ANALYSIS OF MANGROVES ASSEMBLAGE USING AVIRIS-NG DATA AND THEIR CORRELATION WITH *IN SITU* EDAPHIC AND TOPOGRAPHIC ATTRIBUTES IN SUNDARBANS, INDIA

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KEY WORDS: Mangrove species mapping, Hyperspectral data, Soil salinity and nutrients, Mangroves health.

ABSTRACT: Sundarbans is the world's largest mangrove forest shared by India and Bangladesh with rich faunal diversity. Mangroves act as one of the largest carbon sinks of the world with species specific differentiated capacities. Assessment of species distribution of mangrove within this forest area is therefore essential for any scientific conservation approach. This study explored the potential of the very high resolution Airborne Visible InfraRed Imaging Spectrometer-New Generation (AVIRIS-NG) data in mapping the mangrove species distribution in parts of Sundarban's Lothian Wildlife Sanctuary along with its ecological and environmental attributes. The AVIRIS-NG hyperspectral image enabled discrimination between mangrove species and various assemblages of different species. Support vector machine (SVM) has been used for classifying the mangroves and it was found to be considerably precise (overall accuracy ≈80%). Soil salinity, topography and soil nutrient (Nitrogen, Phosphorus, Potassium) maps developed from *in situ* data are compared with the species distribution which depict a positive relation of mangrove's health with low soil salinity, comparatively lower nutrient availability and frequent tidal flushing.

Sundari (*Heritiera fomes*), a fresh water loving mangrove, now rare in Indian parts of Sundarbans, has been found to occur at the lowest salinity zones in relatively higher elevation. *Phoenix paludosa*, a climax community indicator species capable of tolerating variable salinity conditions, is often found with *H. fomes* indicating the climax stage of the ecological succession, particularly in topographically higher positions. *Avicennia officinalis* and *Aegiceras corniculatum* were found in medium salinity zones, whereas, species like *A. marina*, *Ceriops decandra* and *Excoecaria agallocha* are distributed in high salinity zones. Despite the rigorous spatial mixing of species, edaphic physico-chemical parameters and geomorphological settings are observed to play crucial role in the mangrove's health which is indicated by varying canopy density, tree height, slenderness coefficient of same species occurring at spatial locations with contrasting physicochemical attributes.

INTRODUCTION

Forests in India are categorised as tropical ecosystems spread over nearly 67.83 million ha (M ha), which is 20.66% of the geographical area of the country of which 0.45 M ha (0.14%) is covered by mangroves (FSI, 2003). India has been reported with 22,351,000 tons of biomass stored in mangrove trees spread over 404,390 ha (Blasing, 2014). The term "mangrove" designates the trees in intertidal ecosystem or the explicitly physio-morphologically specialized plant families that live in coastal environment (Tomlinson, 1986). Mangroves cover the coastal inter-phase giving a natural protective encapsulation, exclusively to the tropical and lesser subtropical land-sea frontiers. At the same time, they help bridging and limiting the land sea boundary and are well recognized for maintaining an ecological balance between the land-sea fluxes (Blasco *et al.*, 1996). These ecosystems are spread over large number of countries flanked between 30° N and 30° S. As identified by Spalding *et al.*, (1997), mangroves cover 75 % of all the tropical coastlines of the world. The total mangrove cover accounts to 15.2 million hectares (M ha) worldwide as in 2005 which declined from 18.8 million hectares in 1980 (FAO, 2007). Mangroves in Asia itself accounts for 38.7 % of global mangrove coverage (Spalding *et al.*, 2010). Then again, satellite data based estimations by Giri *et al.*, (2011) puts forward that in the year 2000, the mangrove cover of the world was 137,760 km^2 distributed in 118 countries and territories which is 12.3 % less than the estimates of FAO (2007). Such reports foster inconclusive debates on both, the actual spatial extent of the mangroves and the consistency of the estimation methods. That aside, global studies unequivocally lend support to the speculation that mangrove's are being degraded at an alarming rate (Ong *et al.*, 2004) with global threat on them (Bouillon *et al.*, 2008). In the past fifty years the global mangrove cover has been reduced to it's one third (Fromard *et al.*, 1998).

Sundarbans, the largest mangrove forest is geographically shared by India and Bangladesh. This forest thrives on the Ganges-Bramhaputra-Meghna (GBM) delta and being very dynamic, it incessantly changes its geomorphological settings. It harbors a very rich floral diversity, and the ecosystem, owing to its unique and rich community structure has been recognized as UNESCO world heritage site since 1987. It derives its name from the mangrove called 'Sundari' (*Heritiera fomes*). The inaccessibility to

Sundarban can reason out the rare availability of diverse studies on these mangroves. The mangrove ecosystems can be apprehended through studies focusing on species dynamics for their conservation, restoration and sustainable management.

Over five decades, various air and space borne sensors have collected useful data and are continuing to do so, for the understanding and policy- & decision-making for future sustenance, management and restoration of various biophysical realms on earth, especially the forests. One of the fundamental advantages of remote sensing is its competence in providing synoptic and non-destructive spatial data with continuity at frequent intervals making it the tool of choice for researchers. Hyperspectral remote sensing has opened up numerous avenues for understanding the very basic as well as complex nature of bio-physical attributes of vegetation, which is limited in multispectral datasets. These sensors capture the imageries in large number of spectral bands. The present study is first report on the potential of the Airborne Visible InfraRed Imaging Spectrometer-New Generation (AVIRIS-NG) in mapping the mangroves in part of Sundarban Wildlife Sanctuary (Lothian Island) along with its ecological and environmental attributes. A discriminative classification technique, Support Vector Machine (SVM) has been used to classify various species in the Sanctuary. Given the lack of studies in forests of Indian Sundarbans, this study demonstrates the capability of state of the art hyperspectral imager with very high spatial and spectral resolution.

Figure 1: Map showing Indian part of Sundarbans.

MATERIALS AND METHODS

Study area

The Lothian wildlife Sanctuary is located in the south-western fringes Indian Sundarbans and in exposed to the Bay of Bengal (Figure 1&2). The area of the island is approximately ≈28 km^2. The complex estuarine flow pattern results in to an atypical mixing of marine and fresh waters, which creates a wide range of salinity regimes. It is mostly surrounded by human settlements; however, its protected status has kept it as a naturally growing mangrove forest. The Island, as a result of accretion is expanding in its northern bounds from enormous sediment loads.

There are around 35 mangrove species present in Indian part of Sundarbans including true mangroves, back mangroves and mangrove associates. Most of them have developed adaptive modifications to thrive in the hypersaline and anoxic substratum. The meso-macrotidal estuary gets inundated and exposed twice every day by diurnal tides having amplitude of 2.5–7 m (Chatterjee *et al.*, 2009) which facilitates lot of mixing and flushing of water, nutrients and sediments into and through this estuarine ecosystem. The soil texture is chiefly clayey-loam whereas certain parts also have sandy-loam and silty soils.

Satellite data

The AVIRIS-NG hyperspectral mission was jointly accomplished by Indian Space Research organization (ISRO) and Jet Propulsion Laboratory (JPL), NASA from airborne platform over various sites of India. Atmospherically and geometrically corrected level-2 reflectance data for the study area was acquired from the VEDAS (Space Application Centre, ISRO) server (http://vedas.sac.gov.in:8080/aviris/). The sensor assimilated spectral information between 380 – 2510 nm at 5 nm band interval. There are 425 spectral bands over a continuous electromagnetic spectrum and the spatial resolution varied between 4-8 m at different sites spread all over India. We have acquired the data with 5 m resolution. The huge data has enormous amount of information, however the data has noisy bands. The noisy bands are result of various absorptions like water vapour, oxygen and

CO_2 absorption regions (Gao *et al*., 2009) which were removed prior to data dimensionality reduction. After locating the presence of similar spectral information over certain contiguous ranges, 367 bands were found suitable and used for this study.

In situ data

The AVIRIS-NG campaign was conducted over Indian parts of Sundarbans during 20th February to 3rd March, 2016. We have conducted ground truthing concurrently in synchronization with flight sorties. GPS location data using Garmin 72, mangrove species identification data and soil samples were collected through stratified random sampling from the Lothian and adjoining islands in order to cover the study area. For detailed mapping of mangroves, the locations of both mono-specific and mixed mangroves patches were recorded. The priori stratification was done by ocular ground assessment of species assemblage and type-density mapping from satellite imageries.

SVM Classification

The classification of satellite hyperspectral imagery was performed using SVM in ENVI 5.0 (Exelisvis Inc., USA). The SVM is a nonparametric discriminative classification algorithm which uses statistical learning theory (Foody and Mathur, 2004). The technique takes user defined training sets and uses them for classifying the entire data. The categorizing of classes is done by separating different pixels through generation of the optimal hyperplane. SVM classification can use four type of functions viz., linear, polynomial, radial basis function (RBF), and sigmoid. We have used RBF kernel as it fits mathematical function to measured points and makes no assumption about the data (Bishop, 1995).

Soil nutrient, soil salinity and elevation maps

Soil salinity is crucial variable affecting the health and community structure of mangroves. Apart from that, the nutrients present in the soil can also act as limiting or supporting variables for the growth of mangroves. We have collected *in situ* samples for analysing the ranges of the edaphic variables (Table 1) present in the study area. The values were used to generate spatial maps of all the parameters, which were later compared with the species distribution map. The elevation maps were generated from Google earth which helped in comparing topographic profile of various species.

Table 1. Soil salinity and nutrients in the Lothian Island

Soil salinity	1.02-30.7 ppt
Soil Nitrogen	18.23-254.5 mg kg^{-1}
Soil Phosphorus	1.51-201.28 mg kg^{-1}
Soil Potassium	14.89-951.58 mg kg^{-1}

RESULTS & DISCUSSION

Species zonation

The mangroves are adapted to survive and propagate under extreme environmental conditions like diurnal tidal inundation and exposure, hyper-saline waters, anoxic soils and high temperatures. Consequently, mangrove species, despite belonging to different genus, have marked similarities in their anatomical and biophysical properties. Furthermore, the spectral responses of these species are near analogous and the species are difficult to differentiate using multispectral data having spectral information from 5-8 different wavelengths. The classification result of this study (Figure 2) indicated that AVIRIS-NG data has very discrete information which helped in discriminating not only different species, but also the assemblage of same species with different health conditions. The results of SVM showed that various mono-specific and mixed mangrove assemblages can be distinguished precisely. We have been able to map several mangrove species with high accuracy (overall accuracy ≈80 % and Kappa statistic ≈0.79). The SVM classification showed that at least 20 landcover classes (Table 2) including various mangrove assemblages could be differentiated spectrally (Figure 3) with high precision.

Table 2. List of landcovers including different mangrove species assemblages (abbreviations).

AA(M/T)	*Avicennia alba* (Matured/ Tall)
AA(y)	*A. alba* (young)
Acacia	Babool trees
AM	*A. marina*
AM (bs)	*A. marina* (bushy shrub)
AM (deg)	*A. marina* (degraded)
AM, AR, CD	*A. marina, Agialites rotundifolia, Ceriops decandra* assemblages
AO, CD, EA	*A. officianlis, C. decandra, Excoecaria agallocha* assemblages
AR (dom)	*A. rotundifolia* dominated
Bare Soil	Man-made earthen tracks
BG (dom)	*Bruguiera gymnorrhiza* dominated
CD, AC, AR	*C. decandra, Aegiceras corniculatum, A. rotundifolia* assemblages
CD, EA	*C. decandra* and *E. agallocha* assemblages
CD, EA, HF	*C. decandra*, *E. agallocha, Heritiera fomes* (Sundari) assemblages
EA, HF	*E. agallocha* and *H. fomes* assemblages
Fresh W	Fresh water bodies & aquacultures.
Mudflat	Exposed inter-tidal mudflats
PP	*Phoenix paludosa*
SB	Saline blanks
Sea W	Sea water

We have recorded a total of 14 mangrove species (Table 3) in the island and except few, most of them are trees. The outputs revealed that the island is dominated by three species of genus *Avicennia* i.e., *A. alba, A. marina and A. officinalis*. *A. marina* is ubiquitously present throughout the island with different morphological stature and health.

Table 3. List of mangrove species recorded in the study area

Scientific name	Local name
Avicennia alba	Kala bani
A. marina	Peyara bani
A. officinalis	Jaat bani
Acanthus ilicifolius	Hargoja
Agialites rotundifolia	Tora
Bruguiera gymnorrhiza	Kankra
Ceriops decandra	Jaat/Jele Goran
C. tagal	Mot goran
Excoecaria agallocha	Genwa
Heritiera fomes	Sundari
Phoenix paludosa	Hental
Sonneratia griffithii	Ora
Xylocarpus granatum	Dhundul
X. mekongensis	Passur

Ceriops sp. assemblages are present in the form of small bushy plants mostly away from the coast. The intertidal zones were occupied by *A. alba*, whereas the elevated zones were occupied mostly by mixed assemblages. Such distribution could be attributed to specific salinity tolerance of different species. The edge of the creeks and crevices are dominated by *A. officinalis*. *H. fomes* is a fresh water loving species and it is not naturally present in Indian parts of Sundarbans in abundance. The increasing salinity regime has forced replacement of this species by higher salt tolerant species like *E. agallocha*. However, exceptional natural growth of Sundari has been recorded in western boundary of Lothian Island. It is found mostly in association with *C. decandra*, *E. agallocha*, *P. paludosa and X. mekongensis*. Time series data has shown that the island is prograding northwards in to the estuary and the new landform are gradually getting populated by *A. alba*.

The distribution of species is dependent on various factors including tidal inundation, sand-silt-clay content, availability of nutrients, elevation and particular specie's ability to withstand salinity and water stress. Accordingly, the acting environmental parameters like rainfall and solar flux influences the spatial distribution of the mangroves. *H. fomes*, the Sundari trees were found in low salinity and moderate elevation zones (Figure 4a). Their distribution is dependent on the availability of fresh water around the western bank of the island that receives certain amount of fresh water. The moderate elevation allows the trees to receive fresh water and restricts long inundation periods which is probably the reason for their existence in Lothian, whereas the same species is not seen anywhere in Indian Sundarbans naturally. *A. marina* was found widely distributed (Figure 4b) throughout the island. It is found concentrated in moderate elevations and medium salinity zones. Although the species is omnipresent, the difference in elevation and soil salinity has affected their health and morphology. *A. officinalis* is having an affinity towards low salinity and therefore it was found in the similar fringes (Figure 4b) occupying moderate to high elevations zones, especially the creeks. *A. alba* is a very tolerant species with respect to long inundation periods and salinity. They were found particularly growing across intertidal mudflats and to medium elevation zones with high soil salinity (Figure 4c). Most of the species follow a spatial hierarchy from intertidal zones (with different tide levels) to topographically elevated zones (inundated only in spring tides). Also, there exists a preference of cohorts among different species e.g. *A. marina*, *C. decandra* and *A. rotundifolia* could be found together, whereas, *A. alba* would never be seen with *P. paludosa*. The entire phyto-dynamics is naturally controlled by environment and species specific physiology, however, anthropogenic influence in the form of reduction in fresh water flow has impacted the distribution of mangroves adversely.

Mangrove health

The health of mangroves is significant indicator of the tropical estuarine ecosystem's sustainability. Mangrove diversity and their spatial spread contribute intricately to the dynamics of such deltaic ecotone. Concurrently, the health of mangroves depends on the prevalent as well as active physico-chemical variables and tidal dynamics. As a result of sea level rise; saline intrusion and coastal erosions are serious threats to the mangroves. Most importantly, the salinity acts as major determinant for health and distribution of mangroves having an inverse correlation. The detailed mapping revealed spatial variations in the stress of some species. The spatial variation in salinity and topology determines their health in a critical way. In Figure 3b, the red patches show the dwarfed bushy trees of *A. marina* where the salinity is towards higher ends and elevation is just near the high tide mark leaving them with infrequent tidal inundation. Whereas, the green patches shows the *A. marina* reforestation done by department of forests, which eventually grew into a plantation with poor health (short canopy with less branches). The condition could be attributed to the high salinity and rare tidal of the areas. Species having affinity towards lower salinity are better in terms of carbon sequestration. Naidoo (2009) found that high levels of soil Nitrogen can enhance the resource allocation to shoots increasing growth and productivity. *A. officinalis* [N (58-138 mg kg^{-1}), P (40-178 mg kg^{-1}), K (314-528 mg kg^{-1})] is one of such species which prefers medium salinity (6.7-15 ppt.) having vigorous growth and high biomass content in these zones.

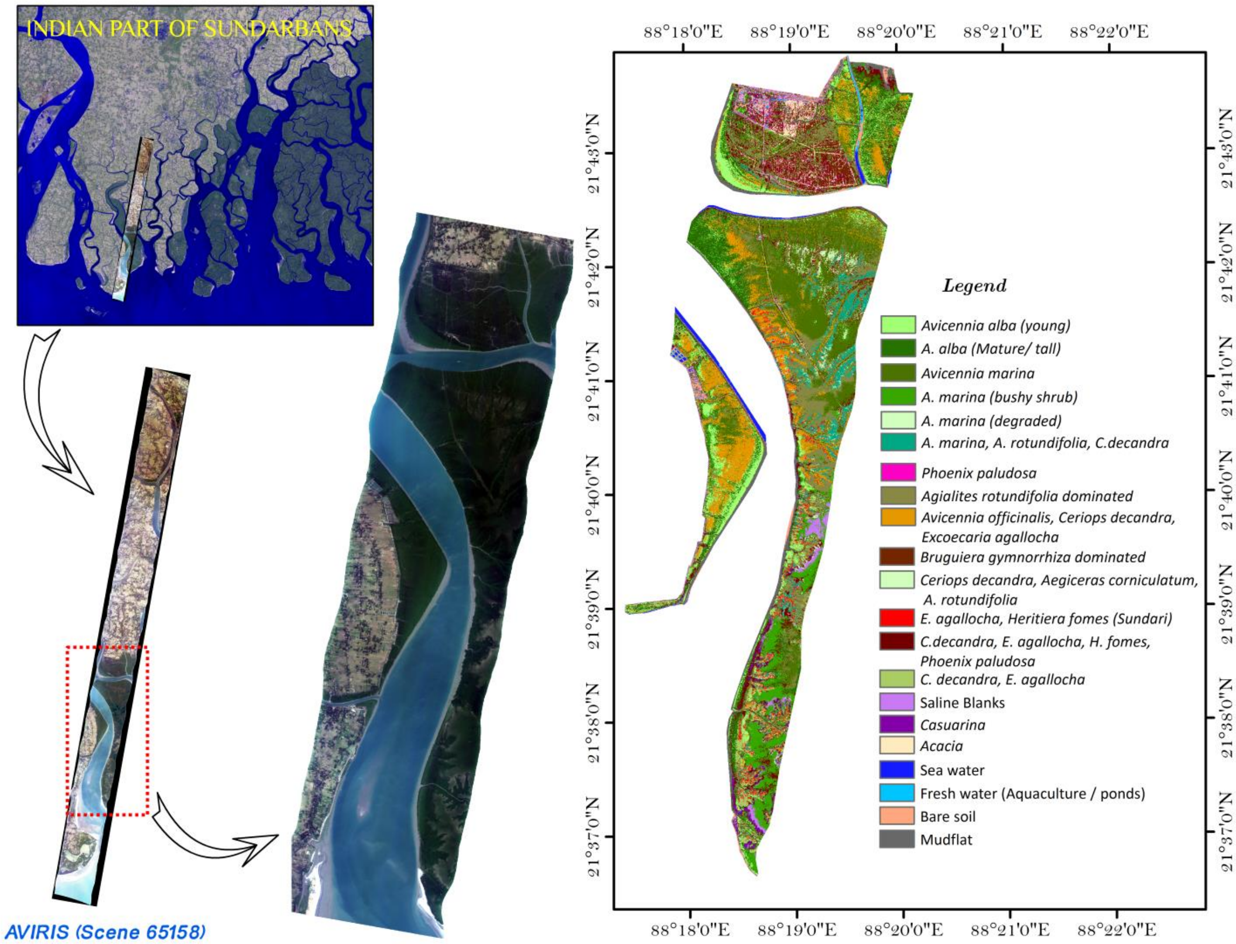

Figure 2. Classification map showing the distribution of mangrove species in Lothian Island.

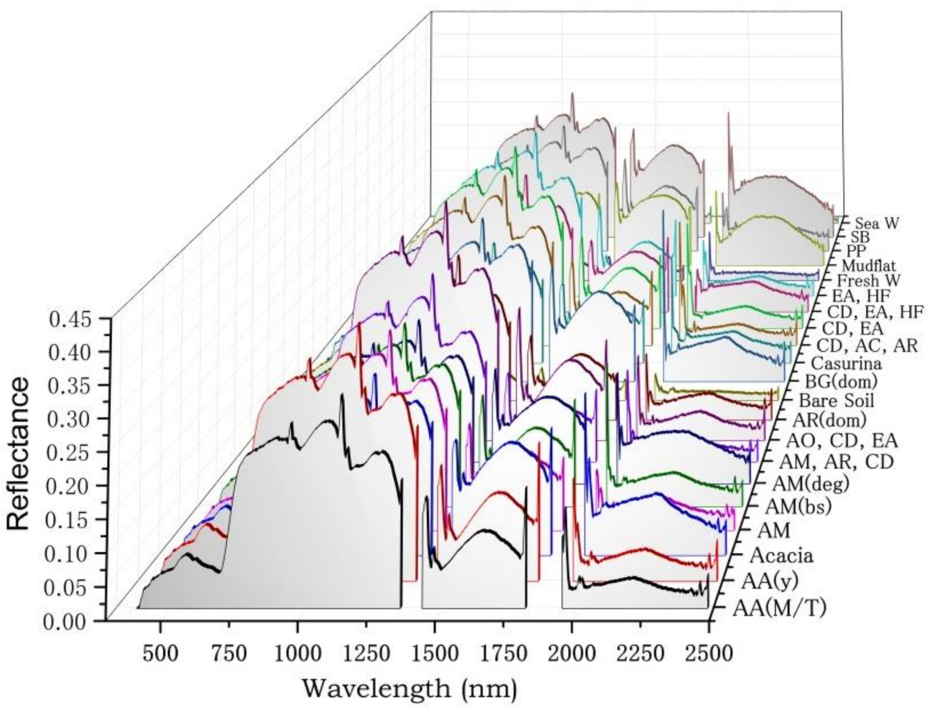

Figure 3. AVIRIS NG satellite image derived mean reflectance curves (absorption bands were masked) of the various mangroves and other landcovers used for SVM. (Z axis abbreviations are explained in Table 2)

Sundari (*H. fomes*) is sparsely present in Lothian Island in contrast to other parts of Indian Sundarbans. The edaphic variables in substratum under Sundari trees and its assemblage sites are particular with specific ranges [N (33-59 mg kg^{-1}) P (15-160 mg kg^{-1}), K (288-520 mg kg^{-1})]. It grows in areas with low soil salinity values that ranged here between 6-9 ppt. The forest morphology including green canopy of mangrove species is found better in higher Potassium zones (K is vitally important for osmotic regulation) and low Nitrogen and Phosphorus zones (limiting nutrients), while there is a considerable control of soil salinity on the mangroves zonation, growth and survival. Many researchers have propounded the view that intricate factors like nitrate, ammonium and salinity (Naidoo, 1990), salinity variation (Ball, 1988) and nutrient limitation (Woodroffe, 1985 and Lin, 1992) may be coupled causing variation in mangroves primary production. However, nutrient limitation dynamics in mangrove ecosystems are multifaceted and different processes respond in diverse manner to the same nutrient (Feller *et al.*, 2003). All these factors, in conjunction to each other control the growth and morphology of the trees e.g. Tall/Dwarf or Bushy/lean canopy.

P. paludosa is a climax community indicator (Naskar, 1988) that are present in topographically elevated positions, often in association with the most adaptive species *E. agallocha*, which is omnipresent in all salinity zones and topographic domains. Climax community is the stable state where other species are likely inhibited from entering the community because it does not provide suitable resources. However, any change in environmental and other variables like salinity, topography and sea-level can perturb these ecosystems. Multiple obstructions to the fresh water supply through the upper reaches of Indian Sundarbans are gradually increasing the salinity regime of the estuary. The resulting condition has led to the reduction in the population of fresh water loving mangrove species. Increase in soil salinity has been linked to decrease in aboveground biomass, as it controls early survival and growth of high shore trees (Kirui *et al.*, 2008). The forest is gradually changing by means of dwarfing of the mangrove trees, change in the mangrove community and lessening canopy cover from the salinity stress. Dwarfing could be easily determined from the slenderness coefficient (which is defined as total tree height to *dbh* ratios) of the individuals. Moreover, the reduction of fresh water is almost certainly responsible for change in estuary's salinity regime and consequently distribution of mangrove species. Dangremond *et al.*, (2015) observed that salt stress caused relatively lower growth rates with little or no effect from light exposure. The mangrove canopy in Indian Sundarbans has low density, where light penetration is likely not a limiting factor for photosynthetic activity. Apparently, these observations are explanatory towards the stunted growth which is probable outcome of salt stress only. Such notes most likely account for the low slenderness coefficient in mangroves of Indian Sundarbans.

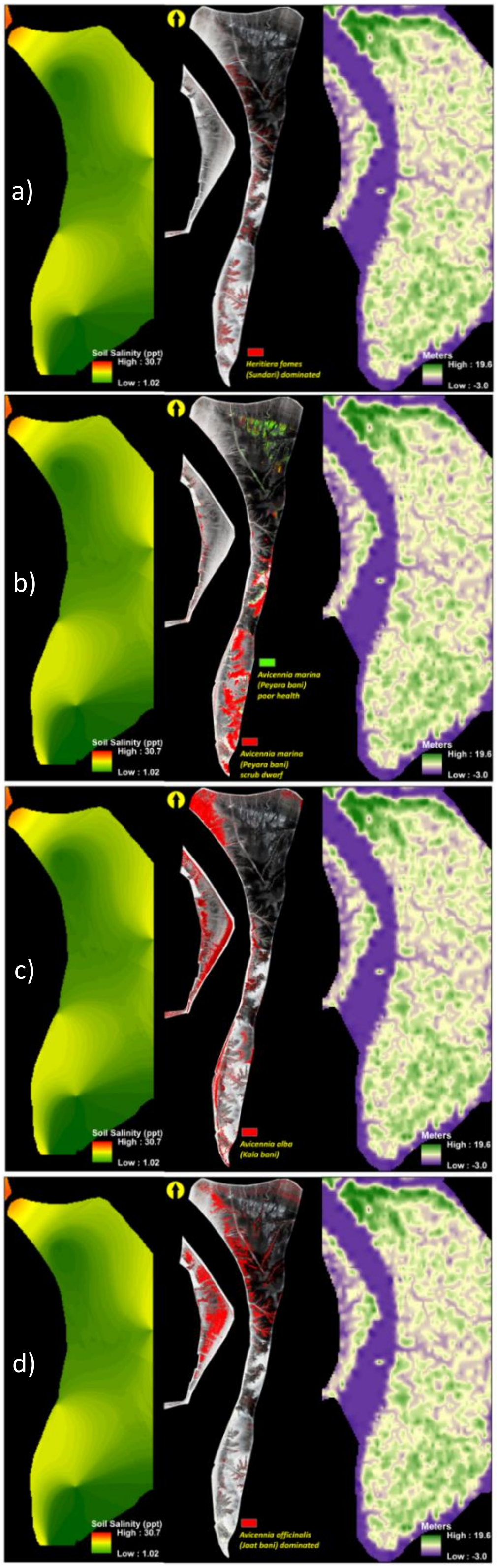

Figure 4. Species distribution maps with salinity and topographic maps of Lothian Island showing a) *Heritiera fomes*, b) *Avicennia alba*, c) *A. marina* and d) *A.officinalis* assemblages.

CONCLUSION

The study is the first report of the capability of very high resolution hyperspectral AVIRIS-NG data to map mangroves of Sundarbans at species level. It is shown that it's possible to precisely map at least 20 landcover classes including various mangrove species and their assemblages. The hyperspectral information captured by the airborne sensor not only identified different mangrove species but also distinguished between trees of same species with different health conditions. The classification of the data using Support Vector Machine learning produced map with overall accuracy of ≈80 % and Kappa statistic ≈0.79. The finer spectral as well as spatial resolution of the data allows discrimination of mangrove species as efficiently as could be done by spectroradiometer data. The spectral curves from the image are comparable to the *in situ* spectral data and can be alternatively used for making repository of spectral library after minor bias correction. Moreover, the use of SVM followed by its precise outcomes further eases the classification and mapping. The finer variations in the spectra can also reveal the canopy biophysical attributes of mangroves, which is to be investigated in further studies. However, in the present study, comparative analysis with the *in situ* data revealed the AVIRIS NG data's predictive capability for the mangroves of Sundarbans.

The analyses indicated that the species distribution has a definite but compounded influence from soil salinity, topography and tidal inundation. Moreover, nutrient profile of the substrate soil is another key factor in controlling the health of the mangroves. Species like *A. alba* and *A. marina* can withstand high salinity but the trees grow with different stature of the woody compartments and canopy structure of the trees when subjected to variable conditions. Soil salinity is the most intricate variable that is inversely proportional the endurance of the mangroves, except for species like *E. agallocha*. Only few species like *A. rotundifolia* can prevail against hyper-haline conditions, which have developed specific salt extrusion mechanism. The natural and exceptional presence of *H. fomes* (Sundari trees) is indicative of certain amount of fresh water resource. Moreover, the stability of the forest in the form of climax community is represented by *P. paludosa*. Gradually increasing salinity can disturb the ecosystem's equilibrium and stability.

ACKNOWLEDGEMENTS

The authors thank Director, Space Applications Centre, ISRO, GoI, Ahmedabad for providing the AVIRIS NG data over Sundarbans and supporting the research. We are also thankful to the Dept. of Forests, Govt. of West Bengal for their utmost support and assistance in the fieldwork.

REFERENCES

Ball, M.C., 1988. Salinity tolerance in the mangroves *Aegiceras corniculatum* and *Avicennia marina*. I. Water use in relation to growth, carbon partitioning, and salt balance. Functional Plant Biology, *15*(3), pp.447-464.

Bishop, C. M., 1995. Neural networks for pattern recognition; Oxford Press, Oxford, 482p.

Blasco, F., Saenger, P. and Janodet, E., 1996. Mangroves as indicators of coastal change. Catena, 27(3), pp.167-178.

Blasing, T. J., 2014. Recent Greenhouse Gas Concentrations, Carbon dioxide information analysis center, Retrieved May 2. 2014 from http://cdiac.ornl.gov/pns/current_ghg. html.

Bouillon, S., Borges, A.V., Castañeda-Moya, E., Diele, K., Dittmar, T., Duke, N.C., Kristensen, E., Lee, S.Y., Marchand, C., Middelburg, J.J. and Rivera-Monroy, V.H., Smith III, T. J., Twilley, R. R., 2008. Mangrove production and carbon sinks: a revision of global budget estimates. Global Biogeochemical Cycles, 22(2), pp.1-12.

Chatterjee, M., Massolo, S., Sarkar, S.K., Bhattacharya, A.K., Bhattacharya, B.D., Satpathy, K.K. and Saha, S., 2009. An assessment of trace element contamination in intertidal sediment cores of Sunderban mangrove wetland, India for evaluating sediment quality guidelines. Environmental Monitoring and Assessment, 150(1-4), pp.307-322.

Dangremond, E.M., Feller, I.C. and Sousa, W.P., 2015. Environmental tolerances of rare and common mangroves along light and salinity gradients. Oecologia, 179(4), pp.1187-1198.

FAO, 2007. The world's mangroves 1980-2005: A thematic study prepared in the framework of the Global Forest Resource Assessment 2005. FAO Forestry paper 153, ROME 2007.

Feller, I.C., Whigham, D.F., McKee, K.L. and Lovelock, C.E., 2003. Nitrogen limitation of growth and nutrient dynamics in a disturbed mangrove forest, Indian River Lagoon, Florida. Oecologia, 134(3), pp.405-414.

Foody, G.M. and Mathur, A., 2004. A relative evaluation of multiclass image classification by support vector machines. IEEE Transactions on geoscience and remote sensing, 42(6), pp.1335-1343.

Fromard, F., Puig, H., Mougin, E., Marty, G., Betoulle, J.L. and Cadamuro, L., 1998. Structure, above-ground biomass and dynamics of mangrove ecosystems: new data from French Guiana. Oecologia, 115(1-2), pp.39-53.

FSI, 2003. State of the forest report 2003. Forest Survey of India, Ministry of Environment and Forest, Govt. of India, Dehradun.

Gao, B.C., Montes, M.J., Davis, C.O. and Goetz, A.F., 2009. Atmospheric correction algorithms for hyperspectral remote sensing data of land and ocean. Remote Sensing of Environment, 113, pp.S17-S24.

Giri, C., Ochieng, E., Tieszen, L.L., Zhu, Z., Singh, A., Loveland, T., Masek, J. and Duke, N., 2011. Status and distribution of mangrove forests of the world using earth observation satellite data. Global Ecology and Biogeography, 20(1), pp.154-159.

Kirui, B.Y., Huxham, M., Kairo, J. and Skov, M., 2008. Influence of species richness and environmental context on early survival of replanted mangroves at Gazi bay, Kenya. Hydrobiologia, 603(1), p.171.

Lin, G.H. and Sternberg, L.D.S., 1992. Effect of growth form, salinity, nutrient and sulfide on photosynthesis, carbon isotope discrimination and growth of red mangrove (*Rhizophora mangle* L.). Functional Plant Biology,19(5), pp.509-517.

Naidoo, G., 1990. Effects of nitrate, ammonium and salinity on growth of the mangrove *Bruguiera gymnorrhiza* (L.) Lam. Aquatic Botany, 38(2), pp.209-219.

Naidoo, G., 2009. Differential effects of nitrogen and phosphorus enrichment on growth of dwarf Avicennia marina mangroves. Aquatic Botany, 90(2), pp.184-190.

Naskar, K., 1988. Economic potentialities of the tidal mangrove forests of Sundarbans in India. Journal of the Indian Society of Coastal Research, 6(2), pp.149-158.

Ong, J.E., Gong, W.K. and Wong, C.H., 2004. Allometry and partitioning of the mangrove, *Rhizophora apiculata*. Forest Ecology and Management,188(1), pp.395-408.

Spalding, M., 2010. World atlas of mangroves. Routledge, Earthscan, London.

Spalding, M., Blasco, F. and Field, C., 1997. World mangrove atlas. International Society for Mangrove Ecosystems, Okinawa, Japan.

Tomlinson, P. B., 1986. The Botany of Mangroves. Cambridge University Press, London (1986) pp. 1–12.

Woodroffe, C.D., 1982. Litter production and decomposition in the New Zealand mangrove, *Avicennia marina* var. resinifera. New Zealand Journal of Marine and Freshwater Research, 16(2), pp.179-188.