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Opportunities for the application of Red-edge reflectance-based indices in coastal vegetation and agro-ecological studies

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Abstract

Remote sensing is an advanced tool that provides electromagnetic information about the Earth's surface and atmosphere. In ecological studies, the applications of vegetation indices (VIs) derived from remote sensing data have continued to increase, especially in capturing and monitoring vegetation properties and environmental changes. This study reviews the application of VIs with special focus on red-edge based indices in the evaluating coastal landscapes and other conservation studies. The spectral characteristics of vegetation is briefly reviewed in order to exploit the potential information of the reflectance spectrum, and the possible key role of vegetation indices in future research of coastal vegetation as well as resilience indicator in the ever-changing landscapes.

Keywords: *red edge-based indices; coastal vegetation; dynamic environments; repetitive coverage; conservation research*

Abstrak

Penginderaan jauh adalah salah satu teknologi yang mampu menyajikan informasi tangkapan gelombang elektromagnetik tentang permukaan dan atmosfer Bumi. Pada studi-studi yang terkait dengan ekologi, pengaplikasian indeks-indeks vegetasi yang diperoleh dari data penginderaan jauh terus mengalami peningkatan, terutama terkait dengan kemampuannya menangkap dan memonitor sifat-sifat tutupan vegetasi serta perubahan lingkungan. Studi ini mencoba mereview secara singkat berbagai pemanfaatan indeks-indeks vegetasi, khususnya indeks vegetasi yang berbasis atau menggunakan panjang panjang gelombang red-edge terkait dengan kemampuannya mengevaluasi lanskap pantai dan studi konservasi lainnya. Karakteristik pantulan spektral vegetasi ditinjau secara mendalam untuk mengetahui kemampuannya dalam memberikan informasi sifat-sifat vegetasi, serta kemungkinan peran dari indeks-indeks vegetasi tersebut untuk penelitian-penelitian selanjutnya, khusus terkait dengan vegetasi pantai serta indikator ketahanan lanskap yang selalu berubah.

Kata Kunci: *indeks berbasis red-edge; vegetasi pesisir; lingkungan yang dinamis; cakupan berulang; penelitian konservasi*

1. Introduction

Remote sensing is one of the most cost-effective approaches that provide valuable insights for investigating and interpolating earth surface features and detecting change (Medina et al., 2019; Pettorelli et al., 2013). Remotely-sensed data using both airborne and satellite platforms have raised a novel prospect as proxies of ecosystems properties, including conservation and monitoring of biodiversity, forestry, agriculture, coastal and marine ecosystems, and other related fields (Hossain et al., 2019; Goetz & Dubayah 2011; Zolkos et al., 2013). In recent decades, hyperspectral sensors have offered both relatively higher spectral and spatial resolution than previously available, allowing the extraction of more detailed information on spectral variability of the landscape features (Salas & Henebry, 2014; Weng et al., 2008; Thenkabail et al., 2000).

Advances in remote sensing sensors combined with machine learning algorithms have proved to be the most robust approaches for detecting, mapping, and monitoring complex nature patterns and dynamic of vegetation as well as their biophysical and structural properties (Klemas, 2012; Husnayaen et al., 2018; Verrelst et al., 2019).

Numerous approaches have been developed for the purpose of extracting remote sensing information relevant to particular indicator of earth components across large spatial extents (Li et al., 2018; Pettorelli et al. 2005). Vegetation Indices (VIs) derived from remote sensing data are among advanced approaches and techniques developed by scientists and practitioners for quantitative and qualitative evaluation of vegetation, such as vegetation cover, vigor, growth stages, forest health and dynamics (Kross et al., 2015; Pettorelli et al., 2005; Zhang et al., 2018). Vegetation indices (VIs) are spectral transformations of two or more bands designed to enhance spectral features sensitive to a vegetation characteristic and enable data interpretation of vegetation surface, allowing reliable spatial and temporal inter-comparisons of vegetation and other earth components, including phenological, biophysical, and structural parameters of vegetation (Li et al., 2018; Xu et al., 2019).

In this study, we present an overview on the application of vegetation indices (VIs) in recent ecological and conservation studies. Particular emphasis was given to the potential use of red-edge spectral reflectance-based indices for investigating and mapping coastal vegetation.

2. Challenges in mapping and monitoring coastal vegetation

Coastal ecosystems provide imperative functions that support a diverse array of life forms and numerous goods and services to human well-being and the environment. These services include biodiversity, regulation (nutrient regulation, climate regulation, carbon sequestration, detoxification of polluted waters), provision (energy resources, natural products, supply of food), support (buffering from natural hazards, marine life nursery functions, shoreline stabilisation), tourism and cultural services (recreation, culture and amenity) (Barbier et al., 2011; Nehren et al., 2016; Unsworth et al., 2018). Despite such benefits and services, coastal zones are currently identified as one of the most threatened ecosystems. Degradation of coastal ecosystems cause biodiversity loss, landscape modifications, and habitat degradation; and thereby threatens the capacity of coastal ecosystems to provide good and services that contribute to human wellbeing (Husnayaen et al., 2018; Ferrol-Schulte, et al. 2015; Gilman et al., 2008).

Coastal ecosystems are increasingly being threatened by human pressure, such as tourism, urban development, pollution, and farming practices (Ciccarelli, 2014). Environmental changes will cause serious long-term consequences along with the potential impacts of climate change relevant to coastal ecosystems, including variations in temperature and associated rise in sea level, changes in precipitation, ocean circulation, wave conditions, storm surge, and ocean acidification due to higher levels of CO2 (Lotze at al., 2006). In this case, anthropogenic climate change can alter the atmospheric composition, resulting in variations and change the intricate dynamics of the coastal landscapes (Frosini et al., 2012). Moreover, natural forcing drivers, such as coastal hazards (e.g., coastal erosion, flooding), can drive the probability and severity of which is expected to increase with climate change (Delgado-Fernandez et al., 2019). Under the influence of complex mechanisms and high pressures of both natural and anthropogenic stressors, protecting coastal ecosystems therefore requires an understanding of the nature of coastal systems and the dynamic way these systems evolve to prevailing changing environments.

Satellite and airborne remote sensors have great abilities to detect, measure, and map coastal ecosystems and their changes at appropriate scales and resolutions; minimizing the need for extensive field-based measurements (Carranza et al., 2008; Lyons et al., 2012). However, spectral responses of vegetation provide one of the greatest challenges for remote sensing interpretation in several ecosystems since the spectral response of vegetated areas presents a complex mixture of vegetation, soil brightness, environmental effects, shadow, soil color and moisture (Ollinger, 2011), especially in coastal systems. Coastal ecosystems exhibit vegetation mosaic and complex relationships between the physical and biological processes that form dynamic geomorphic structures at with extreme variations in spatial complexity and temporal variability (Pinna et al., 2019). Due to their unique position between marine and terrestrial environment, coastal zones constitute complex transitional systems subjected to variety of natural process and environmental drivers such as topography, soil salinity, substrate instability, marine aerosol, wind and aeolian processes (De Luca et al., 2011). The recent development of remote sensing sensors and data analysis techniques offer an opportunity to detect and monitor biophysical features of landscape components, particularly coastal vegetation.

3. Spectral Characteristics Of Vegetation And Red Edge Indices

The spectral signatures, patterns and heterogeneity recorded by remote-sensing techniques have been widely exploited for investigating and interpolating vegetation properties. The main electromagnetic spectrum that are relevant to the applications of vegetation remote sensing are the following: (i) the visible spectra, which are composed of the blue (450–495 nm), green (495-570 nm), and red (620–750 nm) wavelength regions; and (ii) the near and mid infrared band (850–1700 nm) (Figure 1). Numerous studies have exploited spectrum of possibilities associated with vegetation indices (VIs), and in particular the Normalized Difference Vegetation Index (NDVI). NDVI, which is computed as ratio-based vegetation indices using visible (red) and Near Infrared, is highly associated with photosynthetically active radiation**.** The reflectance within the visible wavelength, especially red and blue, is associated to absorption of two major chlorophyll pigments (i.e. chlorophyll a and b), whereas reflectance at the NIR band is highly related with the leaf structure (e.g. plant geometrical and internal biophysical structure) rather than pigment composition (Miller et al., 1990; Kumar et al., 2002).

Normalized Difference Vegetation Index (NDVI) is the most well-known and widely used vegetation index, particularly in research related to regional and global vegetation assessments. This greenness index can be applied as robust indicator of photosynthetic capacity, leaf area index (LAI), net primary production, carbon assimilation and evapotranspiration, among other applications (e.g. Kawabata et al., 2001; Schloss et al., 1999). However, NDVI commonly saturate at moderate-to-dense canopies. NDVI does have some limitations, especially when plant species or vegetation are reaching mature stage with complete canopy closure or having high biomass and leaf area index (LAI) (Gitelson et al., 2003). This index is reported to be sensitive to the effects of soil brightness, soil color, atmosphere, cloud and cloud shadow, and leaf canopy shadow (Buma & Lee, 2019; Xue and Su, 2017).

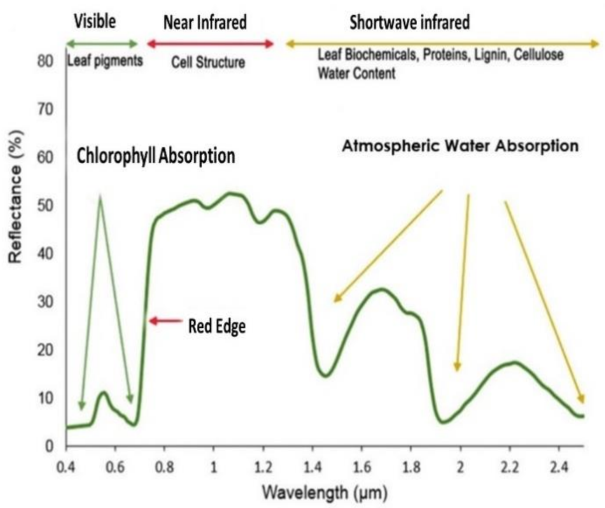

Figure 1. Spectral reflectance curve of vegetation showing energy wavelength, absorption features and vegetation components controlling vegetation reflectance characteristics (Roman & Ursu, 2016).

Red edge is also regarded as one of the most obvious characteristics of green vegetation, since it is strongly correlated with chlorophyll content (Baranoski & Rokne, 2005). Red edge approximately refers to 680 -740 nm in the electromagnetic spectrum, reflecting the spectrum of transition platform from the strong absorption of red light to the near-infrared multiple scattering of vegetation chlorophyll (Horler et al., 1983). Red edge parameters include red edge position, red edge slope, red edge area, red edge average refectivity, red edge amplitude, ratio of red edge amplitude and minimum amplitude. A high correlation was found between both amplitude of the red edge peak (dr_{re}) and the area of the red edge peak ($\sigma_{680-780}$ nm) with LAI (leaf area index), while the wavelength of the red edge peak (λ_{re}) was the best estimator of chlorophyll content (Filella & Penuelas, 1994). Red-edge position is reported to be less sensitive to the changes of canopy structure, plant coverage, and leaf properties (Cho et al., 2008; Pu et al., 2003).

Table 1

Red-edge spectral reflectance-based indices, references, and equations.

Index	Acronym	Equation	Reference
Red-edge normalized difference vegetation index	NDVIred edge	(NIR - Red Edge)/ (NIR + Red Edge)	Gitelson and Merzlyak, 1994
Red-edge simple ratio vegetation index	RERVI	RERVI= ρ780/ρ730	Cao et al., 2015
Normalized difference red-edge	NDRE	NDRE= (ρ780−ρ730)/ (ρ780+ρ730)	Peng and Gitelson, 2012
Red-edge re-normalized difference vegetation index	RERDVI	RERDVI= (ρ780−ρ730)/ √ρ780+ρ730)	Cao et al., 2015
Red-edge difference vegetation index	REDVI	REDVI= ρ780−ρ730	Cao et al., 2015
Red-edge soil adjusted vegetation index	RESAVI	RESAVI= 1.5*[(ρ780−ρ730)/ √(ρ780+ρ730+0.5)]	Huete, 1988
Red-edge optimal soil adjusted vegetation index	REOSAVI	REOSAVI= (1+0.16)(ρ780−ρ730) / (ρ780+ρ730+0.16)	Cao et al., 2013
Red-edge wide dynamic range vegetation index	REWDRVI	REWDRVI= (0.15*ρ780−ρ730)/ (0.15*ρ780+ρ730)	Gitelson, 2004
Red-edge chlorophyll index	CI_{RE}	CI_{RE}= ρ780/ρ730-1	Gitelson et al., 2005

The use of red-edge based indices has been reported in research especially related to chlorophyll concentration and nutritional status. Table 1 shows several vegetation indices that have been developed on the red-edge region. The derivative-based red-edge indices were reported to be more sensitive to changes on both leaf chlorophyll content and the LAI at dense plant canopy or biomass (Pu et al., 2003; Cho et al., 2008). This higher sensitivity can be attributed to derivative analysis which can magnify signal properties at an absorption region and also changes of scattering properties at longer wavelengths (Boochs et al., 1990). The advantage red-edge reflectance is highlighted due to its position being between the bands where strong absorption of light by plant pigments and high leaf reflection occur. However, indices that incorporate the reflectance of red-edge bands were mostly derived from narrow and field spectroradiometers, medium resolution spectrometers, and airborne spectrographic imagers (e.g. Viña et al., 011; Nguy-Robertson et al., 2012; Haboudane et al., 2004).

4. Current contributions of Red Edge based indices to coastal vegetation mapping and conservation studies

Several studies have evaluated the sensitivity of VIs derived from the red-edge band for mangrove forests. Zhu et al. (2017) developed an estimation model of LAI of mangrove forests based on WorldView-2 (WV2) imagery. They demonstrated that for all machine-learning algorithms used in their study (i.e. artificial neural network regression, support vector regression, and random forest regression), the spectral transformations of the red-edge band on WV2 imagery were consistently had the highest prediction accuracy compared with other traditional bands of WV2, such as near-infrared-1 and near-infrared-2 band. Similarly, Castillo et al. (2017) demonstrated that based on biophysical variable Leaf Area Index (LAI) derived from Sentinel-2, red edge-based Inverted Red-Edge Chlorophyll Index was more accurate in predicting the overall above-ground biomass of mangroves in Philippines. Other study highlighted the potential use of Red Edge NDVI for mangrove species mapping in Malaysia, using Maximum Likelihood Classifier based on the RapidEye satellite imagery (Roslani et al., 2014).

Mukaromah (2017) highlighted the applicability of vegetation index computed using algorithm based on the red-edge band in combination with ancillary and field data to classify and map comprehensive cover of various vegetation on Rottnest Island. The Red Edge Normalized Vegetation Index (Red Edge NDVI), also known as NDVI705, is a narrowband greenness modified from NDVI, and is measured by the ratio of within-leaf scattering and the effect of leaves' chlorophyll content. The Red Edge NDVI is applied by using bands along the red edge instead of the main absorption and reflectance peaks. Compared to other vegetation indices, Red Edge NDVI provide an increased sensitivity in detecting plant physiological status at low coverage plant biomass. Testing on HyMap imagery, this study also demonstrated that several sites of vegetation have Normalized Vegetation Index (NDVI) values below zero. The range of NDVI values for vegetation should be between 0 and 1, with the higher value attributed to healthy-dense vegetation and the lower value related to sparse vegetation. The low value (NDVI values below zero) on the HyMap image in this study reflects the low biomass and vegetation cover of the most sparse and disturbed heath communities (the negative value of NDVI should be represented water and built-up area). NDVI may reflect a sensitive response to green vegetation even for low vegetation covered areas; however, this index does not successfully differentiate the densely vegetated from the sparsely vegetated area (Adams and Gillespie, 2006). The findings of this study indicated that red edge band in the HyMap imagery has potential for subsequent mapping methods, while enable the enhanced characterization of vegetation biophysical properties and land surface condition. These findings are vital for vegetation monitoring, especially those of sparse and dry heathlands. The Red Edge NDVI hyperspectral index is reported to be highly sensitive to changes in canopy foliage, gap fraction, and senescence phenological stages, and has the advantage of not being affected by leaf surface reflectance (Gupta et al., 2003; Jung et al., 2006). Other studies reported that most VIs that are computed on the red-edge region attempt to minimalizing the effects of backgrounds caused by variations in soil reflectance (Dorigo et al., 2007; Glenn et al., 2008). Jung et al. (2006) also indicated that Red Edge NDVI is very useful as a sensitive environmental indicator for detecting vegetation stress, for instance caused by drought and disease. While HyMap may cost exorbitant for extensive planning and synoptically monitoring of large regions, this airborne hyperspectral sensor enables to evaluate fine scale landscape assessment.

There are several existing studies that use Red Edge parameter to improve the precision agriculture and yield prediction (Cui & Kerekes, 2018; Chlingaryan et al., 2018; Cho and Skidmore, 2006). Based on the red-edge inflection point (REIP) computed from derivative analysis, Kanke et al. (2016) evaluated grain yield prediction of two rice varieties with different canopy structure and other agronomic parameters (biomass, N uptake and plant coverage). Red-edge inflection point (REIP) defined as the maximum of the first derivative reflectance between the red and NIR regions. They calculated REIP based on the maximum first derivative analysis by polynomial fitting technique (REIPDF), linear interpolation technique (REIPLI), linear extrapolation technique (REIPLE), and the Lagrangian technique. They demonstrated that REIP had a strong correlation with agronomic parameters (i.e. biomass, N uptake, and grain yield), and this relationship is stronger than those of red-based indices. Van der Meer and De Jong (2006) also reported similar findings that REIP is significantly related with N concentration particularly at dense plant canopy ground coverage. Similarly, other studies also reported that reflectance at the REIP can be used as a good indicator of biomass, N content, and chlorophyll content (Lukas et al., 2016; Raper & Varco 2015).

5. Conclusion

Red edge-based indices have significantly enhanced the sensitivity of chlorophyll concentration and allowing biophysical measurements, including biomass estimation, nitrogen content and leaf area index (LAI). Strong correlation of red edge with chlorophyll content also provide more sensitivity to detect dry and sparse vegetation, making this index a useful indicator of environmental stress. Vegetation index computed using algorithm based on the red-edge band could also potentially be used to strengthen NDVI as red edge is strongly correlated with both leaf chlorophyll content and leaf area index (LAI), especially at dense plant canopy or biomass. With the development of remote sensing sensors, specific red edge indices can be developed to improve the capability of robustness against chlorophyll change, providing high-quality reference information and broadening research areas to address rapid environmental changes and continuous vegetation estimates in the near future, especially in coastal landscapes that constitute complex vegetation mosaics subjected to constantly changing environments.

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