi Arabia
[c] Space Research Institute, King Abdul Aziz City for Science and Technology (KACST), Riyadh 11442-6086, Saudi Arabia

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ABSTRACT

Across the Earth, mangroves play an important role in coastal protection, both as nurseries and carbon sinks. However, due to various human and environmental impacts, the coverage of mangroves is declining on a global scale. The Red Sea is in the northern-most area of the distribution range of mangroves. Little is known about the surface covered by mangroves at this northern limit or about the changes experienced by Red Sea mangroves. We sought to study changes in the coverage of Red Sea mangroves by using multi-temporal Landsat data (1972, 2000 and 2013). Interestingly, our results show that there has been no decline in mangrove stands in the Red Sea but rather a slight increase. The area covered by mangroves is about 69 Km^2 along the African shore and 51 Km^2 along the Arabian Peninsula shore. From 1972 to 2013, the area covered by mangroves increased by about 0.29% y^{-1}. We conclude that the trend exhibited by Red Sea mangroves departs from the general global decline of mangroves. Along the Red Sea, mangroves expanded by 12% over the 41 years from 1972 to 2013. Losses to Red Sea mangroves, mostly due to coastal development, have been compensated by afforestation projects.

1. Introduction

Mangroves form highly productive ecosystems, providing habitat for marine and terrestrial species (Nagelkerken et al., 2008), protecting coastal areas from storms and sea level rises (Koch et al., 2009), and acting as intense carbon sinks (Donato et al., 2011). Unfortunately, mangroves are found within the most threatened ecosystems on Earth; about 1/3 of their global area has been lost since World War II (Alongi, 2002). This decline continues at an annual rate of about 2.1% (Valiela et al., 2001). A recent assessment of regional mangrove trends, however, showed that reported rates were highly variable between regions (Friess and Webb, 2014). These reports identify aquaculture and urban developments as the main drivers of mangrove decline across these regions (FAO, 2007).

The Red Sea is adjacent to the northern limit of the Indo-Pacific mangrove, located in the Sinai Peninsula at 28°N. Along the Red Sea, mangroves experience some of the most difficult conditions in their distribution range, including no permanent freshwater inputs, salinities over 40 ppt, sea surface temperatures over 31 °C in summer and recent abrupt warming of the sea (Raitsos et al., 2011). On the other hand, urban development and aquaculture in the Red Sea are comparatively limited and, because the desert nature of the coast, direct anthropogenic impacts have been relatively contained. The Red Sea therefore provides a good model to study the resilience of mangrove ecosystems to harsh environmental conditions with as yet limited direct anthropogenic impacts. Even so, information on the area covered by Red Sea mangroves and on changes in this area over time is scarce and often reported only in grey literature at national levels. The world atlas of mangroves (Spalding et al., 2010) reports that Red Sea mangroves are scattered along the coast of Djibouti, cover only 500 ha in Egypt, while in Sudan they are found around creeks and near-shore islets. Eritrea's mangroves are patchy and distributed along approximately 380 km of shoreline (De Grissac and Negussie, 2007), while mangroves are abundant along Yemen's Red Sea coast although mostly absent along the Gulf of Aden coastline in Yemen (Spalding et al., 2010). Mangroves are found as fragmented stands in the intertidal zones of the Red Sea coast of Saudi Arabia (Kumar et al., 2010). An additional study (El-Juhany, 2009) reported that mangrove stands covered an area of 36.15 Km^2 between the southern border of Saudi Arabia in Jazan to the Jeddah's southern corniche. One-third (35%) of this area was in Jazan (12.77 Km^2), while the remaining two-thirds (65%) was in Makkah and Asir (23.38 Km^2) Provinces.

Although FAO (FAO, 2007) described the status of mangroves in the

* Corresponding author. King Abdullah University of Science and Technology (KAUST), Red Sea Research Center, Thuwal 23955-6900, Saudi Arabia.
E-mail address: Xabier.Irigoyen@kaust.edu.sa (X. Irigoien).

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Red Sea from 1980 to 2005, a comprehensive assessment of the area covered by mangroves and of the stability of this area along the Red Sea is still lacking. Assessments of the areas occupied by mangroves and of any changes to these areas are fundamental to the estimation of the ecological services provided by the mangroves in the region. In addition, such assessments inform conservation plans and provide basic information to improve our understanding of the resilience of mangrove ecosystems to harsh environmental conditions and warming. Here, we report changes in the status and distribution of Red Sea mangroves over 41 years, from 1972 to 2013, using Landsat images to determine the area and stand structure of mangroves in the Red Sea and their dynamics over the past four decades.

2. Methods

2.1. Satellite imagery

We used Erdas Imagine V9.3 and ArcGIS 10.2 to assess mangrove vegetation along the Arabian Peninsula and African coastlines of the Red Sea based on the analysis of Landsat images for three periods: 1972, when the first satellite in the series (Landsat 1) was launched (Chander et al., 2009) to 2013 (Landsat 8), and including 2000 (Landsat 7). Briefly, the Landsat 1 mission carried a Multispectral Scanner (MSS) sensor with a resolution of 60 m, whereas the sensors on board the Landsat 6 and 7 missions were Enhanced Thematic Mapper (ETM) and Enhanced Thematic Mapper plus (ETM+), respectively, both with resolutions of 30 m (Chander et al., 2009). The Landsat 8 mission also carried an Operational Land Imager (OLI) and a Thermal Infrared Sensor (TIRS), with resolution of 30 m (Lulla et al., 2013). Details on the images used in the study are provided in the supplementary materials (Tables S1, S2, and S3). The data set is available in PANGAEA (Almahasheer et al., 2015, http://www.pangaea.de).[1]

2.2. Data processing

Vectors were drawn to delineate the coastline because mangroves in the Red Sea only occur along the coastline because there are no permanent rivers and estuaries. Furthermore, the desert reaches to the coast around the Red Sea and large vegetation along the coastline is limited to mangroves. This means that classification problems are limited to presence/absence of vegetation. We applied an atmospheric correction to the data in which the pixels were converted to top of atmosphere (TOA) spectral radiances using the radiance rescaling factors provided in the metadata file: $L_\lambda = M_L Q_{cal} + A_L$ (USGS_Landsat_Missions, 2013), except for the 1972 images, which were corrected by the local data provider. The Normalized Difference Vegetation Index (NVDI) was used to estimate the vegetation in the coastal fringe, through unsupervised classification. Briefly, NVDI uses near-infrared and red light reflected by the vegetation and captured by the sensor of the satellite to measure absorbance of red light by chlorophyll and the reflection of near-infrared by the mesophyll leaf structure (Pettorelli et al., 2005). NDVI values range from -1 to $+1$, where any value below zero does not correspond to green vegetation (Hunink et al., 2010). Hence, the images were classified using the NDVI > 0 as mangrove and NDVI ≤ 0 as non-mangrove. The robustness of this classification was verified through the ground referencing (see below). This index was applied only to the areas where mangroves were expected to occur (i.e., vegetation along the coastline and coastal vegetation on islands). Inland and open-sea areas were excluded because mangroves do not occur in such areas (Giri et al., 2011). We generated vegetation thematic images and shape files assuming that any green vegetation farther than 1 km from the coast was not mangrove. Images were mosaicked and the surface of the mangroves was estimated using ArcGIS from the shape files and retrieving the area for each mangrove stand located along the Red Sea coast. Mapcarta and British Admiralty Maps (numbers 158, 171, 10, 116 and 1157) were used as sources for the location names. Moreover, we used four high-resolution images (GeoEye Satellite) of the central Red Sea and Google maps to verify that no other type of vegetation besides mangroves can be found along the Red Sea coast.

2.3. Accuracy assessment

The assessment of mangrove vegetation was crosschecked with ground-referencing data in various ways: using reported locations where mangroves occurred in 1972 and 2000 (Price et al., 1987), visiting a number of locations along a 90 Km strip of coastline between Thuwal and Khor Alkharar between December 2014 and March 2015, and using Google Earth products to verify the classification of mangrove stands in remote locations.

To estimate the accuracy of our estimates, we applied a 100-m buffer around the coast, then randomly selected 500 points to be crosschecked with the vegetation shape files for 2013. Out of the 500 points, 158 were positive for vegetation in the shape files and 342 were negative. Then we visually checked each of the 500 points on Google Earth to determine that 16 out of the 158 were not mangroves (i.e. false positives) and 26 out of the 342 classified as non-mangrove did have mangroves (false negatives). These results were used to calculate the accuracy of the classification (Congalton and Green, 2008; Fatoyinbo and Simard, 2013), resulting in an accuracy of 91.6% (Table 1, Fig. S4).

2.4. Error estimates

We also assessed the error associated with our estimates of stand size by analyzing two to three replicate images along with the original image for different locations in each of the study periods (Supplementary material, Table S5). The resulting estimate of uncertainty around the areas covered by mangrove stands was then propagated, by drawing, for each stand, replicated area estimates randomly from a normal distribution with the mean equal to the estimated area and the standard deviation calculated from the estimated coefficient of variation of area estimates for each year, was calculated from the average and standard deviation and reported as a percentage. (Supplementary material, Tables S1, S2, S3, S5 and S6). This error propagation allowed us to calculate a standard error for the estimates of the total area covered by Red Sea mangroves in each year and was used to assess the significance of changes to the total area over time.

We examined the frequency distribution of mangrove stands along the Red Sea using a Pareto distribution (Vidondo et al., 1997), after removing all stands smaller than 0.00026 Km^2 in size to account for the difference in pixel size between the 1972 and subsequent images used in this study.

3. Results

3.1. Ground-referencing data

Ground referencing data confirmed the reliability of the classification of the presence or absence of mangroves (with an overall accuracy of 91.6%, Table 1, Fig. S4). The coefficient of variation in the assessment of the area covered by individual mangrove stands ranged from 23 to 35.9% (Table S6), which is substantial due to the

[1] http://doi.pangaea.de/10.1594/PANGAEA.855896 (http://doi/org/10.1594/PANGAEA.855896).