QUANTIFYING GROSS PRIMARY PRODUCTIVITY OF AN INDIAN MANGROVE FOREST USING GEO-LEO SATELLITE DATA

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ABSTRACT

Gross primary productivity (GPP) is total carbon assimilation by plants through the process of photosynthesis. In view of increasing anthropogenic influences and global changes, quantification of carbon assimilation through photosynthesis has gained tremendous significance. Precise estimation of GPP is essential part of several ecosystem models. Mangrove ecosystem, that offers significant protection to coastal environment, is governed by changes in salinity and other micro-environment factors. Globally mangroves are facing serious threat and are undergoing degradation due to anthropogenic pressure. In view of global changes, an assessment of carbon assimilation potential of mangroves is required for developing into a carbon sink and conservation of this fragile ecosystem is highly essential.

In the present study, estimation and validation of mangrove GPP was carried out in Bhitarkanika national park (Odisha, India). Light Use Efficiency (LUE) was modelled from seasonal, diurnal *in-situ* photosynthetic rate observations on 11 dominant mangrove species. For estimation of GPP, 'vegetation photosynthetic model' framework was modified using water, temperature and salinity scalars derived from IRS Resourcesat 2 LISS-4, a Low earth orbit (LEO) satellite data. The incident Photosynthetically Active Radiation (PAR) was derived from insolation product obtained from Geostationary (GEO) satellite KALPANA-1 VHRR for the observation period.

Amongst all the species, highest LUE was found in *Excoecaria agallocha* in winter and summer (5.53 and 0.55 g C m^{-2} MJ^{-1}, respectively), and in *Aegiceras corniculatum* in post-monsoon season (0.58 g C m^{-2} MJ^{-1}). Seasonal 8-day average GPP was found to vary from 3.41 g Cm^{-2} to 14.4 g C m^{-2}, with the highest in winter. Comparison of modelled estimates showed fairly good agreement with MODIS GPP (r = 0.89; n=118) having comparable coefficient of variation (41.8% in modelled and 49.5% in MODIS GPP). The present modelling approach of estimating GPP through GEO-LEO satellite can be used to quantify carbon sink in other Indian mangrove ecosystems.

INTRODUCTION

Mangrove forests form one of the primary coastal ecosystems in the tropical and subtropical regions of the world. These are typically formed where mixing of fresh water (through creeks and rivers) and saline water (from sea) intermix together. Due to cyclic nature of high tide and low tide in the coastal areas, these are subjected to constant changes in their environment. These ecosystems are highly productive and have very high economic significance and conservation / protection value and are governed by changes micro-environment factors, primarily the salinity.

Quantification of terrestrial carbon and regular monitoring of carbon storages over time are important for reasons of climate change mitigation. Terrestrial carbon stocks are also important indicators for other development and environmental goals where changes in stocks may have direct implications on the biodiversity. Globally mangroves are facing serious threat and are undergoing degradation due to anthropogenic pressure. In view of global changes, an assessment of carbon assimilation potential of mangroves is required for developing into a carbon sink and conservation of this fragile ecosystem is highly essential.

Terrestrial ecosystems absorb approximately 60 Gt of carbon annually through the physiological process of photosynthesis (Janzen, 2004), also referred to as Gross Primary Production (GPP) (Hamilton et al., 2002). Mangroves are seen as carbon-rich ecosystem and also have shown higher rates of leaf photosynthesis than the leaves of tropical evergreen trees (Alongi, 2009). To estimate GPP of forest system, photosynthesis of a single leaf is key.

The leaf photosynthetic rate depends on photosynthetic capacity and photosynthesis reduction subject to acting stresses in the environment. At the canopy scale, photosynthetic capacity is the integration of single-leaf chlorophyll content and the total leaf area. While it comes to the canopy level, the process becomes complex and theoretical knowledge of leaf-scale photosynthesis needs to be modelled using different approach that is based upon the use of satellite based reflectance measurements of canopy. Among all methods, light use efficiency (LUE) approach proposed by Monteith (1972) has been most widely used (Potter et al., 1993, Running et al., 2000, Xiao et al., 2004; Zhao, 2009). The model is built upon two fundamental assumptions: 1) GPP is directly related to amount of absorbed PAR and 2) realised LUE ($\mathcal{E}_g$) or actual LUE may be lower than potential LUE ($\mathcal{E}_{max}$ or LUE_{max}) values due to presence of environmental stresses (temperature, drought, etc) (Landsberg, 1986). Precise characterisation of LUE_{max}, the stress factor and leaf area index (LAI) estimations are crucial to the GPP estimation.

Accessibility to mangrove ecosystem poses a challenge to collect *in situ* observations. Bhitarkanika national park, situated in Odisha (India) is also one of such places, where frequent inundation due to tides, muddy soils, dense network of pnuematophores and presence of wildlife makes challenging conditions for conducting ground-based measurements. Remote sensing systems with moderately repeat observations allows modelling using limited *in situ* datasets for studying and monitoring landscape level processes. Seasonal observations were carried out at Bhitarkanika national park in order to characterise light use efficiency of dominant mangrove species in the region. These were used as important input for developing remote sensing based model. Till now, there is no assessment of gross primary productivity for Bhitarkanika mangroves using satellite data. In this context, present study using high resolution sensor is particularly important.

DATA

In-Situ Data

In situ data primarily was collected using various field-based instruments such as LICOR portable photosynthesis system (LI-6400) for diurnal measurements of plant photosynthesis rates. It was used to collect data from the dawn to the dusk, when there is no more photosynthesis activity occurring. In all, 11 dominant species of mangroves – *Aegiceras corniculatum*, *Avicennia alba*, *A. marina*, *A. officinalis*, *Bruguiera parviflora*, *Ceriops decandra, Excoecaria agallocha*, *Heiritiera fomes*, *Lumnitzera racemosa*, *Rhizophora mucronata*, *Sonneratia apetala*- dominant in Bhitarkanika were tagged and measurements of photosynthesis rates were carried out on these samples for 3 seasons- post monsoon (during the month of October), winter (during January) and summer (during April). For each plant sample, measurements were taken at every 45-minute interval, such that within single day minimum 15 observations were taken. Considering number of species under study and every 45-minute interval observations for all the 3 seasons, over 550 observations were collected for analysis.

Satellite Data

The present study aims at using finer resolution data (such as LISS-III and LISS-IV) for better estimation of GPP, based on inputs from coarser resolution as well as in situ collected data. Resourcesat 2 LISS-III and LISS-IV data of year 2015-2016 for 3 seasons- winter, summer and post-monsoon- were used as base data for deriving GPP. Additionally, MODIS derived land surface temperature (LST) product was used for respective season, in order to develop temperature scalar. Further, photosynthetically active radiation (PAR) was derived using insolation product from geostationary satellite Kalpana VHRR, downloaded from www.mosdac.gov.in for the same period.

GPP modelling was carried out using modified 'vegetation photosynthesis model' (Xiao et al. 2004; 2005) and modelled estimates are compared with MODIS derived GPP for the study site in different seasons.

GPP MODELING APPROACH

One of the most widely applied concepts for modelling GPP is the light use efficiency approach of Monteith (1972) (e.g. Prince, 1991; Goetz and Prince, 1999; Heinsch et al., 2006), which expresses GPP as the product of the absorbed photosynthetically active radiation (PAR) (μmol m^{-2} s^{-1}), defined as absorbed solar radiation between the 400–700 nm, and the efficiency, with which the absorbed PAR can be converted into biomass:

The general form of the LUE model is:

$$\mathrm{GPP} = \mathrm{fPAR} \times \mathrm{PAR} \times \mathcal{E}\,\mathrm{max} \times \mathrm{f} \qquad (1)$$

where PAR is the incident photosynthetically active radiation (MJ m^{-2}) per time period (e.g., day or month), fPAR is the fraction of PAR absorbed by the vegetation canopy, ε_{max} is the potential LUE (g C m^{-2} MJ^{-1}APAR) without environment stress, and f is a scalar varying from 0 to 1 and represents the reduction of potential LUE under limiting environmental conditions. ε_{max} is reduced to actual LUE (ε_g) by f which considers environmental stresses in ecosystem. Typically in case of terrestrial environment, temperature, water and phenology scalars are used. In the present approach, salinity scalar has been introduced, since mangrove vegetation and its physiological response are controlled by effects of tides and changing salinity conditions. The maximum LUE therefore is reduced as,

$$\varepsilon_g = T_{scalar} \times W_{scalar} \times P_{scalar} \times S_{scalar} \qquad (2)$$

where T_{scalar}, W_{scalar}, P_{scalar} and S_{scalar} are down-regulators for environmental parameters such as Temperature, Water, Phenology and Salinity, respectively. Brief steps in methodology are outlined in figure 1.

T_{scalar} is estimated at each time step, using the equation developed for the Terrestrial Ecosystem Model (Raich et al., 1991):

$$T_{scalar} = \frac{(T-T\,min)(T-Tmax)}{[(T-Tmin)(T-Tmax)]-(T-Topt)^2} \qquad (3)$$

where T_{min}, T_{max} and T_{opt} are minimum, maximum and optimal temperature for photosynthetic activities, respectively. Typically, T_{opt} range is considered to vary between 25 to 32 deg C (as per current experiment), where at higher temperatures photosynthesis activity starts declining owing to inactivation of enzymes. Temperature corresponding to maximum rate of photosynthesis has been considered as T_{opt}. Sample locations for deriving T_{scalar} are single point observations of tagged mangrove species. In order to convert this into spatial scale, MODIS derived Land surface temperature (LST) data was used. Correlation was established between LISS III derived fractional vegetation cover and MODIS and was converted to T_{scalar} images of the region.

For considering W_{scalar} , Resourcesat 2 LISS-III satellite data was used. Short-wave near infrared (SWIR) has higher sensitive towards water in vegetation and soil background while near infrared (NIR) bands have higher reflectance from vegetation- this property has been given by Land surface water index (LSWI),

$$LSWI = \frac{(\rho\,NIR-\rho\,SWIR)}{(\rho NIR+\rho\,SWIR)^2}$$, where ρ is surface reflectance in respective band. (4)

$$W_{scalar} = \frac{1+LSWI}{1+LSWI\,max} \qquad (5)$$

For considering salinity, soil samples were collected from every tagged location, tested for salinity values. Based on information from 20 sample locations distributed across the study region, an interpolation technique was adopted to prepare salinity gradient map for the region by using krigging method. S_{scalar} was estimated using method similar to T_{scalar} where values of S_{min}, S_{max} and S_{opt} were obtained using in situ measured photosynthesis rates at various locations.

$$S_{scalar} = \frac{(S-S\,min)(S-Smax)}{[(S-Smin)(S-Smax)]-(S-Sopt)^2} \qquad (6)$$

Mangrove forests exhibit green canopy throughout the year because foliage is retained for several growing season like in case of evergreen vegetation. Therefore, phenology scalar is considered as 1 in case of mangrove vegetation. (Law et al., 2000; Xiao et al. 2004).

These set of environmental stressors and light use efficiency estimates are applied to Resourcesat 2 LISS-III (having 4 bands including SWIR) and LISS-IV data (having 3 bands). The later has only 3 bands and lacks information from SWIR channel, which is highly sensitive to presence of water. To make use of this information, SWIR band was resampled and added into LISS-IV data to make composite image having 4 bands. Spectral indices computation was carried out using this 5m composite 4 band data, which gives an edge over LISS-III, owing to its better spatial resolution. Simple ratio of vegetation index was computed and minimum and maximum value were used to compute $fPAR_{chl}$ (Fraction of absorbed Photosynthetically Active Radiation by green component of the canopy) using formula:

$$fAPAR_{chl} = \frac{\boldsymbol{(SR-SRmin)\times(fAPARmax-fAPARmin)}}{\boldsymbol{(SRmax-SRmin)}} \qquad (7)$$

where SR_{max} and SR_{min} are maximum and minimum values of Simple Ratio and SR indicates simple ratio of candidate pixel.

Value of $fAPAR_{max}$ and $fAPAR_{min}$ are taken as 0.9 and 0.01, which are considered as maximum and minimum for forest vegetation (Xiao, 2004).

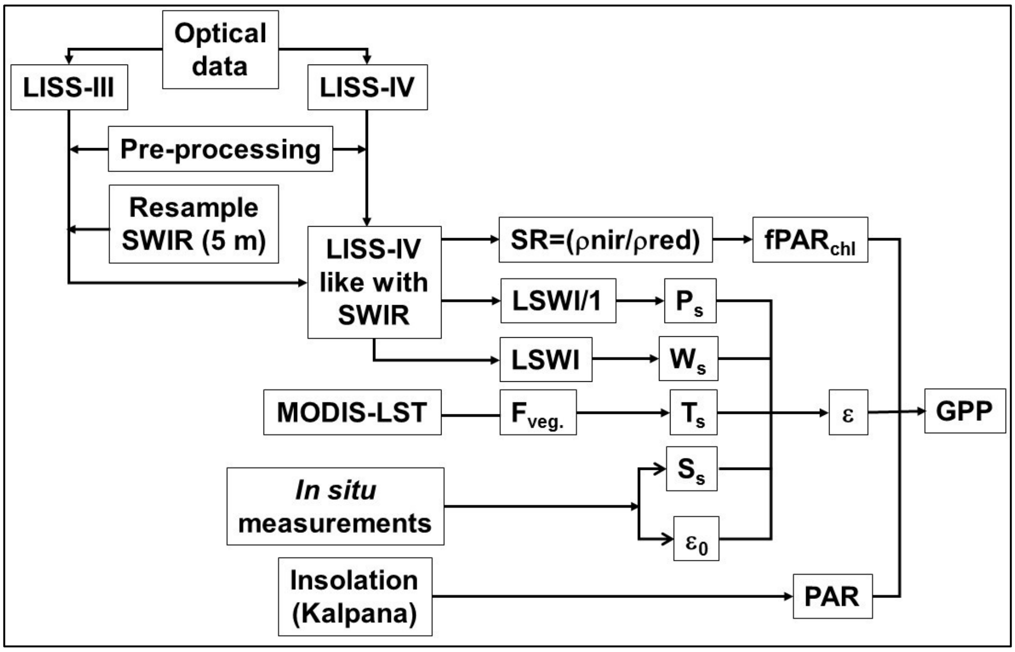

Fig 1: Schematic for estimation of Gross primary productivity by coupling *in situ* light use efficiency with satellite based inputs and derived scalars after modification from 'vegetation photosynthesis model'. ε = light use efficiency (g C MJ^{-1}) , ε_0= maximum light use efficiency (g C MJ^{-1}) also denoted as LUE_{max} , Ps = leaf phenology scalar, Ws = water scalar, Ts = temperature scalar , fPARchl= fraction of PAR absorbed by leaf chlorophyll of the canopy, SR = simple ratio, LSWI = land surface water index, LST = Land surface Temperature, GPP = gross primary productivity, PAR = Photosynthetically active radiation (MJ m^{-2} day^{-1})

RESULTS & DISCUSSION

Environmental Scalars

In addition to inherent physiological nature of each species, seasonality plays important factor in determining the response of plant species. Amount of day light, solar radiation, exposure time, temperature, humidity, presence of winds are some of the other parameters affecting the process, ultimately leading to stress in terms of light, water and temperature. Deriving optimum value of temperature, water and salinity scalar is one of the key parameters. In situ diurnal photosynthesis experiment provided necessary information for deriving optimum values for these parameters. Equation (3), (5), (6) were used to derive each of the scalar (Figure 2).

Light Use Efficiency (LUE)

Daily rate of photosynthesis showed different trends amongst the species. At instances, species indicated standard 'double-peak' pattern of photosynthesis activity. Reduction in leaf-level photosynthesis during higher temperatures (typically in noon) was evident. In mangroves, variations in physiological processes are likely to occur with changes in soil salinity, owing to high tide and low tide timings.

Every 45-minute observations of photosynthesis activity were modelled and integrated for entire day and identified as pE (total photosynthesis) which is measured in μmol of CO_2 m^{-2} day^{-1} which is then converted to g C m^{-2} day^{-1} by using basis of Avagadro's number. Photosynthetically active radiation (PAR) is derived from insolation by using constant factor of 0.47. Daily insolation images were downloaded from Kalpana-VHRR data. Light use efficiency was derived by dividing the total full day integrated pE by total PAR and is expressed in g C m^{-2} MJ^{-1} (Table 1).

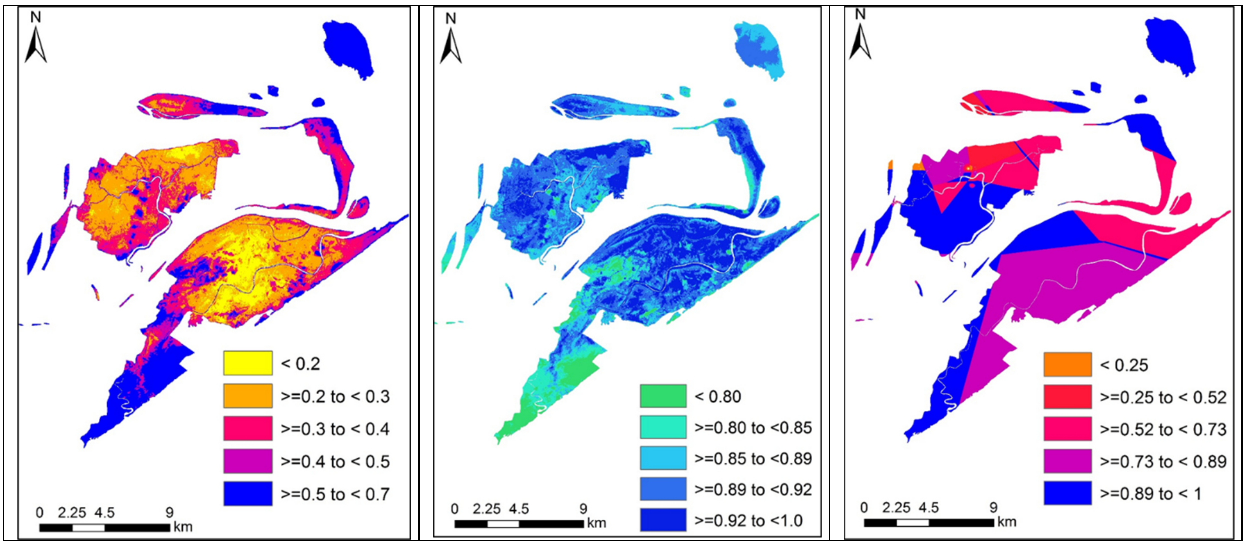

Fig 2: Temperature scalar, water scalar and salinity scalar for Post-monsoon season based on LISS-III data of 06 October 2015. In similar way, scalar images were modelled for each of the season.

Table 1: Maximum Light Use Efficiency ($\mathcal{E}_{max}$) values for 11 dominant species for all seasons. Key to species names- AA: *Avicennia alba*, AC: *Aegicerous corniculatum*, AM: *Avicennia marina*, AO: *A. officinalis*, BP: *Bruguiera parviflora*, CD: *Ceriops decandra* , EA: *Excoecaria agallocha*, HF: *Heritiera fomes*, LR: *Lumnitzera racemosa*, RM: *Rhizophora mucronata*, SA: *Sonneratia apetala*

Species	LUE$_{max}$ (g C m^{-2} MJ^{-1})		
	Summer	Post-monsoon	Winter
A.A	0.39	0.35	0.65
A.C	0.34	**0.58**	2.92
A.M	0.39	0.41	0.66
A.O	0.20	0.33	0.75
B.P	0.31	0.35	1.24
C.D	0.41	0.29	0.71
E.A	**0.55**	0.15	**5.53**
H.F	0.29	0.18	0.94
L.R	0.16	0.23	0.22
R.M	0.17	0.18	0.14
S.A.	0.53	0.44	1.29

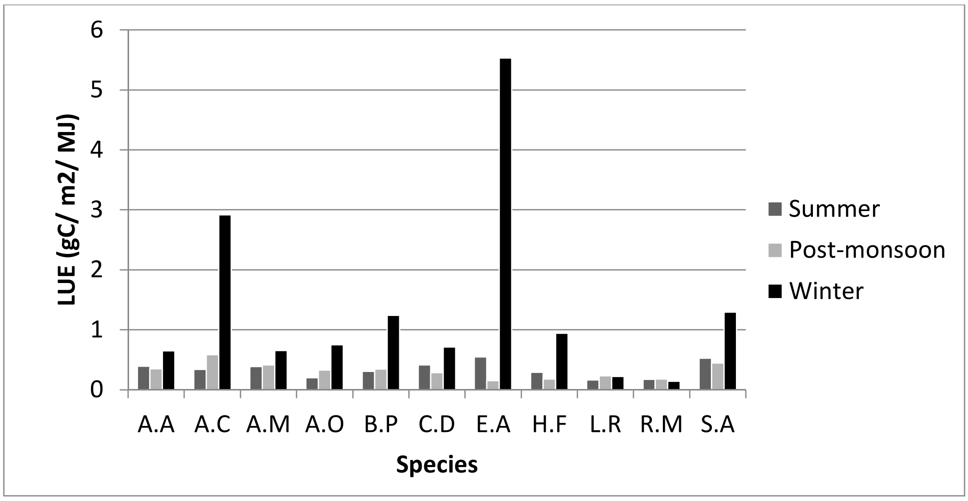

Figure 3: Seasonal variation in LUE$_{max}$ for dominant mangrove species

Across the season, LUE_{max} was seen at peak during winter season in all the species (except RM and LR). Lower temperatures and lesser intensity of solar radiation allows plants to perform photosynthesis without much stresses. During summer, extreme temperatures in coastal regions along with high intensity radiation makes the necessary enzymes inactive. In particular, functioning of Photosystem II (PSII) is affected, which is known as photo-inhibition effect or light-induced damage to PSII. This leads to reduction in photosynthesis rate and light use efficiency during summer season. Species RM and LR are more typically found along the creeks, that experiences continuous high tide and low tide effects, as well as higher levels of salinity. This may lead to physiological stress resulting in reduction of LUE_{max} values. Among 11 species under study, highest LUE was found in *Excoecaria agallocha* in winter and summer (5.53 and 0.55 g C m^{-2} MJ^{-1}, respectively). During post-monsoon highest LUE was observed in *Aegiceras corniculatum* (0.58 g C m^{-2} MJ^{-1}).

GPP Estimation

On the basis of *in situ* measured LUE estimates for 11 dominant species, seasonal mean value of LUE; datasets on Environmental scalars- temperature scalar, water scalar and salinity scalar on seasonal basis were used as inputs for GPP estimation.

As explained in previous section, precise estimation of maximum LUE values are key towards GPP estimation. LUE was found maximum in winter season, moderate in post-monsoon season and lowest during summer. In winter season, conditions are less-harsh and more closer to optimum conditions, which implies lower effect of scalars on LUE. This leads to higher assimilating of absorbed energy and carbon towards plant growth. Across the seasons, maximum value of mean-8 day GPP was found highest in winter, i.e. 14.4 g C m^{-2}

Contrary to this, summer radiation are stronger and temperatures are warmer, which not only causes damage to photosystem II (PSII), thereby reducing LUE_{max} but also increases the scalars. This leads to substantial reduction of GPP in summer season. Across seasons, least values for average GPP were observed during summer i.e. 3.41 g Cm^{-2} . Moderate conditions, lower temperatures prevail during monsoon and post-monsoon seasons, where moderate values of LUE are observed. Overcast conditions in monsoon season leads to lower values of available PAR and can be seen as reduced GPP values compared to winter.

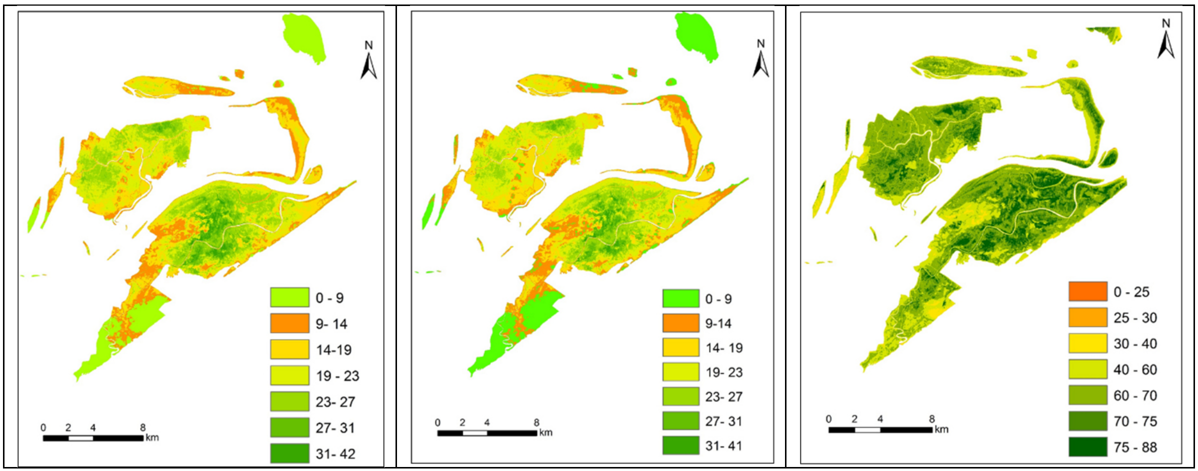

Figure 4: Seasonal 8-day GPP (in g C/ m^2) for Bhitarkanika mangroves- post-monsoon, summer and winter, respectively.

Comparison With MODIS GPP Estimates

GPP estimates based on Resourcesat 2 LISS IV data were resampled to the spatial resolution comparable to MODIS GPP and further converted to 8-day composite. Comparison of modelled estimates showed fairly good agreement with MODIS GPP (R^2 = 0.89; n=118) having comparable coefficient of variation (41.8% in modelled and 49.5% in MODIS GPP). Close match was found in lower GPP lower biomass) values while higher variations were noticed in high GPP values (fig 5).

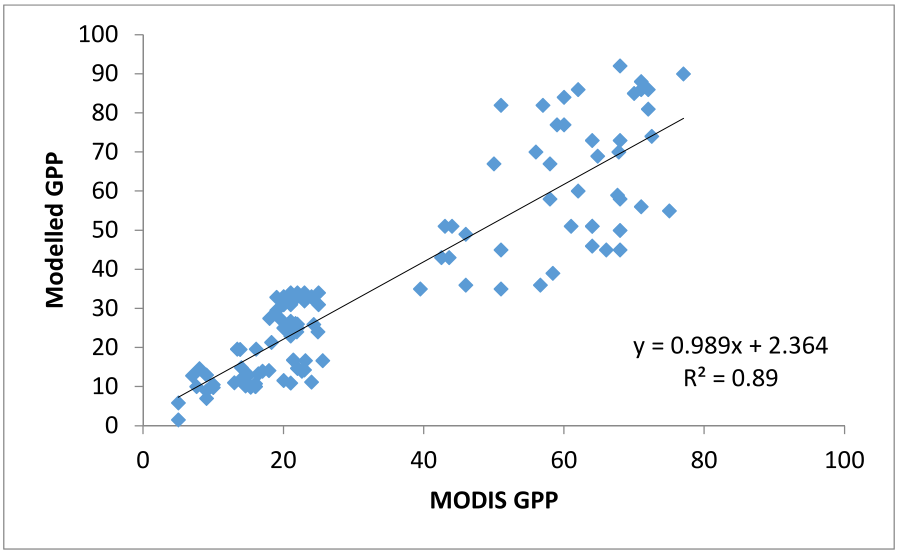

Figure 5: Comparison of modelled product with 8-day MODIS GPP

CONCLUSION

The advent of high spatial resolution optical sensors, capable of detecting vegetation properties with a moderate temporal frequency has allowed the scientific community to revisit a number of existing approaches for modeling GPP, and reassess the potential for using remotely sensed inputs. The approach presented in this work is adopted from vegetation photosynthesis model and is further modified using various inputs from *in situ* estimates. Further, additional environmental scalar in terms of salinity scalar was incorporated to account for stress due to salinity which is particularly evident in costal environment. The approach indicated GPP estimates can be modelled using high resolution satellite data by incorporating specific inputs from coarser scale as well as in situ parameterisation and have shown fairly comparable estimates with existing GPP database. The present modelling approach of estimating GPP through GEO-LEO satellite can be used to quantify carbon sink in other Indian mangrove ecosystems.

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