Tropical Ecology **55**(2): 245-253, 2014 ISSN 0564-3295

www.tropecol.com

Assessment of the health status of Indian mangrove ecosystems using multi temporal remote sensing data

PRABAKARAN CHELLAMANI*, CHANDRA PRAKASH SINGH & SUSHMA PANIGRAHY

EHD/ABHG/EPSA, Space Applications Centre, ISRO, Satellite Road, Ambawadi Vistar P.O., Ahmedabad 380015

Abstract: Mangroves are highly productive intertidal ecosystems in tropical and subtropical regions. Despite the established importance of mangroves to the coastal environment, degradation of this system continues mainly due to anthropogenic pressure. Over the past few decades, satellite remote sensing has been used to map and monitor changes of mangrove forests worldwide. This study was aimed at characterizing the health status of the Indian mangrove on the basis of multiyear, multi-season, remote sensing data. Normalized Difference Vegetation Index (NDVI) from Systéme Pour I' Observation de la Terre - Vegetation (SPOT-VGT) coinciding with the stress period (March - May) for one decade (1999 - 2008) was subjected to maximum value compositing (MVC). This was used to develop a four-category health index status based on threshold values. Results showed that around 38 % and 27 % of total mangrove in India belonged to very-healthy and healthy categories, respectively. In general, the health index was lower in western coast mangroves compared to east coast. The health index was highest for the island mangrove systems (Andaman and Nicobar), and lowest along the Gujarat coast.

Resumen: Los manglares son ecosistemas intermareales muy productivosde las regiones tropicalesy subtropicales. A pesar de la importancia bien establecida de los manglares pare el ambiente costero, la degradación de estesistemacontinúa principalmente debido a la presión humana. En las últimas décadasse ha usado la percepción remota satelital para mapear y monitorear los cambios en los manglares en todo el mundo. El objetivo del estudio fuecaracterizar el estado de salud del manglar de la India a partir de datos multianuales y multiestacionales de percepción remota. El Índice de Vegetación de Diferencia Normalizada (NDVI) obtenido a partir del sensor Systéme Pourl'Observation de la Terre-Vegetation (SPOT-VGT) para el periodo de estrés (marzo-mayo)durante una década (1999 - 2008) fue sometido al procedimiento MVC (Maximum Value Compositing). De esta forma se desarrolló un índice de estado de salud con cuatro categorías, basado en valores umbral. Los resultados mostraron que alrededor de 38 % y 27 % de todo el manglar en la India perteneció a las categorías muy sano y sano, respectivamente. Engeneral, el índice de salud fue menor en los manglares de la costa occidental en comparación con los de la costa oriental. El índice de salud tuvo su máximo en los sistemasde manglar insulares (Andamany Nicobar), y su valor más bajo en la costa de Gujarat.

Resumo: Os mangais são ecossistemas intermareais altamente produtivos em regiões tropicais e subtropicais. Apesar da importância comprovada dos mangais no ambiente costeiro, a degradação deste sistema continua, devido, principalmente, à pressão antrópica. Ao longo das últimas décadas, a detecção remota por satélite tem sido usada para mapear e monitorizar as mudanças nas florestas de mangalà escala mundial. Este estudo teve como objetivo caracterizar o estado de saúde do mangal indiano com base em dados de detecção remota multianual e multi-estacional. O índice de Diferença Normalizada (NDVI) obtido pelo Sistema para a Observação

**Corresponding Author*; e-mail: karanc@sac.isro.gov.in

da Terra - Vegetação (SPOT-VGT), coincidindo com o período de stresse (março-maio) para uma década (1999 - 2008) foi submetido ao valor máximo (MVC) compósito. Este foi utilizado para desenvolver,com base nos valores de limiar, quatro categorias do índice de estado de saúde. Os resultados mostraram que cerca de 38 % e 27 % do total de mangal na Índia pertencia às categorias de muito saudáveis e saudáveis, respectivamente. Em geral, o índice de saúde foi menor para os mangais na costa ocidental quando comparado com os da costa leste. O índice de saúde foi mais elevado para os sistemas de mangal da ilha (Andaman e Nicobar), e mais baixo ao longo da costa de Gujarat.

Key words: Density slicing, health, Indian Coast, mangrove ecosystem, NDVI, remote sensing, SPOT.

Introduction

Mangrove ecosystems are found in intertidal mudflats that fringe sheltered coastal, estuarine and riverine areas in tropical and subtropical latitudes. The physical environment of a mangrove ecosystem includes waterways (estuaries, creeks, canals, lagoons, and back waters), mudflats, salt pans, and islands. It is often highly saline and frequently inundated by the tidal action. These ecosystems support many types of plants and animals. The majority of plants are evergreen trees, although deciduous trees, perennial and evergreen shrubs, parasites and climbers, perennial grasses, and perennial ferns are also common constituents of this ecosystem (Tomlinson 1986), together with algae and fungi. Mangrove ecosystems are important for fish production. They serve as nursery, feeding and breeding grounds for many fishes and shellfishes. Besides fish, mangroves support a variety of wildlife such as the Bengal tiger, crocodiles, deer, pigs, snakes, fishing cats, insects, and birds (Kathiresan 2010).

Mangrove forests in India account for about 3 % of world's mangrove vegetation and are extremely diverse with a record of 4011 biological species including the globally threatened species in the coasts of the country (FSI 2011 & Kathiresan 2010). Inspite of growing threats, the mangrove area has been well protected in the last two decades due to strong policy and good governance (Kathiresan 2010).The mangrove ecosystem is beneficial to humanity in many ways, for example, it provides food, fodder, fuel wood, and shelter for many marine fauna species. In addition, mangroves protect the hamlets behind it from the hurricane, cyclone, tsunami, and coastal erosion (Hogarth 2007 & Kathiresan 2010). However, major threats to this ecosystem are excessive logging for fuel and timber, land conversion to aquaculture, agriculture, shrimp ponds, salt pans, and coastal development for shipping (Hogarth 2007).

Remote sensing is used as a tool for monitoring vegetation changes, especially in forests, because the hilly or swampy terrain is inaccessible and vast in area. It provides relatively accurate information regarding the status of vegetation in the forest and is cost-effective and time saving. Efforts to manage mangroves require wide scale monitoring to track changes in areal extent, health, and ecological functioning. Remote sensing is used to assess and monitor the effectiveness of mangrove restoration and conservation programmes where physical monitoring is difficult (Heumann 2011; Selvam 2003). Indian mangrove wetlands have been studied using remote sensing technology since the last decade for mangrove assessment, restoration, coastal management and estimating mangrove loss in Pitchavaram (Selvam *et al.* 2003), Bhitarkanika (Reddy *et al.* 2007), and in Godavari delta region (Ramasubramanian *et al.* 2006; Satapathy *et al.* 2007). The objective of this study is to assess the health status of the vegetation of Indian mangrove ecosystem using multi-temporal spectral vegetative indices data.

In the field of remote sensing applications, scientists have developed vegetation indices for qualitatively and quantitatively evaluating vegetative covers using spectral measurements of canopy cover. Vegetative indices also indicate the vigor of vegetation. Over forty vegetation indices have been developed during the last four decades (Bannari *et al.*1995). Several widely used vegetative indices derived from remotely-sensed data include Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), Atmospherically Resistant Vegetation Index (ARVI), and

Simple Ratio Index (SRI). EVI was developed to improve the NDVI by optimizing the vegetation signal in Leaf Area Index (LAI) regions by using the blue reflectance to correct for soil background signals and reduce atmospheric influences (Huete *et al*. 1997). ARVI uses the reflectance in blue to correct the red reflectance for atmospheric scattering. It is most useful in regions of high atmospheric aerosol content (Kaufman & Tanre 1996). SRI is a simple, well known index and is the ratio of the highest reflectance and absorption bands of chlorophyll (Sellers 1985). NDVI is a normalized ratio of red and NIR spectral reflectance (NDVI = (NIR − RED) / (NIR + RED)), and is one of the most popular and widely used indices. Ultimately, the NDVI is determined by the degree of absorption by chlorophyll in the red wavelengths, which is proportional to leaf chlorophyll density, and by the reflectance of near infrared (NIR) radiation, which is proportional to green leaf density. The use of the NDVI vegetative index has been shown to be sensitive to the green leaf area or green leaf biomass (Tucker 1979). Santin *et al.* (2009) used NDVI time series data as a proxy of vegetation productivity. Therefore, the NDVI can be used as a surrogate to the health status of the mangroves.

Materials and methods

Study area

All the major mangrove ecosystems found in India including Andaman and Nicobar Islands were selected for this study (Fig. 1). According to India state of forest report (FSI 2011), the country has about 4,661.56 km^2 mangrove area which is 0.14 % of the country's total geographical area. Nearly 59.62 % of this area is present along the east coast, and 27.11 % along the west coast, and the remaining 13.25 % in the Andaman and Nicobar islands. West Bengal has the maximum mangrove area (46.39 %), almost half of the total area under mangroves in India, followed by Gujarat (22.55 %) and Andaman and Nicobar Islands (13.26 %). Mandal *et al.* (2008) highlighted the diversity of mangrove habitats in India, in relation to environmental factors, mangrove species diversity, along with their distribution, regeneration and growth. Mangrove habitats in India are located in three zones: (1) East Coast, (2) West Coast, and (3) Andaman & Nicobar Islands. These three zones have been further categorized into Deltaic, Coastal, and Island habitats following Thom's (1982) classification of estuarine habitats. Climate of India is characterized by four distinct seasons: (i) winter (December-February), (ii) summer (March-May), (iii) south-west monsoon season (June-September), and (iv) post-monsoon season (October-November). Rivers are the major sources of fresh water to the east coast mangroves of India. Ganges and Brahmaputra are main source of fresh water to Sundarbans. Mahanadi and Brahmani rivers feed the Mahanadi delta. Godavari and Krishna deltas are being fed with their respective rivers. Cauvery river is the main source of fresh water for Pichavaram and Muthupet mangroves. There are no major river systems in west coast and Andaman & Nicobar Islands.

Data used and pre-processing

Satellite Pour l' Observation de la Terre (SPOT) VEGETATION (VGT) Normalized Difference Vegetation Index (NDVI) was used for this study. The VEGETATION Program is developed jointly by the France space agency (CNES), the European Commission, VITO Belgium, Italy and Sweden. The SPOT-VGT sensor, launched in 1998, possesses spectral bands specifically tailored for large-area vegetation monitoring. The VGT-S10 products are composited (maximum-value) products with 1x1 km spatial resolution (Maisongrande *et al.* 2004).To define the study area boundaries, a mangrove map at 1:250,000 scale was derived using temporal IRS 1D-AWiFS images from the year 2004 obtained from the Natural Resource Database (NRDB; http://www.nnrms.gov.in). NRDB system maintains a standardized GIS database of all space based spatial information generated under National Natural Resources Management System (NNRMS) program and position spatial data services from the database as per NNRMS standards.

SPOT-VGT S10 NDVI data files were downloaded from Flemish Institute of Technological Research (VITO, Belgium; http://free.vgt.vito.be/) for 10 years from 1999 to 2008. The VGT-S10 product is essentially a synthesis of all VGT-S1 products generated over a "dekad". Dekads are conventionally defined as follows: the first dekad of the month includes day 1 to day 10, second dekad includes day 11 today 20, and the third dekad includes day 21 to the end of the month. Thus the third dekad has a varying length according to the month, for instance 8 days in February, but 11 days in March. To obtain a synthesized view of the

Fig.1. The study area encompassed all mangroves in India; Mangrove ecosystems are shown in grey.

globe from a set of viewing segments, a pixel-to-pixel mosaicking process is performed, choosing the 'best' measurement obtained for a given pixel among the set of the available measurements for the dekad. The best viewing algorithm chosen is the Maximum Value Composite (MVC), also called "best NDVI". For a given pixel having been viewed several times, the selected reflectance corresponds to the viewing with the highest ground NDVI. Cloudy, bad quality or interpolated views are excluded, if possible.Vegetation indices (NDVI) were calculated from the ten-day syntheses. Each month has three composite NDVI data files. The data format for all the binary files is eight bit unsigned. The valid range of the eight bit (raw) data values is 3 to 255. A RAW value of zero denotes a land pixel with no NDVI calculated due to quality control flagging (i.e., cloud/snow/ice). A RAW value of 1 is not used in the binary files (this is reserved for the graphics plane). A RAW value of 2 denotes a water pixel. VGT Extract - the free vegetation extraction tool - is a program that allows users to extract Regions of Interest (ROIs) from VGT products. To convert the RAW values into scaled NDVI, the following formula was used: NDVI= (RAW*0.004) - 0.1.

Mangrove phenology

Mangrove species are evergreen vegetation and they replace their old leaves with new leaves continuously. However, in some season, they will lose their leaves at high rate. Osborne (2000) stated that mangroves leaf fall pattern was found to be bimodal with a high peak at the end of the dry season. Also, during the dry season, low soil moisture, low tides and high evapotranspiration rates impose water stress on mangroves that enhances both leaf senescence and litter fall. So, we wanted to assess the health of the mangrove ecosystem during the phenological and environmental stressful period. To determine the phenological stress period, mangrove phenological curves (NDVI profile) were prepared from pure

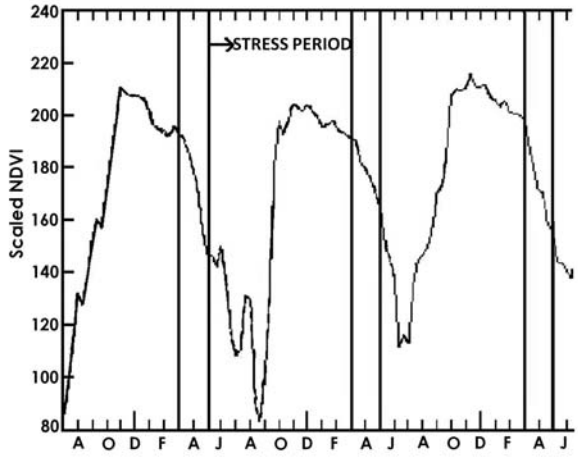

Fig. 2. The phenological curve for the mangrove vegetation.

Table 1. Density slicing algorithm; g (x, y) represents the NDVI value of pixel (x, y).

Density slicing algorithm	
g (x,y) = 0 (No data);	If 0.0 < NDVI
g (x,y) = 1 (Poor);	If 0.0 > NDVI ≤ 0.2
g (x,y) = 2 (Moderate);	If 0.2 > NDVI ≤ 0.4
g (x,y) = 3 (Healthy);	If 0.4 > NDVI ≤ 0.6
g (x,y) = 4 (Very-healthy);	If 0.6 > NDVI ≤ 1.0

pixels of mangrove in different study locations of mangrove ecosystem of the country. The decadal phenological pattern of mangroves revealed that the pre-monsoon dry period - (March, April, and May) coincided with the lowest NDVI; therefore, it was considered the stress period (Fig. 2). Though, mangroves belong to the evergreen vegetation category, the leaf fall rate exceeds the leaf regeneration rate during this pre-monsoon dry period, mainly due to increases in the temperature, salinity, and decreases in humidity, and fresh water influx from the rivers (Ramasubramanian & Ravishankar 2004; Saravanakumar *et al*. 2008; Senthilkumar *et al*. 2008). The pre-monsoon dry period of each year from 1999 to 2008 was considered for this study.

Density slicing

Each month has three composite images viz., 1 - 10, 11 - 20, and 21 - end of the month. MVC images were created from those three images for each month and that MVC image represents that corresponding month. Mangrove ecosystem areas were extracted from MVC images during the stress period for each year using mangrove map vector. Then these images were sliced into four health classes viz., Poor, Moderate, Healthy, and Very-healthy by the NDVI density slicing method (Table 1). The mangrove health classes were defined using thresholds based on ground observations in Sundarbans (Very healthy), Goa (Healthy), Pichavaram (Moderate), Jamnagar and Bharuch (Poor). All samples were collected during summer months between year 2009 and 2011. The chlorophyll content or greenness of plant was measured by SPAD 502 Plus Chlorophyll meter (Spectrum Technologies, Inc.). The GPS sample locations of the ground observation site were overlaid on the NDVI time series along the chlorophyll content of that location and thresholds were fine tuned. Data analysis was completed and mangrove health index maps were created for each Indian state mangrove ecosystem. An accuracy assessment analysis was completed by comparing estimated mangrove health classes with forest density classes from the Forest Survey of India (FSI) digital forest map. Two hundred samples were selected from the mangrove health maps using a stratified random sampling method. Those points were overlaid with FSI maps and their respective classes were retrieved.

Results

Indian mangrove ecosystem

The analysis of decadal mean mangrove health index (average of the 10 year stress period NDVI from 1999 - 2008) revealed that India has about 17 %, 27.3 %, 37.6 %, and 18.1 % of very-healthy, healthy, moderate, and poor mangrove classes, respectively (Fig. 3). Amongst all areas, the highest percentage of very-healthy mangroves was observed in Andaman & Nicobar Islands. The east coast had healthier mangroves as compared to the west coast. Spectrally, the health of mangrove vegetation decreased through March to May (Fig. 2). However, a greening trend from1999 to 2008 was observed in most of the places during this period. On the basis of the accuracy assessment of these mangrove health classes, these were classified with 84 % accuracy.

East coast mangrove ecosystem

The east coast of India has 70.72 % of the country's total mangrove vegetation area. West Bengal (Sundarbans) has the largest mangrove area (56.7 %) of total the country's mangrove area

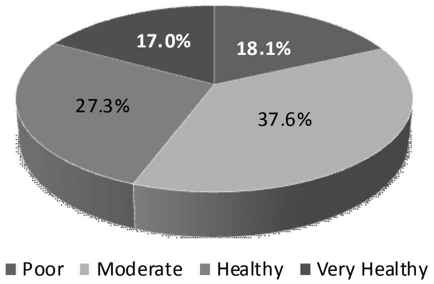

Fig. 3. Mean percentage of mangrove health classes for 10 years (1999-2008).

Table. 2. Mean percentage of mangrove health class for 10 years (1999 - 2008) for each state.

State/Union territory	Poor	Moderate	Healthy	Very healthy
Andaman & Nicobar	1.25	3.22	11.24	84.29
Andhra Pradesh	6.50	37.2	32.63	23.67
Goa	0.74	42.59	54.32	2.35
Gujarat	74.17	25.02	0.80	0.01
Karnataka	35.55	45.76	18.28	0.41
Maharashtra	12.27	72.96	14.33	0.44
Odhisa	5.17	48.49	32.09	14.25
Tamil Nadu	19.83	43.06	29.45	7.66
West Bengal	7.54	20.35	52.42	19.69

found in the delta of Ganges and Brahmaputra. In Sundarbans, the mean percentages of very-healthy and healthy classes are 19.7 % and 52.42 %, respectively (Table 2). There was an overall 27 % increase in very-healthy mangroves from 1999 to 2008 (Figs. 4 & 5). A representative map for the health index was developed for West Bengal state because it had the highest concentration of mangroves (Fig. 5). In Odhisa, mangroves are found in the deltas of Mahanadi and Brahmani (Bhitarkanika wildlife sanctuary) which has 4.7 % of the country's mangrove area. The mean percentages of very-healthy and healthy classes in Odhisa are 14.3 % and 32.1 %, respectively. In Andhra Pradesh, mangroves are found in the Godavari and Krishna delta which has 23.7 % of very-healthy and 32.6 % of healthy mangroves. In addition, there were large increases of very-healthy mangroves from 1999 to 2008 (Fig. 4). In the southeast coast, Tamil Nadu has 0.53 % of the country's total mangrove area. The mangrove ecosystem is found in the Cauvery delta - Pichavaram and Muthupet. Tamil Nadu has 7.7 % of very-healthy and 29.5 % of healthy mangroves. The health of these mangroves improved from 2004 to 2008.

West coast mangrove ecosystem

The west coast of India has about 19 % of the country's total mangrove area. Throughout the west coast, the health of the mangrove ecosystem was low. Gujarat state has about 1,650 km of coastline and 12.3 % of the country's total mangrove area. However, on the scale of NDVI based healthiness, mangroves of Gujarat are not very healthy with approximately 74 % of mangroves designated as poor health. The health of mangroves (healthy class) has started to improve since 2004 (Fig. 4). However, less than 1 % of Gujarat mangroves were classified as healthy and very healthy in the last ten years (1999 - 2008). Maharashtra and Karnataka has 6.11 % and 0.42 % of country's total mangrove area. The health of mangroves (healthy class) of these two states started to improve since 2001. Both of these two states had about 0.4 % of very-healthy mangroves. In Maharashtra and Karnataka,14.3 % and 18.3 % of the mangroves were classed as healthy, respectively. Goa had the lowest mangrove area in the country (0.12 %) and the mangroves showed improvements in health from 2004.

Andaman and Nicobar island mangrove ecosystem

Although, Andaman and Nicobar Islands which are in Bay of Bengal possess only 10.23 % of total country's mangrove area, it had a higher percentage of very-healthy (~84 %) mangroves in comparison to the other states. The health of these island mangrove ecosystems was quite high throughout the study period, but the data suggest that health may be beginning to decline (Fig. 4).

Discussion

Indian mangrove ecosystem

The overall health of Indian mangrove ecosystems has improved over the past decade. East coast mangroves were healthier than west coast mangroves. This can be due to several reasons including differences in riverine inputs and precipitation levels which would reduce the soil and water salinity. Many of the Indian peninsular rivers discharge their fresh water in the Bay of Bengal and no major perennial river is available for the west coast mangrove ecosystems. Annual rainfall of the east coast deltas is higher than that of west coast (Selvam 2003).

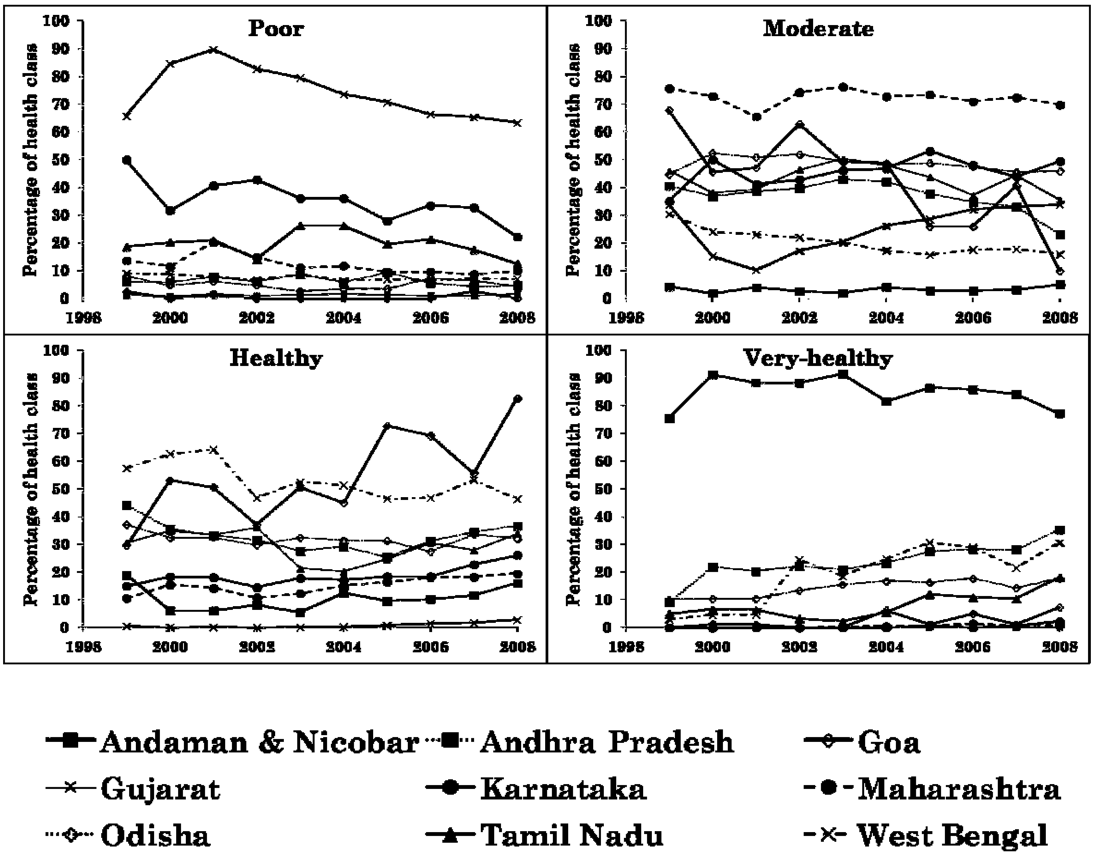

Fig. 4. Mangrove health class percentage of 10 years for all the states and union territory.

East coast mangrove ecosystem

In east coast of India, the health of West Bengal mangroves has substantially improved from 1999. These two mangrove ecosystems are tide-dominated wetlands and its tidal amplitude is also high (Selvam 2003). However, in case of Odhisa, there was not a significant improvement in the health of the mangroves. In Andhra Pradesh, mangrove health has improved constantly since 2000 (Fig. 4). This is due to the restoration of mangroves which had been carried out in 1999 (Ramasubramanian & Ravishankar 2004). Tamil Nadu mangroves are river-dominated wetland ecosystems. The fresh water flow determines the health of mangroves in this locality, because reduced flow of fresh water increases the soil salinity which in due course affects the physiology and health of the mangroves (Selvam 2003). After the Indian Ocean Tsunami in 2004, the importance of this mangrove vegetation was recognized by surrounding communities, as they were protected by this vegetation from the Tsunami (Kathiresan & Rajendran 2005).

West coast mangrove ecosystem

Gujarat mangroves have suffered severe deforestation and grazing. They were over-exploited for fuel wood and fodder in the past (Nayak & Bahuguna 2001). However, the mangrove health has started to improve since 2003. This is due to the mangrove restoration program carried out by the state government along the Gujarat coast since 1999 (Hirway & Goswami 2004). The mangrove ecosystems in Gujarat, Maharashtra, and Karnataka were immensely affected by the industrial development set out along the west coast.

Andaman and Nicobar island mangrove ecosystem

Andaman and Nicobar Island mangroves were in good health condition throughout the study period. Because of the sparse human population and browsing cattle, the mangroves of these islands are well protected. However, the reason for the declining health of mangroves during the study period is uncertain.

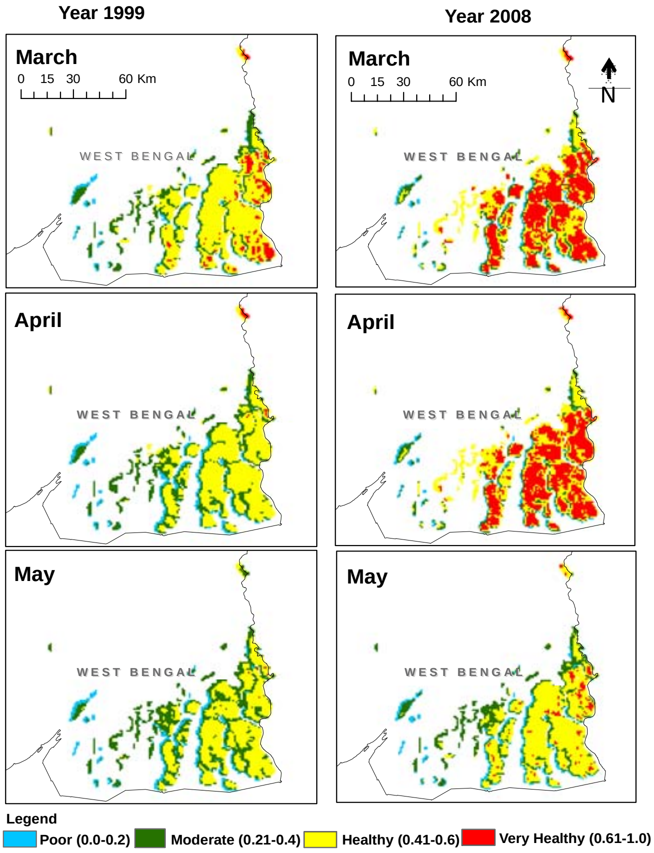

Fig. 5. Mangrove health index map for the year of 1999 and 2008 for the West Bengal state.

Limitation of this study

This present study on the health index of mangrove vegetation helped us to understand the temporal changes in the mangrove growth and vigor. However, there are some limitations to this study because of the coarse resolution of the data and potential classification errors. Due to the coarse resolution (1 km * 1 km pixel resolution), the combined reflectance of mangrove and non-mangrove vegetation were recorded. Also, boundary pixels may have been merged with creeks, mudflats, and other coastal vegetation. Future similar efforts using higher resolution data may help minimize these limitations.

Conclusions

In the present study, it was found that the greenness of mangroves decreased from March to May, temporally on the phenological scale. The comparative low health index observed in western coast mangroves may be attributed to the climate, absence of major rivers, steep coastline, anthropogenic pressure, pollution in the major cities; and industrial development such as ports, and oil refineries. On the other hand, the eastern coast has major rivers systems discharging fresh water, more or less, throughout the year. The rainfall and the climate are also favorable for the growth of mangroves in eastern coast. Therefore, the health index of mangrove in the eastern region is quite high. Due to less anthropogenic activity and pollution, Andaman and Nicobar island mangrove's health index is highest amongst all. The lowest health was observed in the Gujarat state. Western coast mangrove ecosystems require more attention to improve their health status, through reforestation, protection, monitoring, and controlling pollution.

Acknowledgments

The work has been carried out under the ISRO-EOAM project "Development of Remote Sensing based Bioclimatic Index for Indian Region" at Space Applications Centre, Ahmedabad. Authors are thankful to the project collaborators (M.G. Science Institute, Ahmedabad) for their direct and indirect support during the course of the work.

References

Bannari, A., D. Morin, F. Bonn & A. R. Huete. 1995. A review of vegetation indices. *Remote Sensing Reviews* **13**: 95-120.

Forest Survey of India (FSI). 2011. *India State of Forest Report*. Ministry of Environment and Forest (MoEF), Government of India.

Heumann, B. W. 2011. Satellite remote sensing of mangrove forests: Recent advances and future opportunities. *Progress in Physical Geography* **35**: 87-108.

Hirway, I. & S. Goswami. 2004. *Valuation of Mangroves in Gujarat*. Centre for Development Alternatives. Ahmedabad, India.

Huete, A. R., H. Liu, K. Batchily & W. van Leeuwen. 1997. A comparison of vegetation indices over a global set of TM images for EOS-MODIS. *Remote Sensing of Environment* **59**: 440-451.

Hogarth, P. 2007.*The Biology of Mangroves and Seagrasses*. Oxford: Oxford University Press.

Kaufman, Y. J. & D. Tanre. 1996. Strategy for direct and indirect methods for correcting the aerosol effect on remote sensing: from AVHRR to EOS-MODIS. *Remote Sensing of Environment* **55**: 65-79.

Kathiresan, K. 2010. Importance of mangrove forests of

India. *Journal of Coastal Environment* **1** : 11-26.

Kathiresan, K. & N. Rajendran. 2005. Coastal mangrove forests mitigated tsunami. *Estuarine, Coastal Shelf Science* **65**: 601-606.

Maisongrande, P., B. Duchemin & G. Dedieu. 2004. VEGETATION/SPOT: an operational mission for the earth monitoring; presentation of new standard products. *International Journal of Remote Sensing* **25**: 9-14.

Mandal, R. N. & K. R. Naskar. 2008. Diversity and classification of Indian mangroves: a review. *Tropical Ecology* **49**: 131-146.

Nayak, S. & A. Bahuguna. 2001. Application of remote sensing data to monitor mangroves and other coastal vegetation of India. *Indian Journal of Marine Sciences* **30**: 195-213.

Osborne, P. L. 2000. *Tropical Ecosystems and Ecological Concepts*. Cambridge University Press. Cambridge, London, New York.

Ramasubramanian, R. & T. Ravishankar. 2004. *Mangrove Forest Restoration in Andhra Pradesh, India.* MSSRF/MA/04/13.M.S. Swaminathan Research Foundation, Chennai, India.

Ramasubramanian, R., L. Gnanappazham, T. Ravishankar & M. Navamuniyammal. 2006. Mangroves of Godavari - analysis through remote sensing approach. *Wetlands Ecology and Management* **14**: 29-37.

Reddy, C. S., C. Pattanaik & M. S. R. Murthy. 2007. Assessment and monitoring of mangroves of Bhitarkanika Wildlife Sanctuary, Orissa, India using remote sensing and GIS. *Current Science* **92**: 1409-1415.

Satapathy, D. R., R. J. Krupadam, L. Pawan Kumar & S. R. Wate. 2007. The application of satellite data for the quantification of mangrove loss and coastal management in the Godavari estuary, East Coast of India. *Environmental Monitoring Assessment* **134**: 453-469.

Santin-Janin, H., M. Garel, J. L. Chapuis & D. Pontier. 2009. Assessing the performance of NDVI as a proxy for plant biomass using non-linear models: a case study on the Kerguelen archipelago. *Polar Biololgy* **32**: 861-871.

Saravanakumar, A., M. Rajkumar, G. A. Thivakaran & J. Sesh Serebiah. 2008. Abundance and seasonal variations of phytoplankton in the creek waters of western mangrove of Kachchh-Gujarat. *Journal of Environmental Biology* **29**: 271-274.

Sellers, P. J. 1985. Canopy reflectance, photosynthesis and transpiration. *International Journal of Remote Sensing* **6**: 1335-1372.

Selvam, V. 2003. Environmental classification of mangrove wetlands of India. *Current Science* **84**: 757-765.

Selvam, V., K. K. Ravichandran, L. Gnanappazham & M. Navamuniyammal. 2003. Assessment of community based restoration of Pichavaram mangrove wetland using remote sensing data. *Current Science* **85**: 794-798.

Senthilkumar, B., R. Purvaja & R. Ramesh. 2008. Seasonal and tidal dynamics and chlorophyll *a* in a tropical mangrove estuary, southeast coast of India. *Indian Journal of Marine Science* **32**: 132-140.

Thom, B. G. 1982. Mangrove ecology: a geomorphological perspective. pp. 3-17. *In*: B. F. Clough (ed.) *Mangrove Ecosystem in Australia: Structure, Function and Management*. Australian National University Press, Canberra.

Tomlinson, P. B. 1986. *The Botany of Mangroves*. Cambridge University Press, Cambridge, London, New York.

Tucker, C. J. 1979. Red and photographic infrared linear combination for monitoring vegetation. *Remote Sensing of Environment* **8**: 127-150.

(Received on 27.04.2012 and accepted after revisions, on 29.01.2013)