Assessment of mangrove forests in the Pacific region using Landsat imagery

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Abstract. The information on the mangrove forests for the Pacific region is scarce or outdated. A regional assessment based on a consistent methodology and data sources was needed to understand their true extent. Our investigation offers a regionally consistent, high resolution (30 m), and the most comprehensive mapping of mangrove forests on the islands of American Samoa, Fiji, French Polynesia, Guam, Hawaii, Kiribati, Marshall Islands, Micronesia, Nauru, New Caledonia, Northern Mariana Islands, Palau, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu, Vanuatu, and Wallis and Futuna Islands for the year 2000. We employed a hybrid supervised and unsupervised image classification technique on a total of 128 Landsat scenes gathered between 1999 and 2004, and validated the results using existing geographic information science (GIS) datasets, high resolution imagery, and published literature. We also draw a comparative analysis with the mangrove forests inventory published by the Food and Agriculture Association (FAO) of the United Nations. Our estimate shows a total of 623755 hectares of mangrove forests in the Pacific region; an increase of 18% from FAO's estimates. Although mangrove forests are disproportionately distributed toward a few larger islands on the western Pacific, they are also significant in many smaller islands. [DOI: 10.1117/1.3563584]

Keywords: Pacific islands; mangroves; Landsat; mapping; remote sensing.

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1 Introduction

Mangrove forests are coastal forests found in intertidal zones along estuaries, river banks, and lagoons in the tropical and subtropical regions of the world. They are unique halophytic plant communities that thrive in the environments characterized by periodic variations in salinity of water, level of toxicity, and oxygen content in the soil. To adapt in such stressful and dynamic environments, mangrove forests have developed a number of special anatomical, metabolic, and reproductive features.[1] Mangrove forests are valued for unique ecological environments they create that host a rich assemblage of flora and fauna including many rare and endangered species.[2] They are also the source for a variety of societal goods and services to the local population. Although they cover a very small percentage of global land surface, it is argued that they account for as much as 10% of dissolved organic carbon flowing from land to the ocean.[3]

Mangrove forests grow in a wide variety of climates. They extend from 31° 22′N in Japan and 32° 20′ N in Bermuda to 38°45′ S in Australia, 38° 59′ S in New Zealand and 32°59′ S on the eastern coast of South Africa.[4] This latitudinal extent shows that mangroves can grow primarily

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Fig. 1 Study area (source: http://www.janeresture.com/melhome/map.jpg).

in tropical, sub-tropical regions of the world. Mangrove forests can also thrive on a wide variety of soil types, and salinities ranging from close to 0% to about 90%.[5] The Indo-Pacific region between South India, Oceania, and northern Australia has the greatest concentration and diversity of mangroves. About 80% of all known mangrove species are found in this region, with 9% occurring in East Africa, 6% in West Africa, and 5% each in the Caribbean and South America.[1] The total area of mangrove forest in the world for the year 2000 is 13776000 hectares.[6]

2 Study Area

The Pacific Ocean is a huge body of water scattered with thousands of islands, atolls, and archipelagos, many of which are uninhabited. These islands are broadly divided into three groups: Melanesia, Micronesia, and Polynesia (Fig. 1). Our study area includes 19 countries, and territories distributed in all three sub-regions. They are, in alphabetical order: American Samoa, Fiji, French Polynesia, Guam, Hawaii, Kiribati, Marshall Islands, Micronesia, Nauru, New Caledonia, Northern Mariana Islands, Palau, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu, Vanuatu, and Wallis and Futuna Islands. Many of these islands are volcanic, and are quite young in geological terms. They are mountainous and some of them rise thousands of feet above the sea level. There are also much lower and older reef islands and atolls that are just a few feet over the sea level.[7]

3 Mangroves of the Pacific

The distribution, diversity, and extent of the mangrove forests vary greatly among the Pacific islands. Although the sheer difference in the sizes of the islands generally explains the variation, the environmental settings, topography and the location of these islands also play key roles in determining the extent of mangroves.[8–11] Mangroves luxuriate most in the deltas and estuaries of well-developed river systems. Many islands of the region are mountainous offering little room for suitable mangrove environment. The reef islands of the region also do not have ideal environmental setting for abundant growth of this vegetation. In terms of location, mangrove forests in the Pacific islands display a unique distribution pattern. In general, from the west to the east across the Pacific, there is a great discontinuity in the number of species and decline in the forest stature.[8] To the east, mangrove forests do not occur in the islands like Cook Islands, Niue, Kermadec Islands, Tuamotu Archipelago, and others. There is a total absence of mangroves from the central and north central parts of the Pacific region. Some of islands in this region include Tokelau, Line Islands, and Baker Islands, along with numerous atolls. The largest areas of mangrove forests are found in Papua New Guinea, Solomon Islands, New Caledonia, and Fiji.

Woodroffe[8] recognizes four environmental settings within which mangrove forests occur in the Pacific region. The largest and most diverse mangroves are found in deltas and estuaries such as the ones in Fly River Delta in Papua New Guinea and Rewa Delta in Fiji where rivers deposit huge quantities of sediments to lowlands.[9,10] Mangrove forests of embayments, harbors, and lagoons are also common in many islands of the region where they grow in intertidal slope built mostly by accumulation of vegetative detritus. Mangrove forests in Tongatapu, Tonga are found in such a setting.[10] Some mangrove forests of the Pacific, like the ones in Funafuti, Tuvalu, thrive on reef flats where they grow on sandy or muddy substrates, or directly over a reef flat surface.[8] Although in smaller extent, some mangrove forests stand on inland sink-holes and in low wet spots called “mangrove depressions.” The islands of Niutao and Nanumanga in Tuvalu host mangrove forests in such a setting.[8]

Mangrove forests are recognized for a wide range of products, services, and benefits they provide to coastal environment and its inhabitants. They play a key role in the reduction of coastal erosion, filter pollutants, trap sediments run off, as well as enable a wide range of economic activities such as forestry and aquaculture products, traditional medicine, tourism, and a host of other services for coastal communities. Pacific islanders have developed a number of uses for mangrove forests over the years including some specialized local applications.[1]

4 Objectives

Despite the significance of mangrove forests to the Pacific islands, comprehensive and reliable information on their spatial extent is lacking. While there has been a lot of interest for larger islands such as Papua New Guinea, smaller islands have often been ignored. Past regional estimates such as the ones by FAO[12] and Scott[13] are based on compilations from disparate and often outdated sources whose methodologies vary, or sometimes are unknown. Our research is driven by the goal of addressing the issue of incompatibility of data seen in the past regional estimates by accurately mapping the mangrove forests for the year 2000 using remote sensing science to produce an assessment that is comprehensive and regionally consistent.

5 Data and Methodology

5.1 *Data Acquisition and Preprocessing*

We used Landsat Enhanced Thematic Mapper (ETM+) data made available through the Global Visualization Viewer (http://glovis.usgs.gov) by the US Geological Survey (USGS) Center for Earth Resources Observation and Science. A total of 128 images were collected during epoch centered on the year 2000. The use of multiyear data for regional land-use/land-cover assessment and monitoring is not uncommon.[14,15] 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.[16] Owing to the unavailability of data on atmospheric conditions of the region, atmospheric correction was not performed. 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 intertidal 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 regional scale. We also acquired very high resolution images such as IKONOS and Quickbird, for selected areas to validate the classification results. Ancillary sources such as Google Earth™, land use/land

Table 1 Class definitions.

Classes	**Definition**
Mangrove	Areas covered by both closed and open mangrove forests.
Non-mangrove	Areas with by land cover other than mangrove forests.
Water	Area of open water with no emergent vegetation.

cover maps, forest classification maps, GIS datasets and past research were also collected to aid the study, particularly in the areas where quality of images were problematic. The images acquired were not enhanced prior to the classification.

5.2 *Classification*

We used hybrid supervised and unsupervised classification techniques to classify the images. Water bodies were classified with a supervised classification. The ISODATA clustering algorithm using ERDAS image processing software was used to generate 50 to 150 spectral clusters at the 99% convergence level. Through iterative labeling, three land cover classes were generated: mangrove, non-mangrove, and water. The definitions of these classes are listed in Table 1. Post-classification editing such as "recoding" with the aid of ancillary sources was performed to minimize classification errors. The thermal band (Band 6) and the panchromatic band (Band 8) were excluded from the classification because they are of different spatial resolution and our test study showed no apparent advantage adding these channels. A 3×3 pixel window was used to avoid errors due to misregistration. For greater accuracy in our assessment, we have excluded water bodies and barren lands within mangroves from the mangrove areas and classified them in their respective classes. The minimum mapping unit used in this study is 0.08 hectares.

Table 2 Comparison of mangrove forests areas in the Pacific Islands (in hectares).

Countries	**Our Estimate**	**FAO**	**Others**
French Polynesia	1.17	n.a.	
Marshall Islands	2.34	n.a.	
Nauru	3.6	2	1 (Ref. 15)
Tuvalu	9.09	40	40 (Ref. 15)
Wallis and Futuna	13.86	25	
Kiribati	17.91	250	
Northern Mariana Islands	28.08	7	10 (Ref. 16)
Guam	34.20	60	
American Samoa	89.91	57	91 (Ref. 17)
Samoa	372.15	370	700 (Ref. 18)
Hawaii	636.84	n.a.	
Tonga	778.86	1300	1000 (Ref. 19)
Vanuatu	1378.17	2500	2500 to 3000 (Ref. 15)
Palau	5666.40	4700	4025 (Ref. 20)
Micronesia	9900.45	8500	
New Caledonia	25098.50	17140	20250 (Ref. 21)
Solomon Islands	47099.60	45300	52550 (Ref. 22)
Fiji	52503.00	38700	41000 (Ref. 23)
Papua New Guinea	480121.00	410000	411600 (Ref. 24)
Total	623755.13	528951	

6 Results and Discussion

Our results indicate that the mangrove forests of the Pacific region cover a total area of 623,755 hectares representing 4.52% of the total mangrove forests in the world.[6] The forests are concentrated disproportionately toward a few larger islands on the western side of the Pacific. With the total area of 480,121 hectares (Table 2), Papua New Guinea ranks as the eighth most mangrove rich country in the world.[6] The islands of French Polynesia, on the other hand, hold only 1.17 hectares of mangrove forest, the smallest extent in the region. Almost 97% of the mangrove forests in this region are accounted for by only four countries: Papua New Guinea, Fiji, Solomon Islands (Fig. 2) and New Caledonia. Nine islands in the region hold less than 100 hectares of mangrove forests. With the notable exception of Papua New Guinea, the extent of the forests may be very negligible on a global scale, but they are valuable resources to many local communities.[9] In some cases, the areas of the mangrove forests are quite significant in relation to the size of the country. For instance, the mangrove forests in Palau cover a total area of only 5666 hectares, but represent more than 12% of its total area. Federated States of Micronesia has more than 14% of its land covered with mangrove forests.

Our assessment identified mangrove forests in French Polynesia and Marshall Islands that were absent from FAO's report. These island countries have 1.17 and 2.34 hectares of mangrove forests, respectively. On the other hand, we did not find any mangrove forests in Niue which FAO reported as having 3000 hectares. We also included Hawaii in our study which holds 637 hectares of mangrove forests on the islands of Oahu, Molokai, and Kauai. Our total estimate for the 19 islands is 94804 hectares (18%) higher than FAO's estimate. Comparing the islands that are common to both the assessments, our estimation is higher by 94,162 hectares. Similarly, we mapped more mangrove areas than FAO estimates in New Guinea, Fiji, New Caledonia, and Micronesia. These countries have 70121, 7958, 1800, and 1400 hectares of more mangrove forests respectively. The islands of Kiribati and Vanuatu show significantly less area compared to the FAO estimate. In the case of Samoa, both estimates were similar.

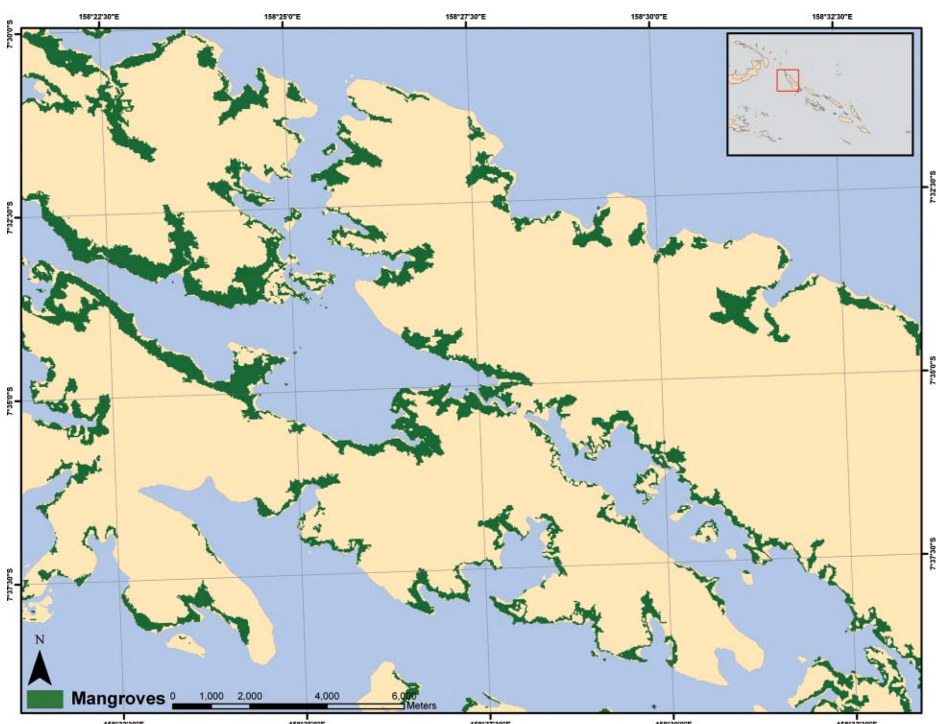

Fig. 2 Mangroves in Solomon Islands.

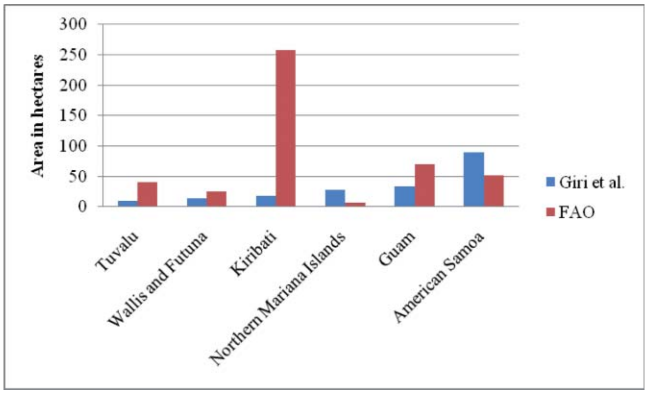

Fig. 3 Comparison of estimates for selected islands.

The result of our investigation is the first comprehensive account of the mangrove forests in the Pacific region that is based on remote sensing. This approach eliminates the greatest source of error that was prevalent in earlier comprehensive studies: differences in definitions, scales, and methodologies used over time in acquiring the data. Spalding et al.[4] stressed the need of greater resolution and detailed investigation for more accurate mapping of mangroves. FAO also noted the difficulty of verifying methodologies of some estimates included in the report. Likewise, methodologies adopted in several reports, inventories and literatures on mangrove extents that are compiled in "A Directory of Wetlands in Oceania,"[13] are not known. This issue is evident in the difference in mangrove estimates (Figs. 3 and 4) seen in various published literature over the years. Frodin[25] reports 411,600 hectares of mangrove forests in Papua New Guinea while Scott[13] estimates anywhere from 162,000 to 2, 00000 hectares. Whistler[26] recorded 52 hectares of mangrove forests for American Samoa, but Amerson et al.[18] reported 91 hectares for the same island. Ellison[9] points out a greater need of a regional level assessment of mangroves in the Pacific using remote sensing technologies. Saenger et al.[19] emphasized the problem of mangrove assessments being quickly outdated due to continuing deforestation.

The use of multitemporal Landsat satellite data at a regional scale poses a number of challenges, such as data availability, cloudy pixels, and noisy pixels. We have taken several measures to improve the accuracy of our study. However, some positional and classification errors may still exist. Cloud cover is a significant issue in any optical remote sensing application. We have used multiple subsets for each of the 128 Landsat scenes in order to avoid cloud coverage. Mixed pixels in some scenes were also potential source of errors. We have utilized high resolution imagery, previous publications, and literature; land use and land cover maps, and post classification editing to minimize errors. Exclusion of water bodies, barren lands, and roads within mangrove forests we implemented during the classification process reflects a better ground reality. An accuracy assessment was performed on the dataset resulting from our investigation. Randomly generated points were compared against high resolution imagery to check the validity of the classified images. The mangrove area had 93% accuracy and the non-mangrove area showed an accuracy of 95%.

Papua New Guinea needs a special consideration in our study as it put a unique challenge during the image classification process. Mangrove forests in some parts of this country border swamp forests which are spectrally similar to one another in Landsat imagery. These vegetations blend in so well in some areas that it is difficult to delineate the boundaries. Ellison[9] also notes this issue in mangrove areas that are contiguous to inland freshwater swamp. Taylor and Stewart [27] found difficulty in differentiating mangrove species. We have implemented the aforementioned methods to minimize errors in this area of the region (Fig. 5).

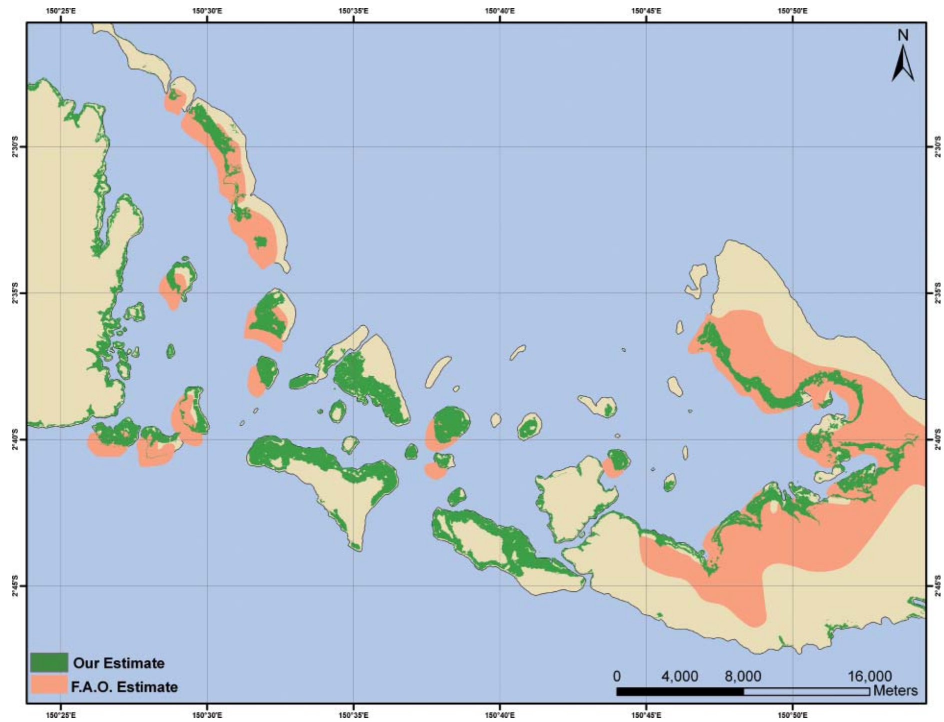

Fig. 4 Comparison of estimates for the northeastern part of Papua New Guinea.

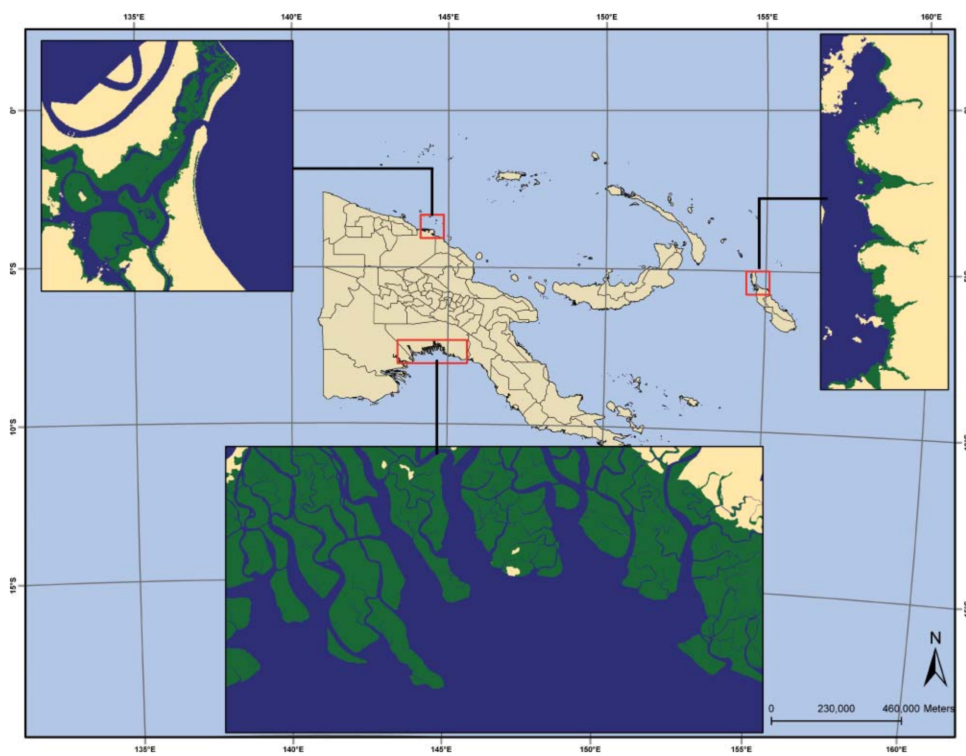

Fig. 5 Mangrove forests of Papua New Guinea.

Table 3 Error matrix.

Reference data	Classified data: Mangrove	Non-mangrove	Water	Row total	Producer's accuracy	Error of omission
Mangrove	**93**	5	2	100	93%	7%
Non-mangrove	5	**44**	1	50	88%	12%
Water	1	1	**48**	50	96%	4%
Column total	99	50	51	200		
User's accuracy	93.9%	88%	94.1%			
Error of commission	6.1%	12%	5.9%			
Overall accuracy				92.5%		

7 Results Validation

Results validation was performed in two stages: qualitative validation and quantitative validation. Qualitative validation was performed with the help of high resolution satellite data such as QuickBird and IKONOS. 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. Quantitative assessment was performed using high resolution satellite data, Google Earth, classified maps, and aerial photographs stratified random sampling approach was applied to select 100, 50, and 50 sample points for mangrove, non-mangrove, and water classes, respectively. An error matrix (Table 3) was generated with an overall classification accuracy of 92.5%. Producer's and user's accuracy for mangrove is 93% and 93.9%, respectively. The Kappa coefficient, a statistical measure of the agreement, beyond chance, between classified map and ground truth data, was 0.90.

8 Threats to Mangroves

Global climate change and sea level rise are serious long term threats the mangrove forests are facing today. Many islands of the Pacific region, such as Tuvalu, are just a few meters above the sea level. The level of sea water is very crucial to the functioning of mangrove ecology, and sea level rise will affect every aspect of the ecosystem.[10] The Intergovernmental Panel on Climate Change (IPCC) projects the global mean sea level to rise by 0.09 to 0.88 m between 1990 and 2100.[28] A recent study done by United Nations Environment Programme[29] on 16 pacific island countries, which are also included in our study, shows that based on the IPCC's upper extreme projection, about 13% of mangroves could potentially disappear in these countries at the turn of the century. Other than sea level rise, changes in air, and sea-surface temperature, stresses from storms, variations in precipitation as well as anthropogenic disturbances, will adversely affect the mangrove ecosystem in coming decades. How mangroves will respond to such changes is a complex issue and much research needs to be done to understand and mitigate the impacts of climate change.[30]

The islands of the Pacific region lie in one of most seismically active regions of the world. Mangrove forests in these islands are not only affected by seasonal hurricanes and cyclones, but also by seismic disasters such as tsunamis. For the coastal population mangrove forests are often the first line of defense against such natural calamities. The coastal mangrove forests arguably played a significant role in reducing the effect of a tsunami in coastal communities in Indonesia, Thailand, India, and Srilanka during the Asian Tsunami of 2004.[2,31] The tsunami triggered by an earthquake on September 29, 2009 on Samoa island region exposed the vulnerability of these islands to seismic catastrophes.

While mangrove forests are an important ecosystem for the Pacific region and its people, logging, urbanization, agriculture, and other anthropogenic activities are putting increasing pressure on these resources. Impacts of logging are clearly visible in mangrove forests of Papua

New Guinea at the 30 m resolution of Landsat imagery. Loss of mangrove forests has been substantial in Samoa in the past few decades.[32] Countries like Papua New Guinea, the Solomon Islands, and Fiji have some of the largest and most pristine mangrove forests in the region, but they also have had the biggest loss over the past two decades.[12]

9 Conclusions

We offer the most comprehensive mapping of mangrove forests ever attempted at 30 m resolution for the Pacific region. The use of remote sensing techniques on Landsat imagery along with other ancillary sources (existing GIS datasets, high resolution imagery, land use and forest maps, Google Earth^{TM}, and published literature) enabled us to produce a more consistent and reliable regional mangrove inventory for the year 2000 than previously attempted. We believe the results of this investigation will help fill the knowledge gap and open avenues for further research.

Although the distribution of mangroves in the Pacific region is dominated by only a handful of countries, our assessment accounts for islands with mangrove forests as small as 1.17 hectares. Regardless of the size, mangrove forests are valuable resources for the Pacific islanders. We believe our results can aid in the decision making process for the conservation and rehabilitation of the mangrove forests on a regional, as well as local, scale.

Understanding the role of mangrove ecosystems and their response to climate change should help in making an informed decision and management plan for these vulnerable islands. Further research into change detection and accurate assessment of the causes and consequences of changes based on ground truth are needed to comprehend the true state of mangroves forests in the Pacific region.

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