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A comprehensive geospatial assessment of seagrass distribution in India

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A B S T R A C T

The study deals with the first comprehensive spatial distribution and area estimate of seagrass patches of India with a standardized methodology. Seagrass patches are mainly located in Palk Bay – Gulf of Mannar (Tamil Nadu), Gulf of Kachchh (Gujarat), Chilika Lake (Odisha) and Islands of Andaman & Nicobar and Lakshadweep. Medium resolution satellite images of Landsat 8 OLI were subjected to radiometric, atmospheric and water column correction prior to digital classification and contextual editing. Total estimated seagrass area amounts to 516.59 km^2 of which Palk Bay and Gulf of Mannar of Tamil Nadu together contribute to 398.81 km^2. Overall classification accuracy for the six sites studied, ranged between 64% (Lakshadweep Islands) and 83.5% (Palk Bay). This suggests that for surveillance studies of homogeneous seagrass meadows with low interspersion of other benthic units such as corals, seaweeds etc., digital mapping using medium resolution data sets with mandatory attenuation correction procedures is suitable. The results of this study and the related area statistics were accepted as a baseline at national level for the delineation of Ecologically Sensitive Areas (ESA) and in the formulation of its conservation strategies. For a cursory appraisal of the status of major seagrass regions, a matrix representation of its locational occurrence and habitat characteristics is provided.

1. Introduction

Seagrass are submerged flowering plants found in shallow marine waters such as bays, estuaries, lagoons and along the continental shelf and play an important role in maintaining the biodiversity and overall health of coastal ecosystems. It is observed that there is no comprehensive global inventory of the seagrass area and the documented seagrass area is approximately 177,000 km^2 (Green and Short, 2003). In India, dense seagrass patches are primarily located in the Palk Bay - Gulf of Mannar (Tamil Nadu), Gulf of Kachchh (Gujarat), Chilika Lagoon (Odisha), and in stretches surrounding the Islands of Andaman & Nicobar and Lakshadweep. A comprehensive areal estimate and spatial distribution at country level is lacking, although estimates at selected locations are available. Furthermore, a standardized methodology involving attenuation correction; algorithms that nullify the effect of atmospheric aberrations, sunglint, variable water column, suspended sediments, turbidity, phytoplankton communities etc., were not followed for mapping. Considering the spatial distribution and temporal behaviour of seagrass, mapping and monitoring of seagrass meadows also need to be on a tangible scale.

In the visible region, seagrass meadows tend to have distinctly different spectral signature from their adjacent substrata. Wavelengths between the range 350–950 nm can be effectively used for discriminating benthic features such as seaweeds, seagrass, corals, sand and rock. Seaweeds and seagrass have differences in reflectance within 700–950 nm (near-infrared band) wavelengths. Although near-infrared band gets absorbed in the uppermost part of the water column, floating mats of algae cause increased reflectance, which helps in differentiating it from bottom dwelling seagrass (Fyfe, 2003; Sagawa et al., 2012). Presence of algal epibionts on seagrass is discriminable at 560–670 nm due to increased reflectance peaks (Fyfe and Dekker, 2001).

In recent times satellite-based optical remote sensing and digital image processing have been successfully used as a valuable tool in mapping and in the assessment of benthic habitats (Andréfouët et al., 2001; Eugenio et al., 2015; Fornes et al., 2006; Manessa et al., 2016; Mishra et al., 2006; Mumby and Edwards, 2002; Nayak and Bahuguna, 2001; Phinn et al., 2005, 2012; Purkis and Riegl, 2005; Schweizer et al., 2005; Wicaksono, 2016). Landsat sensors have been widely used in benthic habitat assessment with reasonable success (Blakey et al., 2015; Guebas et al., 1999; Mervyn et al., 1997; Shapiro and Rohmann, 2006; Wabnitz et al., 2008; Yang and Yang, 2009). There are around forty studies dealing with seagrass mapping in India for selected locations of Andaman and Lakshadweep Islands, Palk Bay, Gulf of Mannar and Chilika with disparate methods. Some of the studies are based on *in situ*

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SCUBA - GPS assisted transect surveys. Until recently, the general lack of awareness in India regarding water column correction has been reflected in many of the previous studies, which had been a concern among reef scientists in late ’90s (Mumby et al., 1998). These studies utilised IRS Series of LISS III /LISS IV scenes/aerial photographs (Jagtap and Inamdar, 1991, 2009; Nobi and Dinesh, 2014; Sridhar et al., 2010; Thangaradjou et al., 2008; Umamaheswari et al., 2009), which lacked blue band and had not implemented attenuation correction algorithms.

The present work comprehensively maps the seagrass extent of India using Landsat 8 OLI data incorporating radiometric, atmospheric and water column attenuation correction algorithms. In many areas, seagrass meadows exhibit temporal variations in terms of spatial extent and density due to various seasonal, environmental and anthropogenic causes. This study provides a one-time assessment of the current spatial distribution of seagrass and its comprehensive area statistics. However, repetitive monitoring at appropriate time periods is necessary to develop a holistic perspective of changes caused by physico-chemical and biotic influences.

The spatial distribution of seagrass varies from continuous meadows to highly dispersed heterogeneous patches (Frederiksen et al., 2004; Robbins and Bell, 1994; Turner et al., 1999). Seagrass landscape can be considered as a heterogeneous mix of seagrass patches embedded in a substrate background of soft sediments, sand, clay or coral debris often coexisting with diverse marine fauna. Analysis of the heterogeneity of these habitat mosaics ranging from small discrete patches to landscape meadows using the spatial outputs have helped in configuring these ecosystems into a hierarchy of spatial scales, which also could serve as an indicator of ecosystem conditions. The present study also explores the spatial heterogeneity of the seagrass benthos of the five major regions based on the average nearest neighbour and patch size analysis of the seagrass distribution obtained from map outputs.

2. Materials and methods

2.1. Study area

Six sites (i) Palk Bay (ii) Gulf of Mannar (Tamil Nadu) (iii) Gulf of Kachchh (Gujarat) (iv) Chilika Lake (Odisha) (v) Islands of Andaman & Nicobar and (vi) lagoons of Lakshadweep Islands are the major seagrass sustaining regions in India.

Palk Bay forms the south western portion of the Palk Straight, an inlet of Bay of Bengal between south eastern India and northern Sri Lanka. It is situated within the latitude 9°18′N - 10°18′N and longitude 78°54′E − 79°54′E. Palk Bay is approximately 60–85 km wide and has significantly shallow warm water than the adjacent Bay of Bengal and Indian Ocean. Maximum depth of the sea bed in this region is about 13 m. The water is turbulent during the north east monsoon season and remains calm in other seasons. The spring tidal range is between 0.06 m and 0.7 m and neap tidal range is 0.32–0.48 m. The region is enriched with rich marine flora and fauna and especially significant and diverse submarine habitats. Palk Bay sustains the most extensive cover of seagrass in the Indian subcontinent.

Gulf of Mannar Marine National Park with 21 small islets established in the year 1986 has an area of about 560 km^2. It is separated from Palk Bay by a chain of small islands and reefs known as Ramsethu, also known as Adam's Bridge, which includes the Mannar Island. The region stretches from 08°47′N - 09°15′N; 78°12′E − 79°14′E and is rich in biodiversity with endangered sea cow (*Dugong dugon*), corals, seagrass, salt marshes, algal communities and mangroves. Tidal amplitude of the area is about 0.5 m.

Seagrass in Gujarat are restricted to the Gulf of Kachchh, which extends over an area of about 7350 km^2 and was declared as a Marine National Park in 1982 under the provisions of the Wildlife (Protection) Act, 1972 of India. The Gulf of Kachchh divides Kachchh and the Kathiawar peninsula regions of Gujarat between 22°24′N −23°05′N and 69°00′E − 70°50′E. Because of the geo-physical effects caused by shallow inner regions and narrowing cross section, the tidal amplitude increases significantly towards east in Gulf of Kachchh. The highest high water reaches to about 7 m and tidal influx covers the adjacent areas of creeks and alluvial marshy lands increasing the inter tidal expanse. India's first marine reserve, the Gulf of Kachchh Marine National Park, and the Marine Sanctuary, Jamnagar comprising of about 620 km^2 is located along the Southern part of the Gulf. Gulf of Kachchh sustains a variety of species including corals, sea mammals, mangroves, salt marshes and marine algae.

The Chilika is the largest brackish water lagoon in Asia situated along the eastern coast of India in the State of Odisha. It stretches within the latitude of 19°28′N - 19°54′N and the longitude of 85°05′E − 85°38′E. Based on biogeochemical parameters, the lagoon is broadly divided into four sectors namely northern sector, central sector, southern sector and outer channel. During the monsoon season, it covers an area of 1144 km^2 whereas in the dry winter season it reduces to 780 km^2 (National Wetland Atlas, Orissa, 2010). The average depth of the lagoon is between 1.5 and 2 m. Lagoon experiences a semidiurnal tidal pattern with annual spring and neap tidal range of 1.60 m and 0.50 m respectively. Because of the estuarine intertidal setting in the eastern part and the riverine influences on the north-western part, it experiences a highly dynamic environment with seasonal variations in bio-resources. Chilika is a highly productive ecosystem sustaining rich fishery resources as well as seaweeds, micro algae, seagrass and crabs providing livelihood for people living around the lake. The rare endangered Irrawaddy dolphins is the flagship species occurring in the lagoon.

The Andaman and Nicobar Islands contain a significant share of the seagrass patches. Separating the Bay of Bengal and Andaman Sea, they are a group of 836 islands, of which 36 are inhabited. The Andaman Islands are geographically located at 6°N - 14°N and 92°E − 94°E with total areal extent of 8249 km^2. Shores are rocky with fringing coral reefs intermittent with seagrass and few sandy beaches. Muddy grounds are limited and are found only in protected bays and creeks. The tides are semidiurnal with amplitude of 3 m. Coastal belts of both the archipelago supports littoral forests and various other marine communities. Mahatma Gandhi National park (1983) at Wandoor, Rani Jhansi National Park (1996) sustains rich patches of seagrass in immaculate state.

The Lakshadweep Island group is located in the Arabian Sea towards the south-western side of the Indian peninsula. Located between 10° 00′ N - 12° 00′ N and 73° 00′ E − 92° 40′ E, the islands are the northern portion of the vast undersea mountain range: the Chagos-Laccadive Ridge. Lakshadweep Islands are the only atoll reefs in India. There are 32 small islands of which only 10 are inhabited. The tide over the near shore waters of Lakshadweep islands is of semi-diurnal type with a maximum tidal range of 1.4 m. Islands are surrounded by coral reefs with sandy beaches, seagrass patches in the lagoons, and coralline algal ridges on the seaward boundary.

2.2. Data sets

Selection of satellite data set was a crucial aspect in this study. Decisive factors that steered the selection of the data set were (a) the need to produce the maps and area statistics within a reasonable time span of two years to arrive at a comprehensive national level statistics while taking into consideration seasonal fluctuations and options for temporal analysis wherever necessary (b) extensive, yet disconnected coverage area of interest (c) compatibility of seagrass spectral characteristics and patch size (minimum mappable unit) with the spatial resolution and band characteristics of data (d) open access of suitable medium resolution data in terms of temporal, radiometric and spectral resolutions and (e) data gap and incongruence in the array of scenes of high resolution images with respect to seasonal variations and benthic cover characteristics due to scene multiplicity resulting out of low swath width.

Considering all the above factors, Landsat 8 OLI with a spatial resolution of 30 m was most preferred circumventing the major technical challenges. The products were Level 1 terrain-corrected 16 bit unsigned integer in GeoTIFF format with UTM projection and WGS 84 datum. Several images for respective study sites between the time periods 2014–2016 were downloaded from https://earthexplorer.usgs.gov and scenes with no cloud cover in the area of interest were selected. In the case of Chilika, all the images were substantially affected by scattering due to turbidity. Furthermore, compared to other sites, seasonal fluctuations in seagrass extent is prominent in Chilika. Hence two best suitable images representing pre monsoon (04 April 2014) and post monsoon (29 October 2016) were selected.

2.3. Image processing

To begin with, digital composite images were prepared by stacking the first seven bands of each scene. Geometric accuracy was checked with respect to terrestrial features on corresponding topographic sheets of same projection and datum. It was observed that all the images were maintaining the positional conformity of sub pixel and hence geometric correction was not performed. This was followed by atmospheric correction as the present data can form a baseline and in future, multi-temporal scenes recorded under different atmospheric conditions can be compared. Corrections were carried out for gain and bias of sensors, solar zenith angle and aerosol density with Atmospheric Correction and Haze Reduction (ATCOR) software to obtain the surface reflectance images. Wave-induced specular reflectance effects resulting in sunglint were unseen on images and hence glint correction was not performed.

Mapping submerged substrates is confounded by water column light attenuation (Mumby et al., 1997). Different substratum types, variable water depth and light attenuation in water are the major impediments encountered in mapping underwater habitats. Solar radiation entering the water column, attenuates in an exponential manner with increasing water depth (Gordon and Wang, 1992). Severity of the decline in light intensity is dependent on the absorbing and scattering properties of the transmitting medium and measured wavelength. Hence “the remote sensing reflectance should be corrected for the water column effects to minimize the confusion between bottom types caused by differences in depth and optically active constituents” (Zoffoli et al., 2014 p.16886). *In situ* studies investigating the properties of water column and remote sensing reflectance from various benthic habitats and depth are available (Holden and LeDrew, 2001; Hochberg et al., 2003; Yamano and Tamura, 2004). These studies although demonstrate the usefulness of radiative transfer models, they were utilised only for limited areal extent due to difficulties in the collection of concurrent data pertaining to inherent and apparent optical properties with the time of image acquisition.

An exhaustive review of various water column techniques by Zoffoli et al., 2014 reveals that the Lyzenga's algorithm (Lyzenga, 1978, 1981) “is currently one of the most popular approaches” which is based on various studies by Andréfouët et al., 2003; Benfield et al., 2007; Call et al., 2003; Ciraolo et al., 2006; Hochberg et al., 2004; Mumby et al., 1997; Mumby and Edwards, 2002; Pu et al., 2012; Blakey et al., 2015; Vanderstraete et al., 2006; Valesini et al., 2010. The use of this methodology for water column correction has resulted in increased mapping accuracy by digital classification processes (Ackleson and Klemas, 1987; Green et al., 2000; Mumby et al., 1998; Zainal, 1994). It is a fully imaged based correction technique on the assumption that light attenuation follows an exponential decay curve with depth in Type I & II waters and the ratio of the attenuation coefficients developed from a pair of bands is only dependent on the wavelength of the bands and the clarity of the water and is the same irrespective of bottom type.

In the present study, attenuation due to water column was rectified by developing Depth Invariant Indices (DII) as outlined by Lyzenga (1981). Instead of wet bottom reflectance, a DII depicts a relation between reflectance in two spectral bands without a depth effect. Considering the geographical locations, the scale of the study areas, and the constraints in collecting simultaneous depth and water column characteristics *vis-a-vis* satellite date of pass, a fully band based correction technique where the local depth values were not needed for the entire scene was the most suitable option. Furthermore, interspersion with diverse substratum and significant depth range especially in areas of Palk Bay and Gulf of Kachchh necessitated the reduction of variable depth effects on spectral signatures. The depth of water column under consideration was to the limit of 10 m which depicted vertical and horizontal homogeneity in terms of optical properties.

Prior to water column correction, land features were masked out using the contours developed from band 6 (1.566–1.651 μm) of Landsat 8 OLI. Depth invariant index was developed from each set of bands i and j from blue, green, red and NIR by the equation

$$B_{ij} = \ln(L_i) - [(K_i/K_j) \times \ln(L_j)] \tag{1}$$

where Li and Lj are the outputs from atmospheric correction of band i and band j respectively; K_i/K_j is the ratio of water attenuation coefficients of bands i and j. This was determined from a bi-plot of a log transformed reflectance in the two bands Li and Lj using samples selected from the bottom of a uniform substratum viz., sand at variable depths. An image composite was then developed from band pairs of blue-red, blue-green, blue-NIR, green-red, green -NIR and red- NIR.

2.4. Classification scheme

Typical seagrass patch distribution with varying foliage cover density and patchiness as observed during field survey from various survey sites is presented in Fig. 1. Based on this field observation, a three category density classification viz., highly dense (> 70%) medium dense (40–70%) and sparse (10–40%) that closely correspond to categories derived for seagrass cover in other studies (Mumby et al., 1999; Wabnitz et al., 2008) was planned. This classification was intended to ingrain pixel-wise variation in horizontal and vertical meadow structure. But this distinction could not be accurately established due to the varied phyllotaxy, pigment content and morphology of seagrass species, especially in low density classes where adjacency effect (Kaufman, 1989) due to neighbouring barren sand substratum broadened the signature probability distribution of spectral classes causing lower separability.

Generalisation of this classification scheme for all the study areas entailed normalisation of class values which need further investigation. Although distinct species/community zonation was achieved in few of the extensive areas, all the above classes were merged to a single category of seagrass to maintain uniformity. Other than seagrass, depending on the heterogeneity of the benthic mosaic occurring in each of the study areas, other classes *viz.*, algae, emergent vegetation and water were also included.

2.5. Digital image classification and accuracy assessment

Composite of DII images were subjected to unsupervised classification using Iterative Self Organising Data Analysis (ISODATA). It was selected as the prime classification technique as it requires only minimal initial input, but after classification the resulting spectral classes can be merged or disregarded which permits the intervention of the user. Supervised method as the initial clustering algorithm requires prior comprehensive knowledge of all the seagrass patches which were non-existent for most areas. In order to avoid the uneven polarisation of training sets resulting in unwanted and non-quantifiable omission of seagrass pixels, ISODATA clustering which is iterative and geographically unbiased was selected. The number of initial clusters specified for each of the scenes was determined based on the extent of the area to be mapped and variation within the spectral classes. Misclassified pixels identified from field data and secondary sources

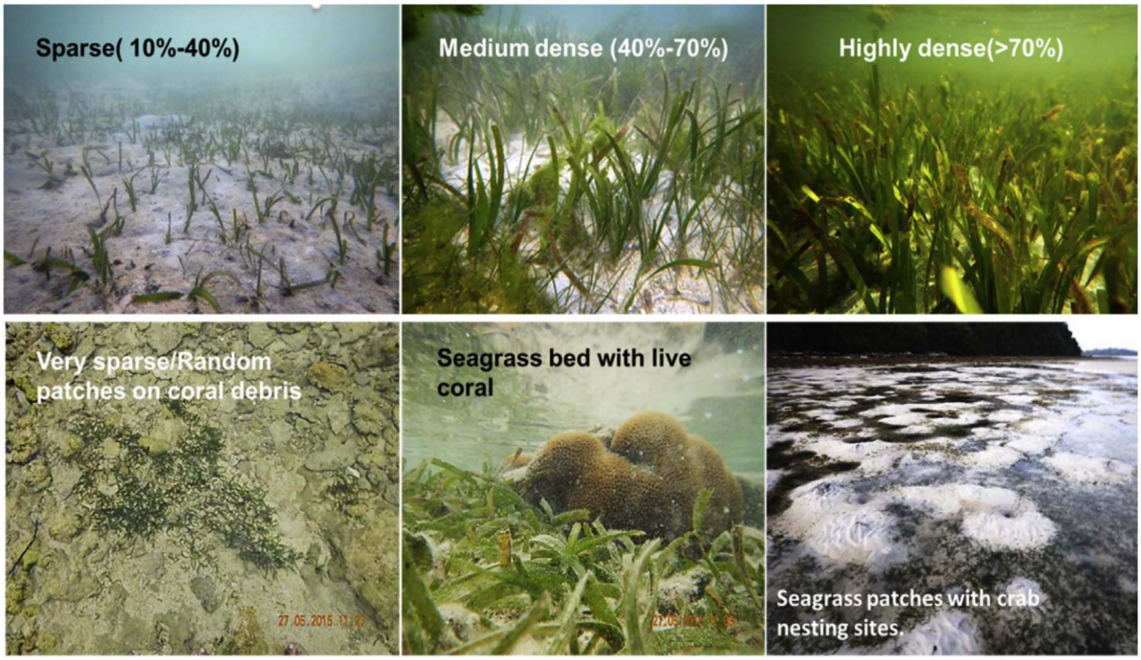

Fig. 1. Seagrass distributions with varying foliage cover density and substratum.

were reclassified using maximum likelihood algorithm followed by contextual editing. The outputs thus obtained were overlaid to produce the final seagrass distribution map.

Classification accuracy of each of the study areas was verified using standard spatial error matrix of Congalton (1991). Stratified random sampling is one of the common sampling techniques (Cakir et al., 2006; Cochran, 1977; Huang et al., 2010; Mayaux et al., 2006; Olofsson et al., 2013) for sample selection as it is a probability sampling design that addresses the key objective of estimating class-specific accuracy (Olofsson et al., 2014). It accommodates the alteration of sample size, which was often the case due to the occurrence of many inaccessible points and rare classes such as algae and emergent vegetation. Stratified random points were generated and reference pixels were collected during the field surveys. Based on optimum allocation (Stehman, 2012) for low variability classes like water, fewer sample size were taken, while a minimum sample size of 50 was maintained for seagrass class except in Lakshadweep islands were patch size was relatively small. Kappa coefficient of agreement (Congalton and Green, 2008) was not included in the present study as it does not serve a useful role in accuracy assessment or area estimation (Olofsson et al., 2014; Pontius and Millones, 2011; Strahler et al., 2006).

The mapping approach followed and the spatial distributions of seagrass cover along with ground truth points in the sub tidal shallow bathymetric surface in Palk Bay region are shown in Fig. 2.

2.6. Patch dispersion analysis

Patch heterogeneity of seagrass meadows is studied using the Nearest Neighbour tool that measures the distance between each feature centroid and the centroid of its nearest neighbour. For this, the raster format of the seagrass distribution is converted into vector format. The mean of all these distances determines the average proximity of seagrass patches, a measure of the patch dispersion/heterogeneity; higher the value the more dispersed the patches are and vice-versa.

3. Results and discussion

Based on the above mapping process, the total seagrass extent of the country is estimated to be 516.59 km^2. The area estimated for the study sites along with the details of images utilised is provided in Table 1. Prominent seagrass regions and their spatial distribution in India are shown in Fig. 3.

Structurally seagrass in Palk Bay, Gulf of Mannar and Chilika characterises meadow formations due to large patch size. These regions depicted higher overall classification accuracy compared to the dispersed patches around the islands of Lakshadweep, Andaman- Nicobar and Gulf of Kachchh (Fig. 4). The obtained overall accuracy range for the six sites along the coast of India varied from 64 to 83.5% and is comparable to the variable overall classification accuracies (46–88%) achieved by the regional-scale seagrass habitat mapping in the Wider Caribbean region using Landsat sensors 5 & 7 (Wabnitz et al., 2008).

3.1. Palk Bay

Palk Bay sustains the most widespread seagrass meadows of the country; an update of its entire areal extent is not available. SCUBA assisted transect surveys between the Mandapam and Thondi stretch of Palk Bay region during the period 2007–2009, estimated a total area of 175 km^2 of seagrass (Manikandan et al., 2011; Mathews et al., 2010). In the present study, seagrass extent of Palk Bay is estimated to cover 329.70 km^2 with an overall classification accuracy of 83.5% for the year 2014.

Seagrass patches (indicated as #2 in Fig. 3) are present along the entire stretch of Palk Bay from Adiramapattinam in the north to Rameshwaram in the south. Towards the offshore, in certain regions it extends to a distance of even 10 km owing to the shallowness of the Bay. Except for a few areas, seagrass meadows exist within a width of about 300 m from the coast, which is followed by a no seagrass zone of approximately 2 km. Seagrass patches occurring towards offshore after this “no seagrass zone” extends for about 6–7 km, however, with low density. Field surveys indicate that towards the Devipattinam - Panaikkulam region, seagrass meadows are almost continuous from the coast and extend for about 4.5–5 km. It is observed that seagrass cover density and diversity is higher in near shore intertidal and shallow sub tidal habitats.

Among the 14 seagrass species occurring along this coast, *Cymodocea serrulata* is the most abundant species and has a wider range

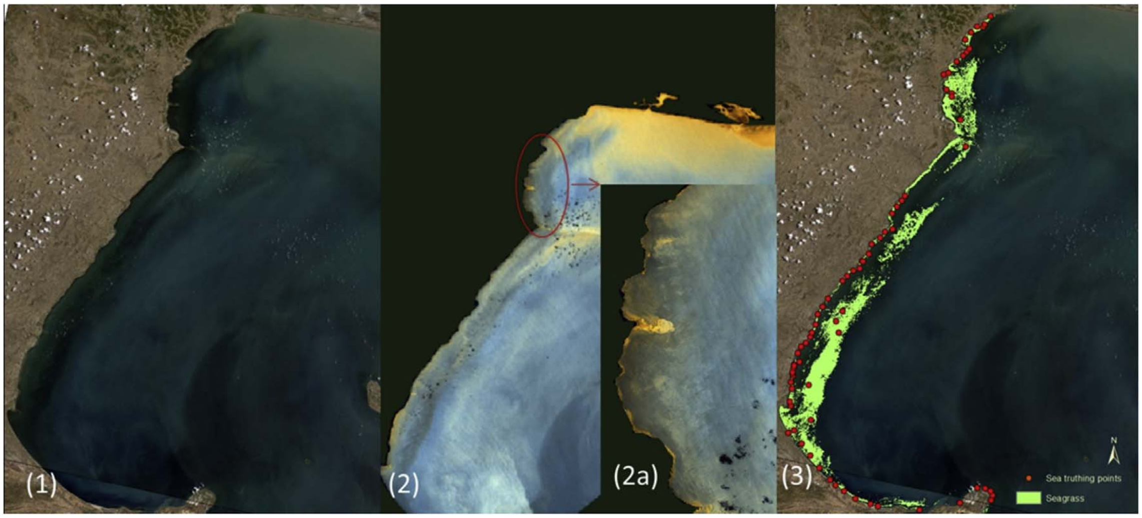

Fig. 2. Attenuation correction and ground truthing of Landsat 8 OLI image - Palk Bay (Tamil Nadu). (1) Image after atmospheric correction (2) Image after water column correction – composite depth invariant index (2a) Enlarged image of the selected region (3) Classified output with sea truthing sites.

Table 1
Seagrass area statistics and overall classification accuracy.

Sl. No.	State	Location	Area in km2	Overall Classification Accuracy	Landsat 8 OLI Date of Pass
1	Andaman & Nicobar Islands	Andaman Islands	5.79	67.00	09-03-2014
2	Andaman & Nicobar Islands	Nicobar Islands	8.81	64.00	02-03-2014
3	Gujarat	Gulf of Kachchh	16.99	69.00	10-04-2014
4	Lakshadweep Islands	Kalpeni	0.57	64.00	26-01-2016
		Kadamat	0.15	66.70	
5	Odisha	Chilika Lake	85.47	73.00	04-04-2014
6	Tamil Nadu	Palk Bay	329.70	83.50	15-01-2014
					09-09-2014
7	Tamil Nadu	Gulf of Mannar	69.11	78.00	14-05-2016
	TOTAL		516.59		

of distribution. *Enhalus acoroides* is less common, seasonal and endemic, and is found in rich clay – silt soil. In the near shore area *Cymodocea* sp. and *Syringodium* sp. are dominant; the middle zone is represented by *Thalassia hemprichii* and *Halodule* sp. dominates the offshore region. Shoot density, biomass and epiphytic biomass gradually decrease from near shore to offshore due to increased depth and decreased light penetration.

Patch dispersion analysis revealed that the seagrass cover of Palk Bay is almost homogeneous and extensive. The largest continuous patch of seagrass recorded in Palk Bay measured about 16 km^2 and the average patch neighbourhood distance is 245 m.

3.2. Gulf of Mannar

Seagrass distribution of Gulf of Mannar was well studied compared to other regions (Table 2). However, the estimate showed considerable variation; other than the temporal differences in assessment, the major reason being the dissimilarities in methods of estimation. In the present study, an initial classification was performed for seagrass estimation without water column correction which produced an areal extent of 44 km^2. This was however an underestimate as revealed from the field survey and post field classification on the depth corrected image which resulted in an estimated area of 69.11 km^2 with better accuracy levels (78%). The importance of water column correction for variable depth effect is highlighted through this case, as many of the additionally discerned patches occurred in the deeper waters between the mainland and the island belt. Around the major island groups of Mandapam and Keezhakkarai, sizeable patches of seagrass are present whereas seagrass distribution decreases towards the Vembar and Tuticorin group of Islands in the south.

The Pamban area and south-east coast of Rameshwaram Island is dominated by *Enhalus acoroides*. The lagoons of Krusadai, Pullivasal and Pumarichan Islands sustain *Cymodocea serrulata, Halodule uninervis and Halophila ovalis*. Other species found in Gulf of Mannar include *Cymodocea rotundata, Thalassia hemprichii* and *Syringodium isoetifolium*. The largest patch having an area of 39.22 km^2 spreads across the shallow coastal stretches of Mandapam and Keelakarai. This is mainly dominated by *Cymodocea serrulata* and *Halodule uninervis*.

3.3. Chilika

Seagrass of Chilika Lagoon can be classified as enduring meadows with an opportunistic behaviour due to seasonal variations. Emergent vegetation like *Phragmites karka* dominate the Northern sector and some portions of Central sector in Chilika along with other invasive species like *Potamogeton pectinatus, Eichornia crassipes* and *Najas graminea* which demanded emergent vegetation as an additional class in Chilika Lagoon. Compared to other sites, substrates were located in more turbid waters with Coloured Dissolved Organic Matter (CDOM). Water column correction with green band combinations (Green-NIR and Green-Red) helped in discriminating aquatic features effectively. Recorded user's accuracy for emergent vegetation/algae and seagrass were 69.47% and 71.43% respectively.

Digital image processing of temporal data sets of Landsat 8 OLI for the months of April and October 2014 are estimated as 85.47 km^2 and 65.12 km^2 of seagrass extent respectively (Fig. 5). A similar reduction in seagrass extent was observed by Samal (2014) using IRS P6 LISS III data though the extent obtained was about 114 km^2 in February 2012 and

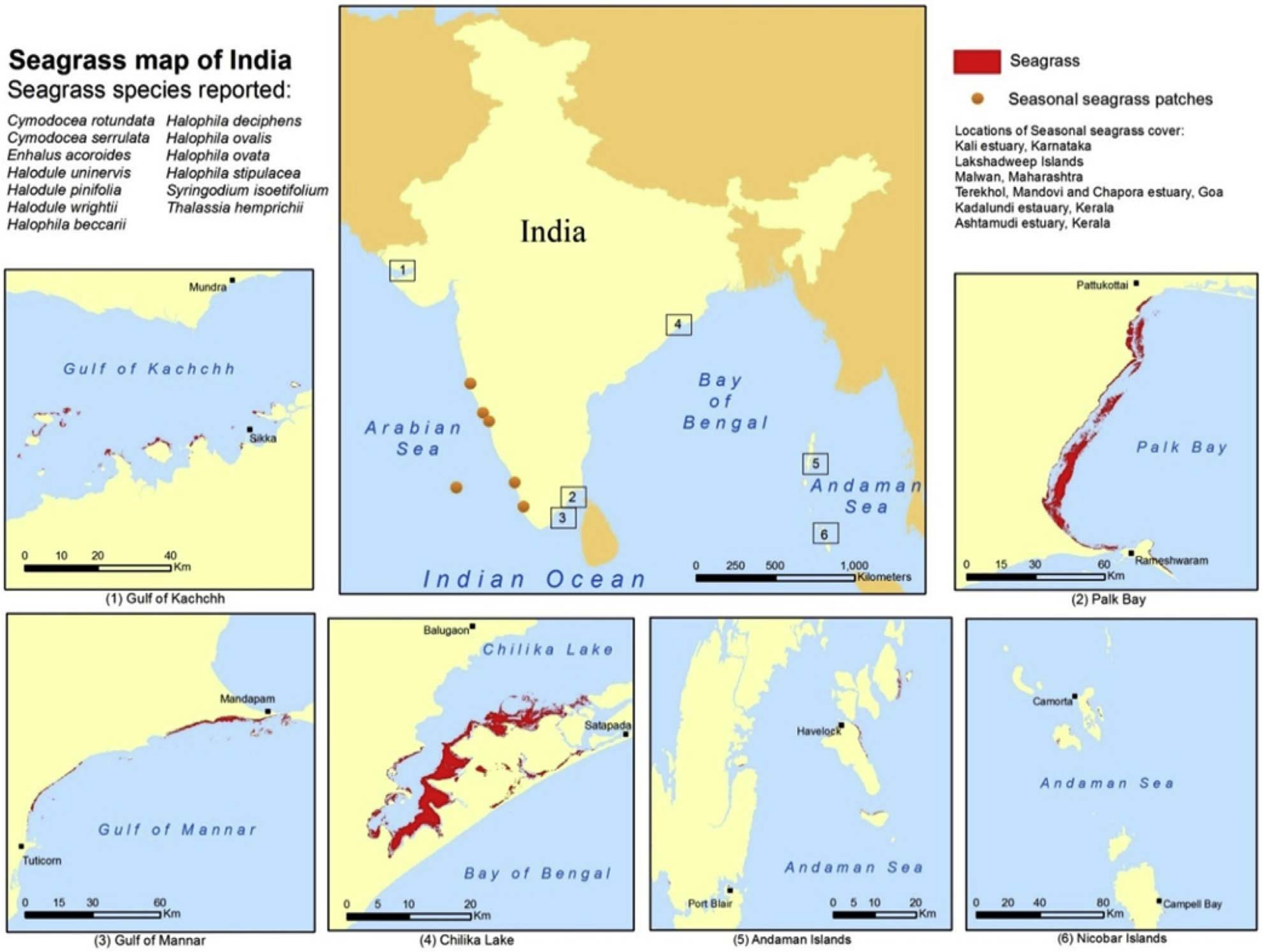

Fig. 3. Prominent seagrass regions in India produced from digital image classification of Landsat 8 OLI images after subjecting to atmospheric and water column correction.

106 km^2 in June 2012.

In Chilika Lagoon the average patch size decreases during the pre-monsoon. This can be attributed to the development of small scattered patches due to congenial environmental characteristics like increased salinity and higher Photosynthetically Active Radiation (PAR). This phenomenon is reversed during post-monsoon when conditions for growth are relatively reduced which causes the destruction of small patches and as only larger patches sustain, providing a higher average patch size with relatively higher spatial dispersion of patches. During pre-monsoon season the average salinity of Chilika lagoon reaches 20 psμ, whereas after the monsoon season the salinity is reduced to 10 psμ (Srichandan et al., 2015). The central sector extending till Kalijai Island was covered greatly with invasive weed *Potamogeton pectinatus* with the highest area cover during post monsoon due to reduced salinity (Shaw et al., 2000). The average direct normal irradiance recorded at Chilika lagoon during pre-monsoon, monsoon and post monsoon season is about 5.5, 3.41 and 5.48 KWh/m^2/day, respectively (URL 1, 2014) of which 48–50% of PAR is utilised for plant growth. Innately, the seagrass patches of Chilika are vast and interconnected though not very dense as observed towards the eastern side of the southern sector of Chilika harbouring the villages of Kuanarpur, Budhibar and Bajrakote.

3.4. Gulf of Kachchh

An aerial extent of about 17 km^2 of seagrass cover is estimated in the Gulf of Kachchh. Seagrass beds in the lower intertidal region of Gulf of Kachchh and a number of islands have experienced a decline (Jagtap et al., 2003). The rare sighting of *Dugong dugon*, the only extant species of the family Dugongidae could be attributed to the obvious decline in seagrass beds.

Halophila beccarii, Halodule uninervis, Halophila ovalis and *Thalassia hermprichii* are the commonly observed species. Maximum seagrass extent is observed in Kalubhar Island, Bhural reef and Pirotan Island. The largest seagrass patch extending nearly 1.35 km^2 is observed to the north of Dhani bet region. The reef area of Bhural and Kalubhar also sustains large seagrass patches of 1.24 and 1.15 km^2, respectively.

3.5. Andaman and Nicobar

The study estimated 5.79 km^2 of seagrass beds spread across the shallow waters around various islands of Andaman for the year 2014. Rich seagrass patches are present around the islands of Little Andaman, Henry Lawrence, Havelock and Neil. Scattered patches are also located in North Wandur, Kalipur, Chatham, Chitiyatapu, Aves Island, Ross Island and Smith Island. Seagrass patches are also observed in Baludera beach near Mayabunder, Kyd Island, Chatham and North Wandoor. Nobi et al. (2013) reported a total area of 12.2 km^2 of seagrass patches to exist in Andaman Islands, discerned mainly through visual interpretation, except in Henry Lawrence group of Islands where digital image processing was employed. New seagrass patches are also mapped in Kyd Island, Baludera and North Wandur in the present study.

The largest single patch of about 0.65 km^2 is observed to the north-eastern shore of Havelock Island. The lagoon regions of Iglis Island and Henry Lawrence Island sustain a very dense and diverse seagrass cover of up to 1.85 km^2. Katchall Island and Camorta Island has a major share of seagrass in Nicobar with 2.43 km^2 and 2.38 km^2 of cover

Chilika Lagoon

	S	W	A/E		UA
S	70	13	15	98	71.43
W	6	83	18	107	77.57
A/E	11	18	66	95	69.47
	87	114	99	300	
PA	80.46	72.81	66.67		OA 73

Palk Bay

	S	W	A		UA
S	135	9	11	155	87.10
W	4	91	11	106	85.85
A	5	3	52	60	86.67
	144	103	74	321	
PA	93.75	88.35	70.27		OA 83.5

Gulf of Mannar

	S	W	A		UA
S	75	14	15	104	72.12
W	4	60	18	82	73.17
A	7	7	54	68	79.41
	86	81	87	250	
PA	87.21	74.07	62.07		OA 78

Gulf of Kachchh

	S	W	A		UA
S	59	13	12	84	70.24
W	12	48	12	72	66.67
A	9	8	40	57	70.18
	80	69	64	213	
PA	73.75	69.57	62.50		OA 69

A & N Islands

	S	W	A		UA
S	50	11	12	73	68.49
W	10	39	13	62	62.90
A	9	7	37	53	69.81
	69	57	62	188	
PA	72.46	68.42	59.68		OA 67

Lakshadweep Is.

	S	W	A		UA
S	28	9	7	44	63.64
W	6	22	7	35	62.86
A	7	5	23	35	65.71
	41	36	37	114	
PA	68.29	61.11	62.16		OA 64

Fig. 4. Spatial error matrix developed to evaluate the accuracy of classified Landsat 8 OLI images of respective study areas. Accuracy is estimated at 95% confidence interval. Columns represent reference and rows denote classified pixels. Major diagonal axis represents correctly classified pixels while all non-diagonal elements represent errors of omission or commission. S - seagrass, W - water, A - algae, E – Emergent vegetation, PA – Producer's Accuracy, UA – User's Accuracy, OA - Overall Accuracy. For Lakshadweep Is. seagrass around Kadamat and Kalpeni Islands are only studied.

Table 2
Seagrass mapping studies of Gulf of Mannar over a period (1998–2008).

S.No.	Area of Investigation	Year of Investigation	Estimated seagrass area (km^2)	Methodology	Reference
1	a. Gulf of Mannar (GoM) b. Palk Bay (Pamban to Thondi)	2007–2008	76 (GoM) 175 (Palk Bay)	SCUBA and GPS Surveys	Mathews et al., 2010
2	Gulf of Mannar	2005	46.67 -Dense seagrass 8.48 -Sparse seagrass	IRS LISS-III data - Digital Classification and contextual editing.	Susila et al., 2012
3	Gulf of Mannar (Rameshwaram, Krusadai, Pullivasal and Pumarichan Island)	2000 & 2004	7.26 -Dense seagrass (2004) 6.01-Sparse seagrass (2004) 8.84-Dense seagrass (2000) 9.71 km2-Sparse seagrass (2000)	IRS LISS-III data - Digital Image Classification and visual interpretation	Thangaradjou et al., 2008
4	Gulf of Mannar	1998	85.5 km2	IRS LISS-III data – Digital Image Classification and DGPS Survey	Umamaheswari et al., 2009

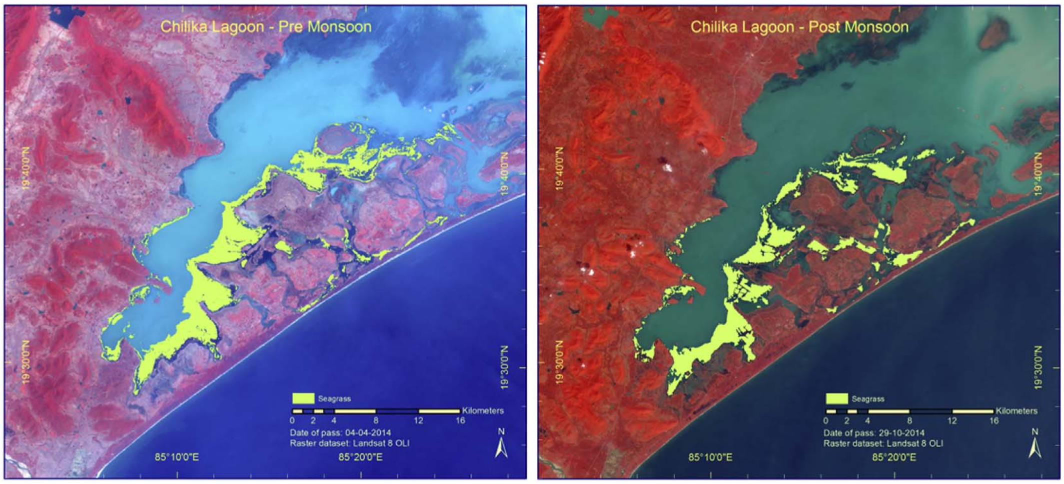

Fig. 5. Seagrass distribution in Chilika lake – Pre monsoon (left) and post monsoon (right).

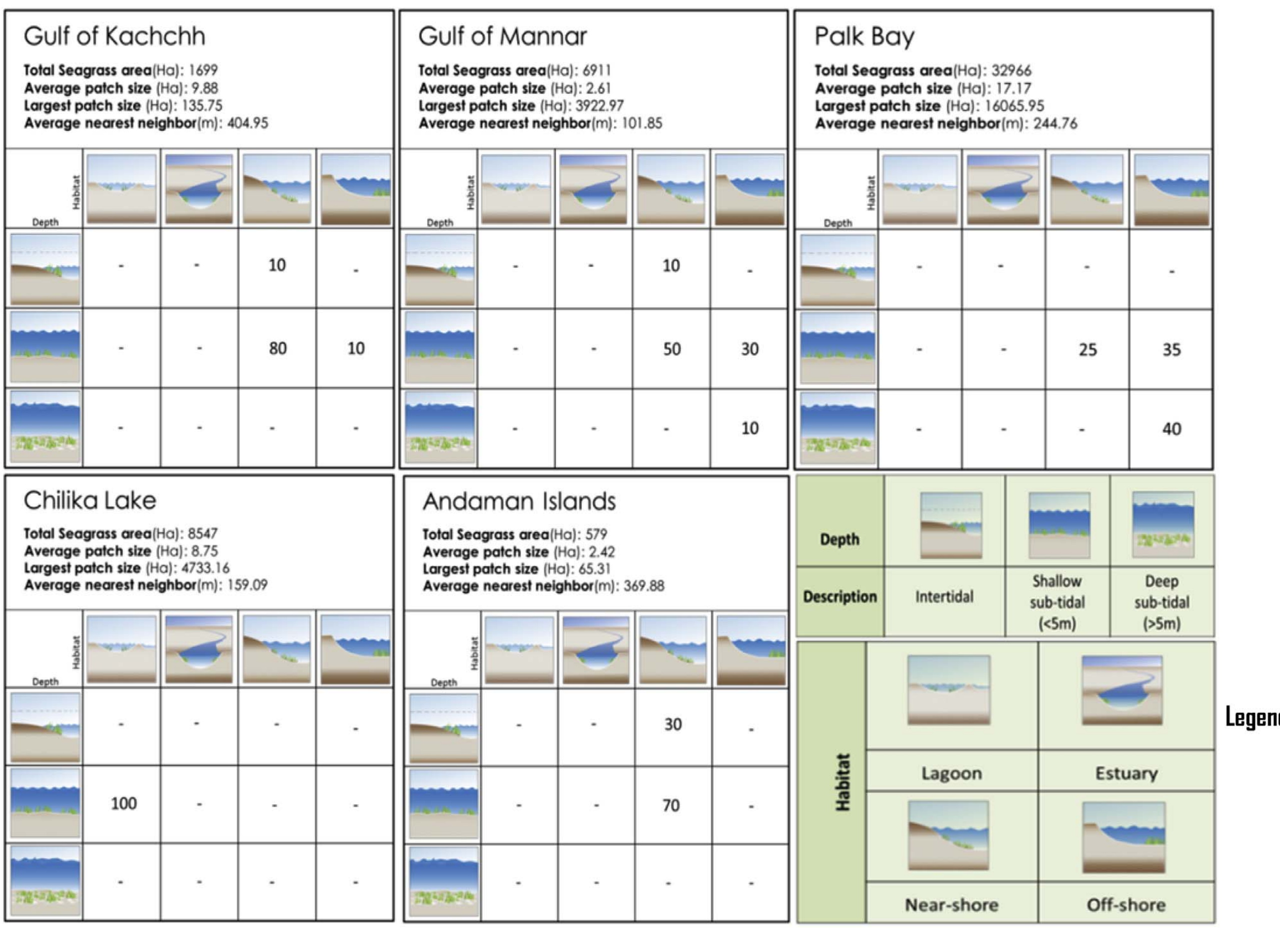

Fig. 6. Habitat – Depth Percentage Distribution Matrix of Indian Seagrass Bioregions. Values in the boxes represent percentage distribution of seagrass (Modified from Kilminster et al., 2015).

respectively. The other regions with significant seagrass cover in Nicobar group are Great Nicobar Island and Car Nicobar Island. Around 8.8 km^2 of seagrass meadows are discerned around Nicobar group of Islands.

3.6. Lakshadweep

Lagoons of Lakshadweep Islands once was believed to have sustained substantial seagrass patches (Koya et al., 2012) is now fast dwindling, due to the overgrazing by turtles (Aparna et al., 2010). Nobi and Thangaradjou (2012) also report a significant decrease of 0.73 km^2 during the period between 2000 and 2008.

The present study mapped the seagrass distribution at Kalpeni and Kadmat for the year 2016 and estimated the total coverage to be 0.57 km^2 and 0.15 km^2 respectively. In the year 2004, Kadmat was reported to sustain seagrass areas of about 6 km^2 whereas in the year 2007 Kalpeni recorded an area of 3.98 km^2 (Nobi et al., 2012). Though seagrass patches are present in the lagoons of other islands such as

Minicoy, Kavaratti and Agatti, the present spread is below the mappable extent and as observed by Prabhakarana and Arunkumar, 2016 is highly sparse in distribution. This reduction in the Minimum Mappable Unit (MMU) by the presence of small and scattered patches challenged the mapping process with a considerable reduction in overall accuracy to 64%.

For all the six sites studied, a spatial matrix is presented in Fig. 6, which allows assessing the distribution of seagrass as a function of habitat type and depth. Also given are statistics of percentage distribution, patch heterogeneity and average patch size.

3.7. Other areas

The distribution of seagrass beds along the west coast of India is minimal with the exception of Gulf of Kachchh, owing to the adverse benthic conditions. They are often transitory and are not traceable to the mappable extent in our field surveys though they have been reported from various locations (e.g. Arunachalam and Nair, 1988; Kaladharan et al., 2011; Kaladharan and Asokan, 2012; Saravanan et al., 2013). Seasonal seagrass beds of *Halophila beccari* are observed along the west coast in Karwar (Karnataka), Malwan (Maharashtra) and Ratnagiri (Maharashtra).

4. Conclusion

The present study estimates the total seagrass area coverage in India as 516.59 km^2. Palk Bay sustains the largest share of 329.70 km^2 followed by Chilika lake with 85.47 km2 and Gulf of Mannar with 69.11 km^2. Although not of considerable extent, dispersed seagrass patches have also been discerned in the Gulf of Kachchh, Gujarat (16.99 km^2) and in the lagoons of Kadmat and Kalpeni of Lakshadweep in the Arabian Sea (0.72 km^2), as well as Andaman and Nicobar in the Bay of Bengal (14.6 km^2).

Compared to earlier studies, this study has utilised a common data set and applied a standard methodology for the entire country. For mapping homogenous patches of seagrass as is the case of major sites like Chilika, Palk Bay and Gulf of Mannar, Landsat 8 OLI with a spatial resolution of 30 m and a spectral suite of blue (0.45–0.51), green (0.53–0.59), red (0.64–0.67), NIR (0.85–0.88) bands with a swath of 170 × 183 km is the best data choice currently available. Utilisation of high spatial resolution (≤ 5 m) optical images with high spectral genre can further augment its classification accuracy which can be made use of in micro level management of highly heterogeneous benthic dispersion as in Andaman-Nicobar and Lakshadweep Islands. Nevertheless, other than the pecuniary aspect of high resolution data, its reduced swath width (11–18 km) and the resultant increase in the number of scenes entails individual pre-processing steps and mosaicking which is inherently time and labour intensive. Also, it is often observed that to obtain cloud free data, the temporal congruence need to be compromised often crossing seasons and even exceeding years which is not advisable as seagrass represent a highly transient ecosystem.

The spatial distribution maps generated can aid in the formulation of seagrass conservation strategies and the methodology employed can be utilised to design cost efficient monitoring programs to assess changes in seagrass distribution. Patch analysis is a valuable tool to gain insight into the degree of patchiness of seagrass beds and assessing its meadow structure.

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