Global Ecology and Conservation 4 (2015) 614–624

Contents lists available at ScienceDirect

Global Ecology and Conservation

journal homepage: www.elsevier.com/locate/gecco

Original research article

Trends in a satellite-derived vegetation index and environmental variables in a restored brackish lagoon

Ji Yoon Kim[a], Gurdeep Rastogi[b], Yuno Do[a], Dong-Kyun Kim[c], Pradipta R. Muduli[b], Rabindra N. Samal[b], Ajit K. Pattnaik[b], Gea-Jae Joo[a,*]

[a] *Department of Integrated Biological Science, College of Natural Sciences, Pusan National University, Busan 609-735, South Korea*
[b] *Wetland Research and Training Centre, Chilika Development Authority, Barkul Balugaon Khurda 752030, India*
[c] *Department of Physical and Environmental Sciences, University of Toronto, Ontario M1C 1A4, Canada*

HIGHLIGHTS

- We used NDVI dataset to evaluate plant productivity after lagoon restoration.
- Plant productivity was mainly regulated by mean salinity level.
- Lagoon salinity influenced by seawater exchange than freshwater input.
- NDVI and lagoon salinity was further influenced by El Niño/Southern oscillation.

ARTICLE INFO

Article history:
Received 30 July 2015
Received in revised form 22 October 2015
Accepted 23 October 2015
Available online 18 November 2015

Keywords:
SPOT NDVI
Ecological restoration
Resilience
Trend
El Niño/Southern oscillation

ABSTRACT

We evaluated relative influence of climatic variables on the plant productivity after lagoon restoration. Chilika Lagoon, the largest brackish lake ecosystem in East Asia, experienced severe problems such as excessive dominance of freshwater exotic plants and rapid debasement of biodiversity associated with decreased hydrologic connectivity between the lagoon and the ocean. To halt the degradation of the lagoon ecosystem, the Chilika Development Authority implemented a restoration project, creating a new channel to penetrate the barrier beach of the lagoon. Using a satellite-derived normalized difference vegetation index (NDVI) dataset, we compared the trend of vegetation changes after the lagoon restoration, from April 1998 to May 2014. The time series of NDVI data were decomposed into trend, seasonal, and random components using a local regression method. The results were visualized to understand the traits of spatial distribution in the lagoon. The NDVI trend, indicative of primary productivity, decreased rapidly during the restoration period, and gradually increased (slope coefficient: 2.1×10^{-4}, $p < 0.05$) after two years of restoration. Level of seawater exchange had more influences on plant productivity than local precipitation in the restored lagoon. Higher El Niño/Southern Oscillation increased sea level pressure, and caused intrusion of seawater into the lagoon, and the subsequently elevated salinity decreased the annual mean NDVI. Our findings suggest that lagoon restoration plans for enhancing interconnectivity with the ocean should consider oceanographic effects due to meteorological forcing, and long-term NDVI results can be used as a valuable index for adaptive management of the restoration site.

---

[*] Corresponding author. Tel.: +82 51 510 2258; fax: +82 51 583 0172.
E-mail address: gjjoo@pusan.ac.kr (G.-J. Joo).

http://dx.doi.org/10.1016/j.gecco.2015.10.010

1. Introduction

Diverse ecosystems have undergone significant degradation, with negative impacts on biological diversity and ecosystem functions (Munang et al., 2011; Staudinger et al., 2012; Turner et al., 2015). Ecological restoration is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed (SER, 2006). It is an intentional activity that initiates or accelerates an ecological pathway towards a reference state. Even though a variety of restoration projects have been conducted on impaired ecosystems, monitoring of the restored sites was limited or continued only for a short period (Bash and Ryan, 2002; Parkes et al., 2012). Regular monitoring during the restoration process is a preliminary requirement for adaptive management and evaluation of a restoration program. It is difficult to evaluate the restoration without considering the long-term response of the target site (Corbin et al., 2015; Daws and Koch, 2015; Thomasen and Chow-Fraser, 2012). In many restoration cases, influence of climatic cycles was usually not considered, even though they are related with fundamental issues for long-term management of restored sites (Hossack et al., 2013; Prober et al., 2015). A more nuanced understanding of the time series change during the restoration is important to ecological restoration research.

Remote sensing is being increasingly applied in diverse disciplines, based on progress in the public distribution of remotely sensed dataset (e.g., SPOT, MODIS, and Landsat). Various remote sensing techniques and instruments have been applied to monitor changes in natural ecosystems (Kerr and Ostrovsky, 2003). Satellite data products have global coverage and decadal time spans. The continuity of global monitoring can provide accurate evaluation of time-related changes, which is difficult to achieve in the field without a long-term scheme. Among the many different approaches, photosynthetic indices are effective indicators of ecosystem change, and have been used to monitor the characteristics of plant productivity in diverse ecosystems, including forests (Czerwinski et al., 2014; Soudani et al., 2012), tundras (Gamon et al., 2013), agricultural fields (Johnson, 2014), deserts (Jamali et al., 2014), lakes (Feng et al., 2012; Sima et al., 2013), lagoons (Bresciani et al., 2014), and coastal ecosystems (Rahman et al., 2011). The use of satellite-derived products would benefit the process of quantifying ecosystem changes caused by natural disturbances and artificial alterations (Goetz et al., 2006; Goodin and Henebry, 1997; Schroeder et al., 2011). Recently, Tian et al. (2015) and Zhang et al. (2012) used NDVI to evaluate relative influence of climate change and ecological restoration in dry lands. Norman et al. (2014) compared riparian vegetation response in control sites and marsh restoration sites for 27 years. Leon et al. (2012) examined effects of pre-fire restoration treatment and long-term vegetation recovery based on satellite images. Remote sensing provides unique evaluation tool for long-term monitoring of restoration sites.

Our main goal was to assess response of plant productivity to lagoon restoration in the Chilika lagoon through considering water quality and atmospheric cycles in order to provide useful data to be considered in future lagoon restoration programs. We hypothesized influence of oceanographic circulation will mostly modulate internal status (i.e. salinity, productivity) in the lagoon after mouth restoration. We discussed important restoration issues, including (1) what is the trend of recovery of plant productivity after lagoon restoration?, (2) which environmental factors, local freshwater input (precipitation) or seawater exchange, is more relevant to change of plant productivity in the restored lagoon? We tested these questions by using a remote sensing technique to estimate changes in plant productivity. We analyzed the trend in normalized difference vegetation index (NDVI) from 1998 to 2014 at Chilika Lagoon, and correlated the NDVI values with meteorological variables and water quality. We also expected that the trend in NDVI would reflect the ecological response of plant productivity in the restored lagoon, and have a distinctive relationship with changes in the lagoon environment.

2. Materials and methods

2.1. Study site

Chilika Lagoon (19° 43′N, 85° 19′E) covers an area of more than 1165 km^2, and is the largest tropical lagoon in the world (Fig. 1). The average length and breadth of the lagoon are about 64.3 km and 20 km, respectively. It bears a wide range of sub ecosystems, such as freshwater marshes, mudflats, sand dunes, and a shallow brackish lake (average depth: 1.4 m). In 1981, Chilika Lagoon was designated as the first Indian wetland of international importance under the Ramsar Convention, due to its rich biodiversity, which includes a unique assemblage of brackish species and millions of migratory waterfowl. A tropical monsoon climate prevails over the drainage basin of the lagoon. The lagoon experiences southwest and northeast monsoons in May to August and November to December, respectively. Chilika Lagoon is a tributary of the Mahanadi River. Three major tributaries of the Mahanadi that drain freshwater to the lagoon are the Daya, Nuna, and Bhargavi, located north of the lagoon. The lagoon is mostly enclosed from the Bay of Bengal, and connected to the sea by only a few channels. The Palur Canal, which is located south of the lagoon, is another point where the lagoon interacts with the sea. The lagoon's water exchange with the Bay of Bengal is mainly through the lagoon mouths, which are located in the outer channel, at its southeastern end. The old mouth was located at the end of the outer channel (Fig. 1).

Chilika Lagoon has been subjected to constant pressures from both natural and anthropogenic factors (Pattanaik, 2007). The management problems have been siltation, degradation in salinity gradient, infestation of invasive macrophytes, and aquaculture activities, resulting in loss of productivity and biodiversity. As the old lagoon mouth channel was closed because of long shore sediment transport, the weak circulation of lagoon water and poor tidal influx further complicated the conditions, leading to deterioration of the environment. As seawater exchange was limited by choking of the lagoon inlet,

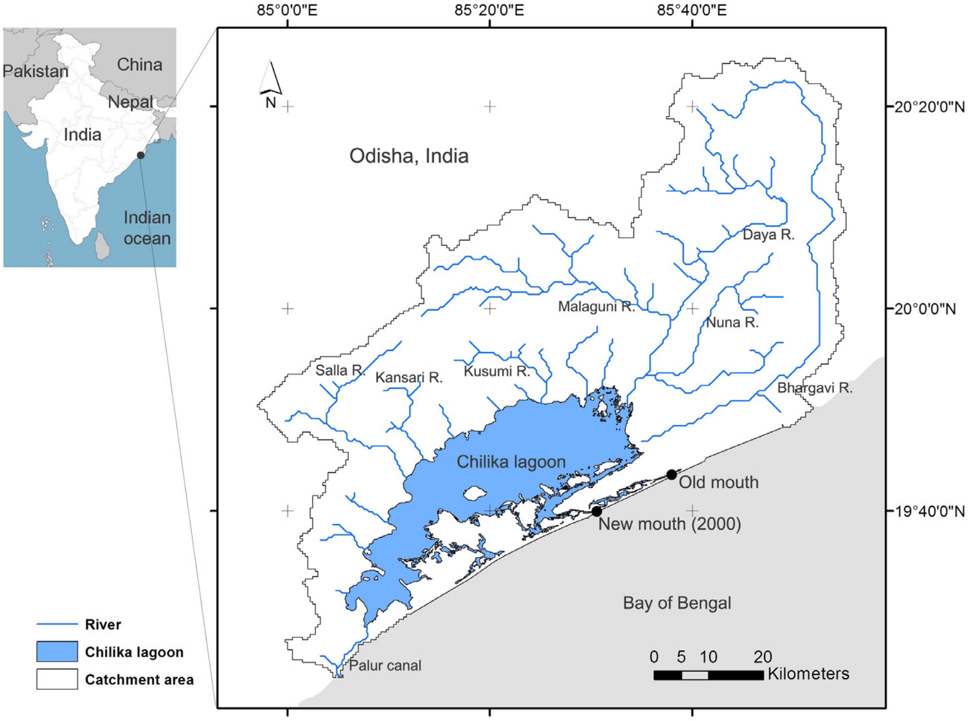


Fig. 1. Location of Chilika Lagoon, Bhubaneswar, India. Black circle shows the location of the lagoon mouth.

the brackish salinity regime and its associated biodiversity degraded over time. Chilika Lagoon was included in the Montreux Record in 1993 by the Ramsar Convention because of the severe degradation of its ecology.

The Chilika restoration project was planned based on hydrological simulations (Jayaraman et al., 2007) and an ecological survey. The Chilika Development Authority (CDA) and Indian government planed a restoration scheme to improve water flux between the lagoon and ocean by dredging a new lagoon mouth in the outer channel of the lagoon. After the restoration project, a new mouth was opened in the sand bar of the outer channel in 2000, which resulted in more water exchange between the lagoon and the sea (Fig. 2). The old mouth became inactive due to natural siltation within three months after the opening of the new mouth. In September 2000, the desiltation of the outer channel, which connects the lake to the sea, and dredging of a new mouth by breaching the existing dune barrier, was carried out. The mouth restoration resulted in a notable increase in the lake's fish yield and a reduction of freshwater weeds. The opening of the new mouth provided a favorable increased salinity regime throughout the lake, with higher fluctuations and improved water clarity due to sediment flushing through the new mouth. A number of studies have evaluated the effects of restoration based on water quality (Patra et al., 2010), plankton (Mohanty and Adhikary, 2013; Panigrahi et al., 2009), plants, and fish (Mohanty et al., 2009). However, most of these studies focused on a site-based approach or species comparisons, thus the time series information on the lagoon restoration is limited because of a lack of regularly monitored biological data.

2.2. Data acquisition and pre-processing

The SPOT program is a series of Earth-observing satellites launched by the French Centre National d'Etudes Spatiales (CNES), in cooperation with other European countries. This sensor is particularly valuable for monitoring ecosystem change because of its capability of imaging the entire Earth every day. SPOT Vegetation 10 day Synthesis (VGT-S10) products, with a spatial resolution of 1 km × 1 km from April 1998 to May 2014, were used in the study. The VGT-S10 products are maximum value composite syntheses, with a 10-day interval for reducing errors from cloud cover and solar zenith angles. The image data has been pre-processed for geometric, atmospheric, and radiometric corrections by the VEGETATION processing center of the Flemish Institute for Technological Research (VITO), Belgium (Maisongrande et al., 2004). The processed VGT-S10 products were transformed from digital numbers (from the vegetation sensor) to real NDVI values ranging from −1 to 1, the original range of NDVI.

$$\text{NDVI} = (\text{Near-infrared band} - \text{Red band})/(\text{Near-infrared band} + \text{Red Band}) \quad (1)$$

$$\text{Real NDVI} = 0.004 * \text{Digital Number} - 0.1. \quad (2)$$

From the 10-day NDVI composite, we calculated the monthly mean NDVI (M_i) and the annual mean NDVI (Y_i). Negative values of NDVI were not included in the following rater calculation to reduce biased influences. Using these values, a

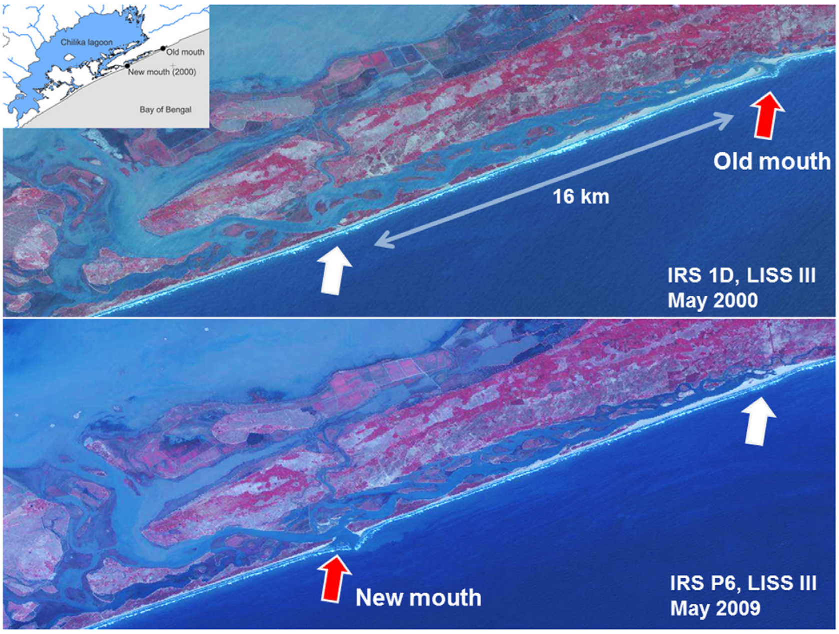


Fig. 2. Satellite image representing new mouth construction in the Chilika lake. Upper image was taken just before the construction, and lower image is taken 9 years after construction.

temporal trend of the NDVI values was defined by the greenness rate of change (GRC), indicating the slope of a linear regression from a least squares fitting of the inter-annual NDVI values (Stow et al., 2003). The spatiotemporal variability of the NDVI is illustrated by the GRC from 1999 to 2012. The corresponding equation is as follows:

$$\mathrm{GRC} = \frac{n \times \sum_{i=1}^{n} (i \times Y_i) - \sum_{i=1}^{n} i \times \sum_{i=1}^{n} Y_i}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2}. \tag{3}$$

The inter-annual variability of the NDVI between 1999 and 2012 was estimated by the coefficient of variation (CV). The larger the CV values, the greater the vegetation change. Images from 1998, 2013 and 2014 were excluded from the GRC and CV calculation, because their annual datasets were not complete. For better visual inspection, the GRC and CV results were reclassified into five classes based on the Jenks optimization method (Baz et al., 2009). The Jenks optimization determines the best arrangement of values into different classes by reducing the variance within classes and maximizing the variance between classes.

Meteorological data were obtained from the Bhubaneswar weather station (50 km away from the study site), operated by the India Meteorological Department, Government of India (IMD, 2014). The meteorological variables include air temperature (°C), precipitation (mm), sea level pressure (hPa), and multivariate El Niño/Southern oscillation index (MEI). El Niño/Southern Oscillation (ENSO) is globally considered to be the most important index associated with the relationship between the ocean and the ambient atmosphere, related to climatic inter-annual variability (NOAA, 2014). Water quality was monitored by the Wetland Research and Training Centre, CDA. The monitoring of the water quality of Chilika Lagoon was conducted based on water samples collected from 30 stations in the lagoon on a monthly basis. The water quality variables included water temperature (°C), salinity (ppt), nitrate content (NO_3-N, ppm), and phosphate content (PO_4-P, ppm). For the correlation analysis, the averages of both the annual and monthly NDVIs were compared with averages of the annual and monthly meteorological and water quality variables from the monitored stations, respectively.

2.3. Statistical analysis

To analyze the NDVI trend during the study period (1998–2014), change point analysis and segmented regression were applied. The time series of the monthly mean NDVI was decomposed into trend, seasonal, and residual components by seasonal trend decomposition (STL) embedded in the statistical software of R package (R Development Core Team, Lucent Technologies, USA). STL is a filtering process based on a locally weighted scatterplot smoothing method (Robert et al., 1990). Change point analysis was used to find time points of change in the mean and variance within a given time sequence using the AMOC (At Most One Change) algorithm (Killick et al., 2012). This method calculates the optimal positioning and potential

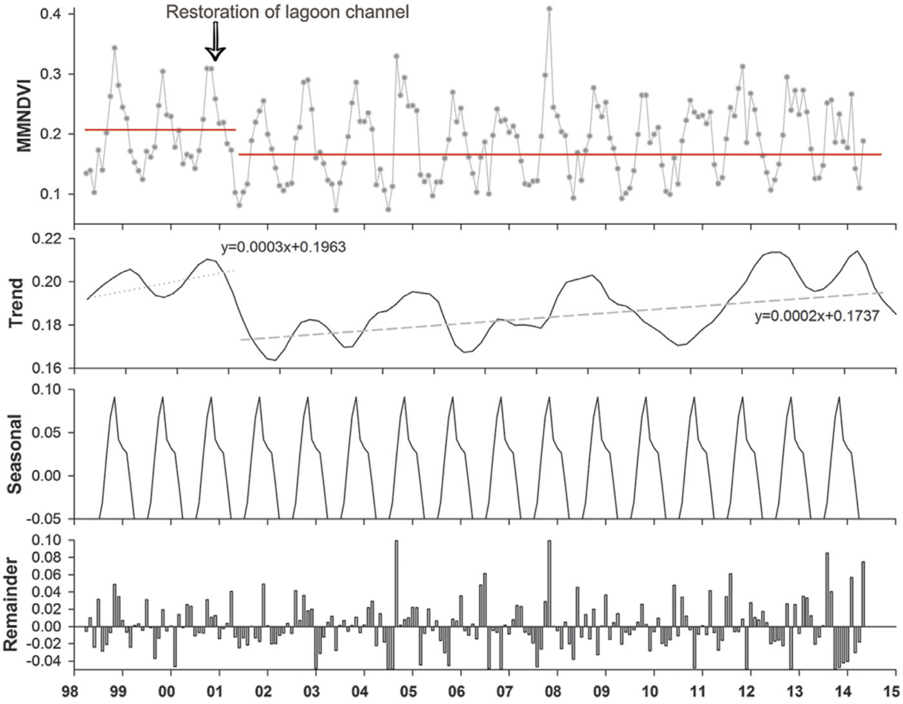


Fig. 3. Plot of monthly mean NDVI (MMNDVI) and its trend, seasonal, and residual components. Parallel lines represent local averages, and dotted lines represent local regression before and after lagoon restoration.

number of change points in the dataset. Segmented regression is a piece-wise regression, in which the independent variables are partitioned, and a regression line is fit to each segment. Segmented regression analysis was applied to compare the direction of the trends and the slope value in the partitioned NDVI time series data based on change point analysis.

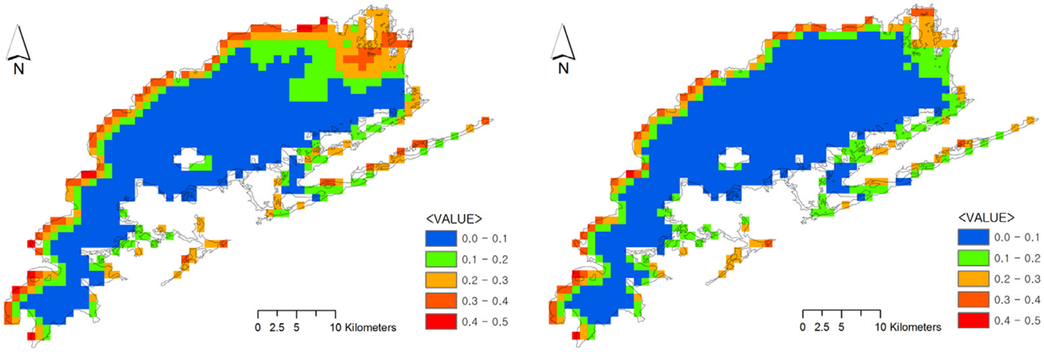
We assessed the relationship between NDVI and the environmental variables, including meteorological data and water quality of the lagoon, with maximal information-based nonparametric exploration (MINE) statistics (Reshef et al., 2011). MINE calculates the maximal information coefficient (MIC) between two datasets, and has broader applications to various relationship types (i.e., linear, exponential, parabolic, and sinusoidal) than other correlation methods. The MIC values range from 0 to 1, which is equivalent to classical correlation coefficients such as Spearman or Pearson correlation. A higher value indicates a stronger relationship between two variables, and vice versa. In order to evaluate the relationship between the annual mean NDVI and environmental variables, we applied a Pearson correlation for the data set of annual mean NDVI. The average values were presented as the mean ± standard error (S.E.).

3. Results

3.1. Spatiotemporal variability of lagoon vegetation

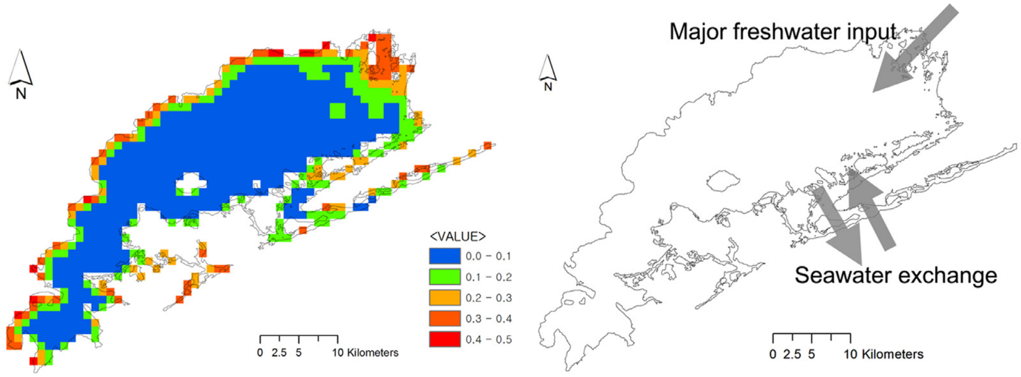
Analysis of the NDVI time series revealed the trends and seasonality of Chilika Lagoon vegetation. Fig. 3 illustrates the temporal variability of NDVI and its seasonal characteristic in the Chilika Lagoon during 1998–2014. The monthly mean NDVI of Chilika Lagoon showed two distinct seasonal peaks, in April and October, and the pattern coincided with the timing of the monsoon periods. The maximum NDVI value appeared in October 2000, just after the mouth restoration. The NDVI trend responded well to the new mouth opening in September 2000. The trend of the monthly mean NDVI dropped sharply for a year, and then increased gradually with annual fluctuations. No statistically significant trend was identified during the entire study period; however, changes in the mean and variance were detected with change point analysis in March 2001 (SIC value: 10.47, seven months after mouth restoration). The average of monthly mean NDVI from April 1998 to March 2001 was 0.201 ± 0.059, and it has decreased to 0.186 ± 0.062 beginning in April 2001. The trend of monthly mean NDVI increased rapidly from April 1998 to March 2001 (3.72×10^{-3} year^{-1}), and then showed a gradual recovery pattern from April 2001 to July 2013 (2.40×10^{-3} year^{-1}). The residual component from NDVI decomposition ranged within $9.63 \times 10^{-5} \pm 0.028$ during the entire study period.

The spatial distribution of NDVI in Chilika Lagoon showed dynamic changes as well (Figs. 4, 5). The average NDVI during each restoration stage is shown in Fig. 5. Notably, high value classes of NDVI were distributed in the northern part of the lagoon during pre-restoration periods, but were largely decreased after the lagoon restoration. The riparian zone of the lagoon generally had stable NDVI values compared with the center of the lagoon. In the 1990s, higher NDVIs were widely



(a) Pre-restoration (1999–2000).

(b) Post-restoration (2001–2006).



(c) Post-restoration (2007–2012).

Fig. 4. Change of spatial distribution of NDVI during pre- (1999–2000) and post-restoration (2001–2006, 2007–2012) in Chilika Lagoon.

distributed in the vicinity of the river mouth. Since 2000, the extent of these higher values has been significantly reduced. The area with an NDVI class higher than 0.2 were decreased rapidly by about 35.2% (194.0 km^2) after the restoration. The CV value was also the highest in the northern part of the lagoon, where freshwater comes in (Fig. 5(a)). The NDVI variation showed a decreasing trend from the river mouth to the southern edge of the lagoon. The average GRC in the entire lagoon area was −0.057, which represents the overall gradually decreasing NDVI trend in Chilika Lagoon over 16 years (Fig. 5(b)). Most of the lagoon has small positive GRCs, which showed little increase over a decade. A considerable area of the northern part, including the river mouth, had the highest negative GRC value in the lagoon. In the 16 years of NDVI composites, the minimum NDVI values were concentrated in the center of lagoon, while maximum NDVI values were observed near the northern part of the lagoon and the riparian area.

3.2. *Relative influence of water quality and climatic variables*

Based on MINE statistics, the correlations between monthly mean NDVI and environmental variables showed a nonlinear relationship due to the fluctuation (Table 1). The correlations between the monthly mean NDVI and environmental variables were significant, except monthly precipitation. Sea level pressure showed the highest MIC value (MIC: 0.41, $p < 0.01$), but had a low Pearson rank due to its nonlinearity. Water temperature (MIC: 0.34, $p < 0.01$) and air temperature (MIC: 0.28, $p < 0.05$) had high MIC values with significant Pearson correlation. We found sequential connections among annual mean NDVI, lagoon salinity, sea level pressure (SLP), and MEI (Fig. 6). The annual mean NDVI responded very well to the variations of MEI (r : −0.52, $p < 0.01$), SLP (r : −0.43, $p < 0.05$), and lagoon salinity (r : −0.51, $p < 0.05$). The change in annual mean NDVI during the study period was well explained by the variation in annual mean salinity (R^2: 0.43, Fig. 6(c)) and annual mean SLP (R^2: 0.54, Fig. 6(d)).

4. Discussion

Changes in nutrient content and salinity in a restored lagoon have been the main issues in the recovery of biodiversity and lagoon productivity. Several studies have focused on salinity and nutrients (Jeong et al., 2008; Parida et al., 2013; Mahapatro et al., 2012) as well as water level (Antunes et al., 2012; Schallenberg et al., 2010) as the determinant factors for the changes

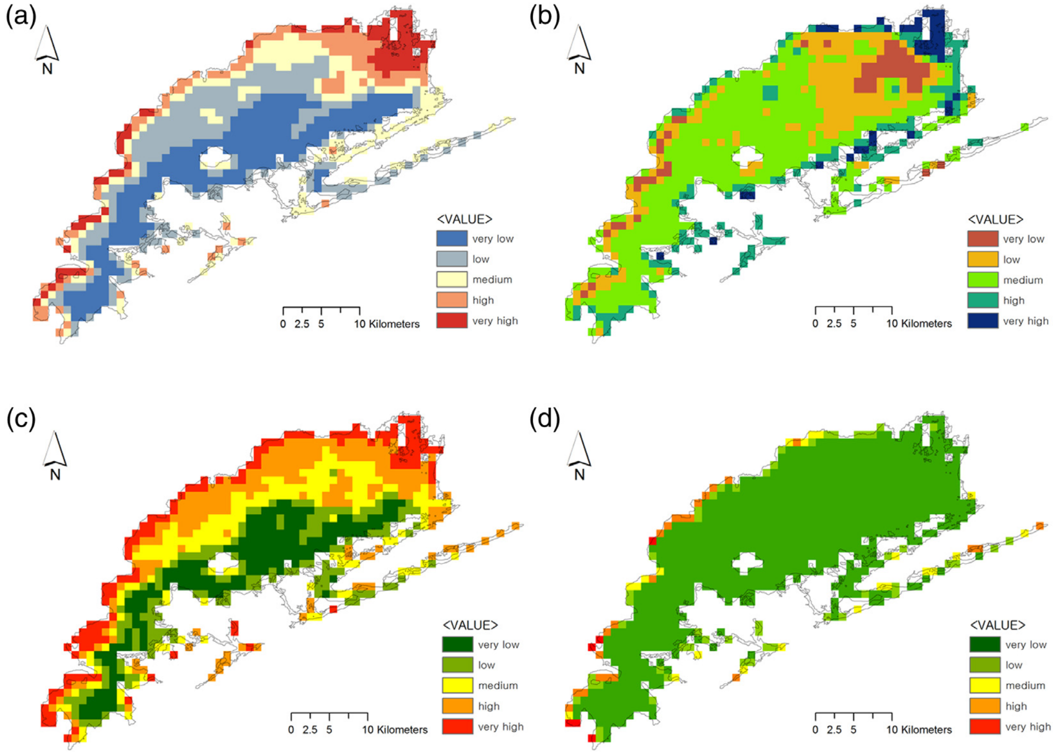


Fig. 5. Spatial distribution and changes in annual mean NDVI from 1999 to 2012. (a) Coefficient of variance (CV), (b) greenness rate of change (GRC), (c) maximum of annual mean NDVI, (d) minimum of annual mean NDVI.

Table 1
Maximal information-based nonparametric exploration (MINE) statistics for NDVI and environmental variables.

Correlation with monthly mean NDVI					Correlation with annual mean NDVI (p)
Variable	MIC	Nonlinearity	Pearson (p)	Pearson rank	
SLP (hPa)	0.41^{**}	0.38	−0.24	3	-0.72^{**}
Water temp. (°C)	0.34^{**}	0.17	0.41^{**}	2	−0.28
Nitrate (ppm)	0.28^{**}	0.27	−0.05	7	−0.49
Air temp. (°C)	0.28^{*}	0.19	0.48^{**}	1	−0.24
Phosphate (ppm)	0.24^{*}	0.28	0.06	6	0.06
Salinity (ppt)	0.23^{*}	0.21	0.14	4	-0.57^{*}
Precipitation (mm)	0.21	0.27	−0.07	5	−0.35

[*] $p < 0.05$.
[**] $p < 0.01$.

after restoration. We also confirmed that salinity and nutrient levels have controlling effects on lagoon productivity and biodiversity. Along with the water chemistry of the lagoon, we found sequential connections between plant productivity (NDVI), lagoon water salinity, and climatic variables, including SLP and MEI. Trend of NDVI and lagoon salinity in the restored lagoon was more influenced by this seawater exchange than freshwater input including local precipitation. Higher lagoon salinity reduced the NDVI of the lagoon, which is caused by a decrease of freshwater-adapted primary producers (Pattanaik, 2007).

The annual average lagoon salinity is significantly influenced by the SLP of the Bay of Bengal. Dangendorf et al. (2013) addressed meteorological forcing, including by SLP, wind, and precipitation, on mean sea level and tides. Changes in sea level and tides have a close connection with the seawater flux of a lagoon system, and can further alter the salinity regime in the lagoon. In addition, atmospheric circulation and oceanographic effects have the potential to produce large scale variations in mean sea level, of up to 0.5 m (Dangendorf et al., 2013). The SLP of the Bay of Bengal was further influenced by El Niño/Southern oscillation of the tropical Pacific. The correlation results for the relationship among annual mean NDVI, lagoon salinity, SLP, and MEI revealed a relationship between oceanographic circulation and lagoon productivity. High MEI values in the Pacific Ocean were related to an increase of SLP in the Bay of Bengal, and this atmospheric change resulted in an increase in lagoon salinity. This annual relationship suggests that plant productivity in the lagoon was concurrently

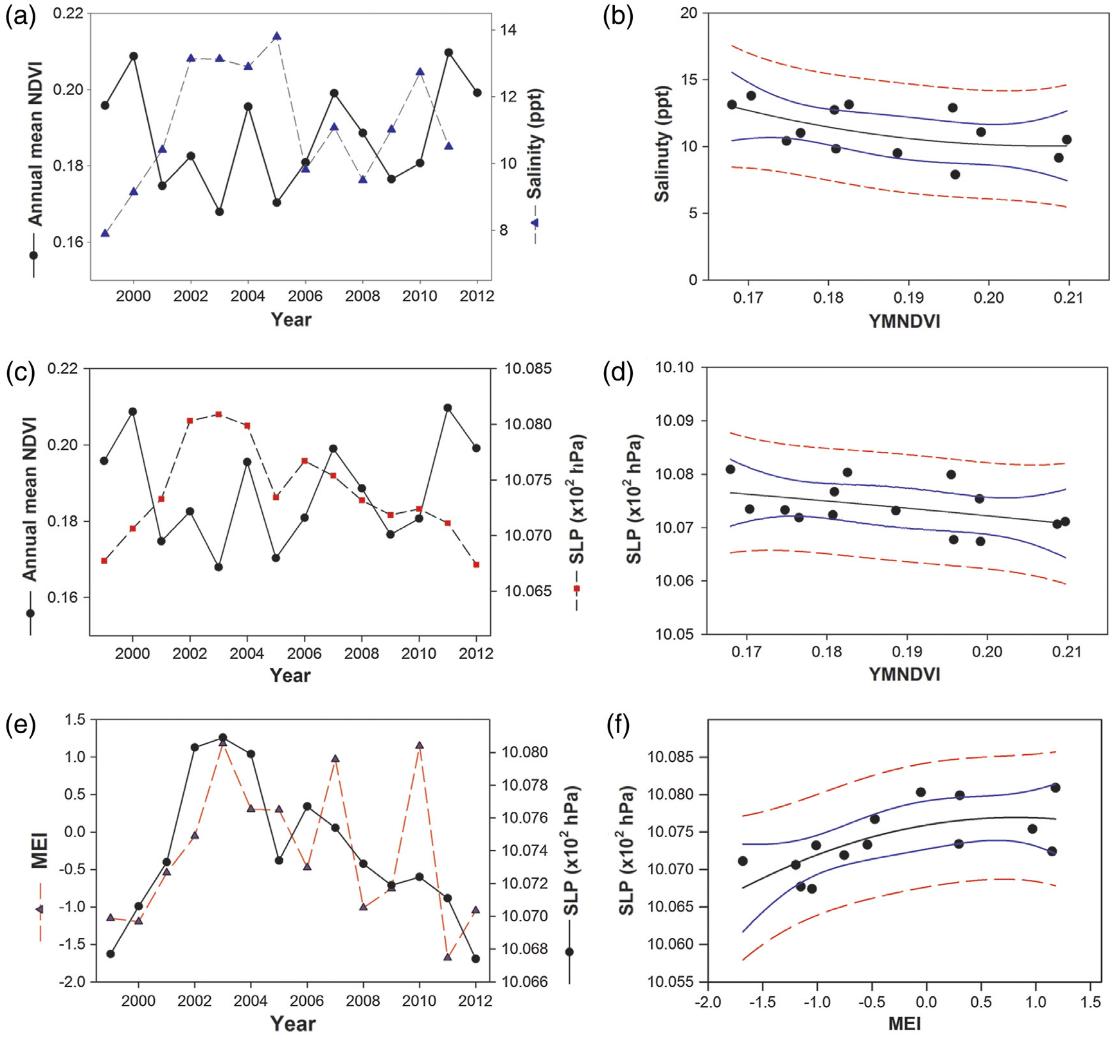


Fig. 6. Changes in annual mean NDVI and selected environmental variables with their regression fits. Solid black line is a regression fit to the data (b, d, f). Blue lines are the 95% confidence intervals on the estimated mean, and red lines are the 95% prediction intervals.

influenced by climatic fluctuations in the long-term, as well as the shift in salinity regime due to the lagoon restoration. In the Chilika case, the lagoon restoration seemed to be more successful because it was done during the rising phase of regional salinity due to periodic ocean circulation. This also emphasizes that lagoon management or restoration should consider the climatic connections (i.e., climate change, sea level rise) and hydrological transitions caused by freshwater discharge and seawater intrusion.

A comparable response of lagoon community was also observed after hydrologic reconnection at the Indian River Lagoon, Florida (Brockmeyer et al., 1997; Rey et al., 1990). At this location, vegetation had showed a varied response depending on the marsh environment. One site experienced rapid elimination of freshwater species, with a recovery of salt tolerant cover in less than three years. Meanwhile, vegetation at another site remained well below the original 75% after ten years (Brockmeyer et al., 1997). Plant productivity seemed to respond more to gradual recovery of the lagoon environment after restoration than to the reestablishment of ocean connectivity. Fish and crustaceans in a restored salt marsh showed similar early responses in species composition, density, size, and distribution (Raposa, 2002). Mouth restoration of a lagoon rapidly benefits the migration of mobile animals by enhancing breeding migration and recruitment from the near shore. However, regeneration of lagoon vegetation takes longer to return to previous levels.

This study also highlighted the potential of short-term averaged images for ecological applications and for responding to artificial and natural changes. We showed that the plant productivity of a restored lagoon can be effectively monitored and evaluated using a satellite-derived vegetation index. A significant change in NDVI was observed after the new mouth restoration. The mean seasonal values of water quality parameters were reported to have shown significant changes in the lagoon environment during the post-restoration period (Patra et al., 2010). A rise in salinity level in Chilika Lagoon was identified following the opening of the new mouth in 2000. The river mouth area, where freshwater invasive plants proliferated, showed the largest decrease of NDVI. The lagoon restoration seemed to have more of an effect on the freshwater area than the brackish area. This results support that the strength of tidal flux in the lagoon increased after the restoration, and the associated circulation is effective in mixing water masses (Rajawat et al., 2007). Compared with other biological studies, long-term analysis of NDVI in the restored lagoon revealed that diverse biological taxa responded differently, and had a range of recovery rates after the restoration event. In this study, plant productivity (NDVI) was decreased for half a year after the restoration, and took about twelve years to return to previous productivity levels. It seems that a rapid decrease of NDVI was caused by the sudden dieback of proliferated freshwater species. The large decrease of NDVI in the freshwater region was caused by dieback of freshwater species in response to the salinity change at the very early stage of restoration. After restoration, gradual increases of brackish lagoon vegetation, including *Potamogeton* sp. and sea grasses, were identified in the field (Parida et al., 2013). In the estuarine ecosystem, the role of the salinity regime is mainly to limit and regulate the distribution of relevant biota with different osmotic regulation types (Telesh and Khlebovich, 2010). In contrast, other studies noted that the biomass of fish and prawns in Chilika Lagoon showed a seven-fold increase (i.e., 8500 tons in 1986, 1600 tons in 1998, and 11,878 tons in 2002) during the two years after the opening of the new mouth (Mohanty et al., 2009; Parida et al., 2013). Increased fishery production was maintained and stabilized for several years. Other lagoon biological taxa, including phytoplankton (Mohanty and Adhikary, 2013; Panigrahi et al., 2009), also showed a recovery response to the levels of the 1980s after the mouth restoration.

NDVI is broadly used for studying wetland ecosystems (Gibbes et al., 2009), even though average wetland NDVI values tend to be lower and noisier than those of terrestrial ecosystems (i.e., forests and grasslands), because of the absorption and reflection properties of water surfaces. Generally, brackish lagoons are shallow (average depth <3 m), thus a similar approach can be easily applied. Considering case of Chilika lagoon, NDVI monitoring was more effective because dominance of floating vegetation was main concern before restoration. In particular, time series NDVI datasets can provide a basis for describing the impact of a restoration and its consequences with repeated monitoring at a fixed interval. Time series analysis of NDVI is considered fundamental for extracting numerical observations related to vegetation dynamics (Hall-Beyer, 2003; Pettorelli et al., 2005). Satellite-derived datasets will greatly help to compensate for the weaknesses of field monitoring at restoration sites. Using historical data bases of long-term operational satellites (e.g., SPOT, Landsat), this product can even be applied to restoration sites for which there is no previous field monitoring data. Nevertheless, NDVI is an ecosystem measure, and does not provide information on changes below the community level (i.e., species composition; Washington-Allen et al., 2008). Thus, caution must be used in interpreting results from times series changes, and auxiliary data (i.e., field observations, hyper-spectral analysis) must be properly referenced.

Aquatic ecosystems, including lagoons and lakes, generally experience temporal changes with short periodicity based on their growth dynamics, as well as the mobile characteristic of their biological components. In considering the vegetation changes in the restored Chilika Lagoon, we also confirmed that the seasonal changes and annual fluctuations depend on environmental conditions. These traits generate complex noise in the time series dataset, and a proper statistical approach is needed to interpret the complex phenomena. Thus, the nonlinear dynamics in the ecosystem (Burkett et al., 2005) should be included in the study, and statistics based on a nonlinear model need to be properly applied. In particular, the relationship between the satellite vegetation index and climatic factors in the lagoon was highly nonlinear, thus nonlinear analysis and seasonal averaging could provide applicable results. Trend decomposition have been applied to find meaningful trends in the complex dataset, and these techniques enable us to characterize ecosystem changes at different temporal scales (Martínez and Gilabert, 2009). Short period satellite instruments have made it possible to monitor weekly to monthly changes in the studied ecosystem. The increased availability of satellite images with public access, combined with time series analysis techniques, will further enhance the evaluation of restored aquatic ecosystems across global coastal areas. Continuity of post-restoration monitoring, and recovery of historical changes at the site, form the basis for adaptive management of restored ecosystems, and can further suggest appropriate actions to recover ecological functions and biodiversity. Increased application of remote sensing in aquatic restoration will enhance in-depth understanding of ecosystem responses to ecological restoration.

5. Conclusion

Our study showed restoration of lagoon connectivity with ocean had more influence on change of lagoon productivity compared with local freshwater input. While relative importance of these influences to lagoon can be varied with morphological trait of lagoon channel (i.e. freshwater input and outer channel to ocean). We also showed that plant productivity of restored lagoon can be effectively monitored and evaluated by using satellite derived vegetation index. This study highlights the potentialities of short-term averaged images in ecological applications and response against artificial and natural changes. The increased availability of satellite images with public accesses combined with time-series analysis techniques will further contribute on evaluating restored aquatic ecosystems distributed across global coastal area. Short period satellite instruments made it possible to obtain weekly to monthly changes of concerned ecosystem. This short-term dataset can provide relationship and influences of climatic and oceanographic oscillation on ecosystem productivity. Spread of remote sensing application in the restoration ecology, will enhance in-depth understanding ecosystem responses against ecosystem restoration.

Acknowledgments

We sincerely thank assistance members of WRTC and CDA for the field survey. This study is international collaborative research by the Korea National Long-Term Ecological Research (KNLTER) by the National Institute of Ecology, Ministry of Environment (S. Korea).

Appendix A. Supplementary data

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.gecco.2015.10.010.

References

Antunes, C., Correia, O., Marques, S.J., Cruces, A., Freitas, M.C., Branquinho, C., 2012. Factors involved in spatiotemporal dynamics of submerged macrophytes in a Portuguese coastal lagoon under Mediterranean climate. Estuar. Coast. Shelf Sci. 110, 93–100. http://dx.doi.org/10.1016/j.ecss.2012.03.034.

Bash, S.J., Ryan, C.M., 2002. Stream restoration and enhancement projects: is anyone monitoring? Environ. Manage. 29 (6), 877–885.

Baz, I., Geymen, A., Er, S.N., 2009. Development and application of GIS-based analysis/synthesis modeling techniques for urban planning of Istanbul Metropolitan Area. Adv. Eng. Softw. 40 (2), 128–140. http://dx.doi.org/10.1016/j.advengsoft.2008.03.016.

Bresciani, M., Adamo, M., De Carolis, G., Matta, E., Pasquariello, G., Vaičiūtė, D., Giardino, C., 2014. Monitoring blooms and surface accumulation of cyanobacteria in the Curonian Lagoon by combining MERIS and ASAR data. Remote Sens. Environ. http://dx.doi.org/10.1016/j.rse.2013.07.040.

Brockmeyer Jr., R.E., Rey, J.R., Virnstein, R.W., Gilmore, R.G., Earnest, L., 1997. Rehabilitation of impounded estuarine wetlands by hydrologic reconnection to the Indian River Lagoon, Florida (USA). Wetl. Ecol. Manag. 4 (2), 93–109. http://dx.doi.org/10.1007/BF01876231.

Burkett, V.R., Wilcox, D.A., Stottlemyer, R., Barrow, W., Fagre, D., Baron, J., Price, J., Nielsen, J.L., Allen, C.D., Peterson, D.L., Ruggerone, G., Doyle, T., 2005. Nonlinear dynamics in ecosystem response to climatic change: Case studies and policy implications. Ecol. Complex. 2 (4), 357–394. http://dx.doi.org/10.1016/j.ecocom.2005.04.010.

Corbin, J.D., Robinson, G.R., Hafkemeyer, L.M., Handel, S.N., 2015. A long-term evaluation of applied nucleation as a strategy to facilitate forest restoration. Ecol. Appl. http://dx.doi.org/10.1890/15-0075.1.

Czerwinski, C.J., King, D.J., Mitchell, S.W., 2014. Mapping forest growth and decline in a temperate mixed forest using temporal trend analysis of Landsat imagery 1987–2010. Remote Sens. Environ. 141, 188–200. http://dx.doi.org/10.1016/j.rse.2013.11.006.

Dangendorf, S., Mudersbach, C., Wahl, T., Jensen, J., 2013. Characteristics of intra-, inter-annual and decadal sea-level variability and the role of meteorological forcing: the long record of Cuxhaven. Ocean Dyn. 63 (2–3), 209–224. http://dx.doi.org/10.1007/s10236-013-0598-0.

Daws, M.I., Koch, J.M., 2015. Long-term restoration success of re-sprouter understorey species is facilitated by protection from herbivory and a reduction in competition. Plant Ecol. 216, 565–576. http://dx.doi.org/10.1007/s11258-015-0459-7.

Feng, L., Hu, C., Chen, X., Cai, X., Tian, L., Gan, W., 2012. Assessment of inundation changes of Poyang Lake using MODIS observations between 2000 and 2010. Remote Sens. Environ. 121, 80–92. http://dx.doi.org/10.1016/j.rse.2012.01.014.

Gamon, J.A., Huemmrich, K.F., Stone, R.S., Tweedie, C.E., 2013. Spatial and temporal variation in primary productivity (NDVI) of coastal Alaskan tundra: Decreased vegetation growth following earlier snowmelt. Remote Sens. Environ. 129, 144–153. http://dx.doi.org/10.1016/j.rse.2012.10.030.

Gibbes, C., Southworth, J., Keys, E., 2009. Wetland conservation: Change and fragmentation in Trinidad's protected areas. Geoforum 40 (1), 91–104.

Goetz, S.J., Fiske, G.J., Bunn, A.G., 2006. Using satellite time-series data sets to analyze fire disturbance and forest recovery across Canada. Remote Sens. Environ. 101 (3), 352–365. http://dx.doi.org/10.1016/j.rse.2006.01.011.

Goodin, D.G., Henebry, G.M., 1997. A technique for monitoring ecological disturbance in tallgrass prairie using seasonal NDVI trajectories and a discriminant function mixture model. Remote Sens. Environ. 61 (2), 270–278. http://dx.doi.org/10.1016/S0034-4257(97)00043-6.

Hall-Beyer, M., 2003. Comparison of single-year and multiyear ndvi time series principal components in cold temperate biomes. IEEE Trans. Geosci. Remote 41 (11), 2568–2574. http://dx.doi.org/10.1109/TGRS.2003.817274.

Hossack, B.R., Adams, M.J., Pearl, C.A., Wilson, K.W., Bull, E.L., Lohr, K., Patla, D., Pilliod, D.S., Jones, J.M., Wheeler, K.K., Mckay, S.P., Corn, P.S., 2013. Roles of patch characteristics, drought frequency, and restoration in long-term trends of a widespread amphibian. Conserv. Biol. 27, 1410–1420. http://dx.doi.org/10.1111/cobi.12119.

IMD, 2014. Climate records. http://www.imd.gov.in/ (accessed 17.12.14).

Jamali, S., Seaquist, J., Eklundh, L., Ardö, J., 2014. Automated mapping of vegetation trends with polynomials using NDVI imagery over the Sahel. Remote Sens. Environ. 141, 79–89. http://dx.doi.org/10.1016/j.rse.2013.10.019.

Jayaraman, G., Rao, A.D., Dube, A., Mohanty, P.K., 2007. Numerical simulation of circulation and salinity structure in Chilika Lagoon. J. Coast. Res. 234, 861–877. http://dx.doi.org/10.2112/04-0225R.1.

Jeong, K.S., Kim, D.K., Pattnaik, A., Bhatta, K., Bhandari, B., Joo, G.J., 2008. Patterning limnological characteristics of the Chilika lagoon (India) using a self-organizing map. Limnology 9 (3), 231–242.

Johnson, D.M., 2014. An assessment of pre- and within-season remotely sensed variables for forecasting corn and soybean yields in the United States. Remote Sens. Environ. 141, 116–128. http://dx.doi.org/10.1016/j.rse.2013.10.027.

Kerr, J.T., Ostrovsky, M., 2003. From space to species: ecological applications for remote sensing. Trends Ecol. Evol. 18 (6), 299–305. http://dx.doi.org/10.1016/S0169-5347(03)00071-5.

Killick, R., Fearnhead, P., Eckley, I.A., 2012. Optimal detection of change points with a linear computational cost. J. Amer. Statist. Assoc. 107 (500), 1590–1598.

Leon, J.R.R., van Leeuwen, W.J.D., Casady, G.M., 2012. Using MODIS-NDVI for the modeling of post-wildfire vegetation response as a function of environmental conditions and pre-fire restoration treatments. Remote Sens. 4, 598–621. http://dx.doi.org/10.3390/rs4030598.

Mahapatro, D., Mishra, R.K., Samal, R.N., Patanaik, A.K., 2012. Study of macrobenthos in relation to eutrophication at Chilika Lagoon, east coast of India. Mar. Sci. 2 (6), 139–148.

Maisongrande, P., Duchemin, B., Dedieu, G., 2004. VEGETATION/SPOT: an operational mission for the Earth monitoring; presentation of new standard products. Int. J. Remote Sens. 25 (1), 9–14. http://dx.doi.org/10.1080/0143116031000115265.

Martínez, B., Gilabert, M.A., 2009. Vegetation dynamics from NDVI time series analysis using the wavelet transform. Remote Sens. Environ. 113 (9), 1823–1842. http://dx.doi.org/10.1016/j.rse.2009.04.016.

Mohanty, D., Adhikary, S.P., 2013. Assessment of changes in the algal diversity of Chilika Lagoon after opening of new mouth to Bay of Bengal. J. Water Resour. Prot. 5, 611–623.

Mohanty, R.K., Mohapatra, A., Mohanty, S.K., 2009. Assessment of the impacts of a new artificial lake mouth on the hydrobiology and fisheries of Chilika Lake, India. Lake Reservoir Manag. 14 (3), 231–245. http://dx.doi.org/10.1111/j.1440-1770.2009.00406.x.

Munang, R.T., Thiaw, I., Rivington, M., 2011. Ecosystem management: tomorrow's approach to rnhancing food security under a changing climate. Sustainability 3, 937–954. http://dx.doi.org/10.3390/su3070937.

NOAA, 2014. MEI. http://www.esrl.noaa.gov/psd/enso/mei/ (accessed 17.12.14).

Norman, L., Villarreal, M., Pulliam, H.R., Minckley, R., Gass, L., Tolle, C., Coe, M., 2014. Remote sensing analysis of riparian vegetation response to desert marsh restoration in the Mexican Highlands. Ecol. Eng. 70, 241–254. http://dx.doi.org/10.1016/j.ecoleng.2014.05.012.

Panigrahi, S., Wikner, J., Panigrahy, R.C., Satapathy, K.K., Acharya, B.C., 2009. Variability of nutrients and phytoplankton biomass in a shallow brackish water ecosystem (Chilika Lagoon, India). Limnology 10 (2), 73–85.

Parida, S., Bhatta, K.S., Guru, B.C., 2013. Study of sectoral variation of some commercially important fish groups in relation to environmental variables of Chilika lake, East Coast of India. Int. J. Bioassays 2 (8), 1118–1123.

Parkes, T., Delaney, M., Dunphy, M., Woodford, R., Bower, H., Bower, S., McDonald, T., 2012. Big Scrub: a cleared landscape in transition back to forest? Ecol. Manage. Restor. 13 (3), 212–223. http://dx.doi.org/10.1111/emr.12008.

Patra, A.P., Patra, J.K., Mahapatra, N.K., Das, S., Swain, G.C., 2010. Seasonal variation in physicochemical parameters of Chilika Lake after opening of new mouth near Gabakunda, Orissa, India. World J. Fish Mar. Sci. 2 (2), 109–117.

Pattanaik, A.K., 2007. Restoration and conservation of Chilika Lagoon: an overview. Lake and coastal wetlands: Conservation, restoration and management. Conf. Proc. 425–430.

Pettorelli, N., Vik, J.O., Mysterud, A., Gaillard, J.M., Tucker, C.J., Stenseth, N.C., 2005. Using the satellite-derived NDVI to assess ecological responses to environmental change. Trends Ecol. Evol. 20 (9), 503–510. http://dx.doi.org/10.1016/j.tree.2005.05.011.

Prober, S.M., Byrne, M., McLean, E.H., Steane, D.A., Potts, B.M., Vaillancourt, R.E., Stock, W.D., 2015. Climate-adjusted provenancing: a strategy for climate-resilient ecological restoration. Front. Ecol. Evol. 3, 65. http://dx.doi.org/10.3389/fevo.2015.00065.

Rahman, A.F., Dragoni, D., El-Masri, B., 2011. Response of the Sundarbans coastline to sea level rise and decreased sediment flow: A remote sensing assessment. Remote Sens. Environ. 115 (12), 3121–3128. http://dx.doi.org/10.1016/j.rse.2011.06.019.

Rajawat, A.S., Gupta, M., Acharya, B.C., Nayak, S., 2007. Impact of new mouth opening on morphology and water quality of the Chilika Lagoon—a study based on Resourcesat-1 LISS-III and AWiFS and IRS-1D LISS-III data. Int. J. Remote Sens. 28 (5), 905–923.

Raposa, K., 2002. Early responses of fishes and crustaceans to restoration of a tidally restricted New England Salt Marsh. Restoration Ecol. 10 (4), 665–676. http://dx.doi.org/10.1046/j.1526-100X.2002.01047.x.

Reshef, D.N., Reshef, Y.A., Finucane, H.K., Grossman, S.R., McVean, G., Turnbaugh, P.J., Sabeti, P.C., 2011. Detecting novel associations in large data sets. Science 334 (6062), 1518–1524. http://dx.doi.org/10.1126/science.1205438.

Rey, J.R., Crossman, R.A., Kain, T.R., 1990. Vegetation dynamics in impounded marshes along the Indian River Lagoon, Florida, USA. Environ. Manage. 14 (3), 397–409.

Robert, B.C., William, S.C., Jean, E.M., Irma, T., 1990. STL: A seasonal-trend decomposition procedure based on Loess. J. Off. Stat. 6 (1), 3–73.

Schallenberg, M., Larned, S.T., Hayward, S., Arbuckle, C., 2010. Contrasting effects of managed opening regimes on water quality in two intermittently closed and open coastal lakes. Estuar. Coast. Shelf Sci. 86 (4), 587–597. http://dx.doi.org/10.1016/j.ecss.2009.11.001.

Schroeder, T.A., Wulder, M.A., Healey, S.P., Moisen, G.G., 2011. Mapping wildfire and clearcut harvest disturbances in boreal forests with Landsat time series data. Remote Sens. Environ. 115 (6), 1421–1433. http://dx.doi.org/10.1016/j.rse.2011.01.022.

SER, 2006. Ecological restoration- a means of conserving biodiversity and sustaining livelihoods. http://www.ser.org/resources/resources-detail-view/ecological-restoration-a-means-of-conserving-biodiversity-and-sustaining-livelihoods (accessed 17.12.14).

Sima, S., Ahmadalipour, A., Tajrishy, M., 2013. Mapping surface temperature in a hyper-saline lake and investigating the effect of temperature distribution on the lake evaporation. Remote Sens. Environ. 136, 374–385. http://dx.doi.org/10.1016/j.rse.2013.05.014.

Soudani, K., Hmimina, G., Delpierre, N., Pontailler, J.Y., Aubinet, M., Bonal, D., Caquet, B., de Grandcourt, A., Burban, B., Flechard, C., Guyon, D., Granier, A., Gross, P., Heinesh, B., Longdoz, B., Loustau, D., Moureaux, C., Ourcival, J.M., Rambal, S., Saint André, L., Dufrêne, E., 2012. Ground-based Network of NDVI measurements for tracking temporal dynamics of canopy structure and vegetation phenology in different biomes. Remote Sens. Environ. 123, 234–245. http://dx.doi.org/10.1016/j.rse.2012.03.012.

Staudinger, M.D., Grimm, N.B., Staudt, A., Carter, S.L., Stuart III, F.S., Kareiva, P., Ruckelshaus, M., Stein, B.A., 2012. Impacts of Climate Change on Biodiversity, Ecosystems, and Ecosystem Services: Technical Input to the 2013 National Climate Assessment. In: Federal Government Series, United States Global Change Research Program, Washington, DC.

Stow, D., Daeschner, S., Hope, A., Douglas, D., Petersen, A., Myneni, R., Oechel, W., 2003. Variability of the seasonally integrated normalized difference vegetation index across the north slope of Alaska in the 1990s. Int. J. Remote Sens. 24 (5), 1111–1117. http://dx.doi.org/10.1080/0143116021000020144.

Telesh, I.V., Khlebovich, V.V., 2010. Principal processes within the estuarine salinity gradient: a review. Mar. Pollut. Bull. 61 (4–6), 149–155. http://dx.doi.org/10.1016/j.marpolbul.2010.02.008.

Thomasen, S., Chow-Fraser, P., 2012. Detecting changes in ecosystem quality following long-term restoration efforts in Cootes Paradise Marsh. Ecol. Indic. 13, 82–92. http://dx.doi.org/10.1016/j.ecolind.2011.04.036.

Tian, H., Cao, C., Chen, W., Bao, S., Yang, B., Myneni, R.B., 2015. Response of vegetation activity dynamic to climatic change and ecological restoration programs in Inner Mongolia from 2000 to 2012. Ecol. Eng. 82, 276–289. http://dx.doi.org/10.1016/j.ecoleng.2015.04.098.

Turner, K.G., Anderson, S., Gonzales-Chang, M., Costanza, R., Courville, S., Dalgaard, T., Dominati, E., Kubiszewski, I., Ogilvy, S., Porfirio, L., Ratna, N., Sandhu, H., Sutton, P.C., Svenning, J.-C., Turner, G.M., Varennes, Y.-D., Voinov, A., Wratten, S., 2015. A review of methods, data, and models to assess changes in the value of ecosystem services from land degradation and restoration. Ecol. Model. http://dx.doi.org/10.1016/j.ecolmodel.2015.07.017. n.d..

Washington-Allen, R.A., Ramsey, R.D., West, N.E., Norton, B.E., 2008. Quantification of the ecological resilience of drylands using digital remote sensing. Ecol. Soc. 13 (1), 33.

Zhang, G., Dong, J., Xiao, X., Hu, Z., Sheldon, S., 2012. Effectiveness of ecological restoration projects in Horqin Sandy Land, China based on SPOT-VGT NDVI data. Ecol. Eng. 38, 20–29. http://dx.doi.org/10.1016/j.ecoleng.2011.09.005.