Monitoring tropical peatland ecosystem in regional scale using multi-temporal MODIS data: Present possibilities and future challenges

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Abstract. Many studies on peatland ecosystem have been focused on forest conversion or forest degradation as a single pathway, meanwhile; in the context of peatland ecosystem, the change in land surface is more complicated since it can be categorized into two types and mechanisms: 1) gradual change, caused by interannual climate variability and forestland degradation, and 2) abrupt change, caused by disturbances such as deforestation and wildfires. Understanding this change types is needed for conservation and management, particularly to improve understanding of terrestrial environmental change in peatland ecosystem. In such situation, simultaneous analysis of land surface attributes from long-term datasets and seasonal variation seems to be a way to monitor the tropical peatland ecosystem. This analysis provides information about how the changes occurred accurately as well as how big are these affected areas. In this article, the feasibility of using long-term MODIS data for monitoring the dynamics change in peatland ecosystem is examined. The temporal vegetation dynamics of long-term MODIS datasets offer great promise for characterizing gradual change as well as abrupt change at large scale, however, the mixed pixel issue and some residual noises in temporal sequences are quite problematic when using MODIS data.

1. Introduction

Importance of peatland in the tropical environment has been studied by many scientists, such as estimation of CO2 emission released by forest fire [1], variation in its ecological function [2], and loss of biodiversity through land conversion [3]. Consequently, the study of sustainable peatland management has been highlighted as a priority study in mitigation of climate change in agriculture and forestry sector [4]. These studies indicated the need to construct an update and accurate database concerning tropical peatland environment, their meaning, their pace and the explanatory factors prompting their dynamic changes.

As an essential ecosystem, the peatland ecosystem is vulnerable to be changed in their water supply [5], and it is expected that climate change will have a pronounced effect on peatlands through alterations in hydrological regimes with climate variability [6]. Therefore, available information on characteristics
of peatland ecosystem and its dynamics change is necessary for many aspects of peatland conservation and management.

Peatlands are complex systems that reflect their geographical and ecological setting. Their characteristics and its changes are the results of interactions between socio-economic and cultural conditions, biophysical constraints and land use history [7]. Development and stability of peatlands are determined as interactions between different land use/cover types, hydrological setting and spatial elements of the landscape [8].

This paper evaluates the feasibility of using time series satellite datasets to consider the peatland characteristics and its dynamics changes occurred in this ecosystem. In some earlier works, monitoring approach to recognizing the peatland characteristics and its dynamic changes on a regional scale is due to simultaneous analysis of land surface attributes from long-term data sets and seasonal variation. Monitoring of land surface continuously can provide information on the ecosystem characteristics, including how the change occurred accurately as well as how big are these affected areas [9].

2. Remote sensing approach for identifying the ecosystem characteristics

Advances in remote sensing technology enable land scientists to characterize some terrestrial ecosystems using satellite data sets. Monitoring of land surface continuously in space and time, at both seasonal and inter-annual scales allows characterization of the temporal vegetation dynamics of terrestrial ecosystem, including peatlands [10].

Characterization of vegetation dynamics has often been made by using vegetation index values [11]. The temporal dynamics of those index values are useful for distinguishing land surface conditions by differentiating among vegetation types and their distributions [12]. The vegetation indices relate to the amount of green leaf biomass. They are computed by algebraic combination of two or more spectral bands and are designed to enhance the contribution of vegetation properties [13].

The normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI) are commonly used to measure reliable spatial and temporal inter-comparisons of terrestrial photosynthetic activity and canopy structural variations [14]. The EVI is more responsive to canopy structural variations, including leaf area index (LAI) and canopy type, rather than the NDVI, as it was developed to optimize the vegetation signal with improved sensitivity in high biomass regions through a decoupling of the canopy background signal and a reduction in atmosphere influences [14].

The uses of multi-year datasets are necessary to develop methodologies that utilize information on inter-annual variations to increase the accuracy of the land surface characterization. The Moderate Resolution Imaging Spectroradiometer (MODIS) satellite datasets provide basic information related to vegetation dynamics in peatland ecosystem. These datasets are provided by the U.S. Geological Survey - Land Processes Distributed Active Archive Center (USGS LPDAAC). The MODIS Vegetation Index composited 16-day product (MODIS MOD13Q1) is available for packaged MODIS that should be useful for a specific need for land surface monitoring and historical trend analysis. Such kind of the high temporal datasets is required to characterize the vegetation dynamics in peatland ecosystem, including detecting the event of forest cover change.

In the previous work, the 25 types of EVI pattern, which represent a specific class of land use in regional scale of Java Island, was determined [9]. The accuracy of this classification revealed the overall accuracy and the overall k-statistics to be 80.16% and 70.94%, respectively. As pointed out previously, locations displaying similar temporal patterns inferred to have a similar ecosystem type, not limited to land use type, which are have relatively homogeneous characteristics such as fractions of vegetation covers and environmental conditions. The global ecosystem characteristics was determined based on their seasonal land cover, floristic properties, climate, and physiognomy [15]. At a continent scale, monitoring the reliable spatial and temporal characteristics of vegetation dynamics allows the classification of African ecosystem at 1 km resolution [16].

Distinguishing among temporal patterns of EVI pattern accomplished using the K-means clustering method based on Euclidean distance in an EVI-space, in which each EVI images provides one dimension of feature space, analogous to spectral clustering. The clustering method yields sets of clusters, which
each cluster represents a significant different EVI pattern of detailed information of characteristics/type of peatlands. As shown by figure 1, the method distinguished temporal vegetation dynamics of the peatlands into different land cover properties such as secondary swamp forest, bush/swamp bush, agricultural lands/plantation and swamp forest mixed bush.

![Figure 1](image)

**Figure 1.** Temporal pattern of EVI accomplished based on K-mean clustering in peatland ecosystem following different land use/cover types: a) swamp forest mixed bush, b) bush/swamp bush, c) agricultural lands, and d) swamp forest

3. **Characterization of tropical peatland ecosystem**

The peatland ecosystem of Sumatra was defined by differentiating the long time-series of typical EVI patterns, which distinguished the specific type of peatland and/or different response of this ecosystem to the environment changes in these given land areas [10]. The study performed initial segmentation of the long time-series of EVI composites by the clustering method and differentiated into 23 clusters. This number of cluster seems sufficient to represent various patterns of vegetation dynamics in Sumatran peatland ecosystems. Each class pattern represents the specific peatland ecosystem type; in turn inferred to have relatively homogeneous environmental characteristics such as peat depth, specific land cover type, and other environmental parameters (table 1).

Most of class patterns in the peatlands were associated mainly with six land cover types; namely secondary swamp forest, swamp bush, timber forest, plantation, agricultural lands and bare lands. Consequently, more than one typical pattern might be characterized by one land cover type, which represents different environmental characteristics of a specific ecosystem. The distribution of each typical pattern in Sumatra is shown in figure 2.
Table 1. Summary of typical pattern characteristics in Sumatran peatland regarding to EVI-based class pattern

| No | Land cover type                                                                 | Peat depth (cm) | Performance of typical vegetation pattern |
|----|----------------------------------------------------------------------------------|-----------------|-------------------------------------------|
| 1  | Water features including lakes and reservoirs                                     | < 50            |                                            |
| 2  | Water features including lakes and reservoirs; mixed vegetated areas               | < 50            |                                            |
| 3  | Swamp bush                                                                        | 100-200         | Pattern change occurred in 2002 (Jan–Jun)  |
| 4  | Swamp bush, paddy field/intensive agricultural lands                               | 50-100          | Pattern change occurred in 2002 (Apr-Sep)  |
| 5  | Swamp bush                                                                        | > 400           | Pattern change occurred in 2006 (Apr-Dec)  |
| 6  | Industrial forest plantation, swamp bush                                           | 50-100; 100-200 | Pattern change occurred in 2005(Apr-Sep)    |
| 7  | Swamp bush                                                                        | 50-100          | Pattern change occurred in 2013 (Apr-Sep)  |
| 8  | Industrial forest plantation                                                      | > 400           | Pattern change occurred in 2002 (Jul-Des), 2008 (Jan-Jun), 2013 (Apr-Sep) |
| 9  | Bare land, swamp bush                                                             | 300-400         | Pattern change occurred in 2011 (Apr-Sep), 2013 (Apr-Sep) |
| 10 | Secondary swamp forest                                                            | 300-400, > 400  | Not significantly changed                  |
| 11 | Industrial forest plantation                                                      | > 400           | Pattern change occurred in 2006 (Jul-Des), 2011 (Apr-Sep) |
| 12 | Secondary swamp forest                                                            | > 400           | Not significantly changed                  |
| 13 | Industrial forest plantation                                                      | > 400           | Pattern change occurred in 2002 (Jul-Des), 2009 (Jul-Des) |
| 14 | Secondary swamp forest                                                            | > 400           | Pattern change occurred in 2013 (Apr-Sep)  |
| 15 | Industrial forest plantation, swamp bush                                          | 50-100          | Pattern change occurred in 2002 (Jul-Des), 2006 (Apr-Des) |
| 16 | Secondary swamp forest, swamp bush                                                | 100-200         | Pattern change occurred in 2002 (Jul-Des)  |
| 17 | Swamp bush                                                                        | 100-200         | Not significantly changed                  |
| 18 | Plantation, swamp bush                                                            | 100-200         | Pattern change occurred in 2005 (Jul-Des)  |
| 19 | Plantation, swamp bush                                                            | 50-100          | Pattern change occurred in 2006 (Jul-Des)  |
| 20 | Plantation                                                                        | 50-100          | Pattern change occurred in 2006 (Jul-Des)  |
| 21 | Secondary swamp forest                                                            | 50-100          | Not significantly changed                  |
| 22 | Secondary swamp forest, swamp bush                                                | 50-100          | Pattern change occurred in 2005 (Jul-Des)  |
| 23 | Secondary swamp forest                                                            | 50-100          | Not significantly changed                  |
Figure 2. Distribution of each typical pattern in peatlands of Sumatra

Due to the temporal vegetation pattern, dynamics changes and their properties could be detected by the distance comparison of EVI. This detection method has been discussed in [17]. Regarding the identification of the pattern change, many significant patterns indicated specific changes of land use/cover in peatland ecosystem. Figure 3 indicates some examples of change trajectories, as follows: a) forest mixed bush converted to barren land through burning at the end of October 2009, b) agricultural development due to crop planting in barren land, and then developed into intensive agricultural lands from July 2011, c) re-growth/re-vegetation processes occurred in a land affected by forest fire/wildfires, where vegetated lands drastically changed to open land by fire on October 2009, and then the recovery process occurs gradually over long periods of time.

Moreover, due to overlay with hotspot data (https://firms.modaps.eosdis.nasa.gov/), the results indicated that some areas of specific peatlands had never been burned from 2000 to 2014. These peatland ecosystems support a natural tree cover and important ecosystem to be preserved. Some of abrupt pattern changes occurred in swamp bush and located at a peat depth of more than 400 cm, which is widely distributed in the central raised part of the peat swamp area. These typical conditions have numerous consequences relevant to the environment as well as changes in carbon storage, land degradation and loss of biodiversity.

Indeed, characterization of typical peatland ecosystem based on temporal pattern analysis would provide useful information regarding the change dynamics in the peatland ecosystems.
Although MODIS data have some advantages in providing basic information related to vegetation dynamics pattern, time-series of these data inevitably contain disturbances caused by atmospheric variability and aerosol scattering [18]. Such noise degrades the data quality and introduces considerable uncertainty in temporal sequences, confusing the analysis of temporal images sequences by introducing significant variations in the EVI time series data. Therefore, noise reduction (de-noising) or fitting a model to observe data is necessary before vegetation dynamics pattern can be determined.

Various strategies for image preprocessing including smoothers have been applied, such as: median filters [19], a moving window to select the local maximum VI [20], principal component analysis (PCA) [21], and the Savitzky-Golay filter approach [22]. Several spectral-frequency techniques have also been used, including Fourier-based fitting methods for separating the high-frequency components of noise and the low-frequency components of seasonal changes of VI [23] and, most recently, wavelet decomposition, which has been used to de-noise and to build a vegetation signatures through feature extraction of MODIS multi-temporal [9].

Moreover, the mixed pixel issue associated with the 250 m grid data is another issue for using the MODIS data. Overlaying the specific coverage type in peatlands ecosystem in Java Island over the image classification result using Landsat ETM+ revealed that in general, approximately only 20% of MODIS pixels contained homogeneous cover types [9]. This result shows that most image pixels contain a mixture of land use/cover classes, which is referred to as sub-pixel mixing. Such issue may lead to the difficulty of obtaining the actual number of clusters.

Regarding the accuracy assessment issue, the creation of a reference data set in order to assess the accuracy of characterization result of the peatland ecosystem is one important step of the study. A complicating factor in assessing the accuracy derived from 250 m image data was the disparity between the image pixel size and the average patch size of the landscape. The same issue was mentioned by [24], that one problem of moderate spatial resolution imagery is that the intrinsic scale of spatial variation in many land covers is finer than the scale of sampling imposed by the image pixels.

Although the mixed pixel issue is quite problematic when using MODIS data, the results indicated that MODIS data offer great promise for monitoring the dynamics change processes of the peatland ecosystem.
ecosystem, including how and when the change occurred accurately. Furthermore, the understanding of the terrestrial environmental changes such as carbon storage change and sequestration by terrestrial plants will be improved. The research of temporal vegetation dynamics could be carried out under the framework of regional analysis, so that better understanding of a typical ecosystem can be achieved in a regional scale.

4. Conclusions
Monitoring land surfaces continuously based on temporal vegetation dynamics allows characterization of the typical ecosystem in peat swamp area. This study is based on the approach that each pattern of vegetation dynamics represents the specific peat swamp ecosystem type; in turn inferred to have relatively homogeneous environmental conditions such as land cover type and peat depth.

Considering the results, the peat swamp ecosystems can be categorized into two types as follows: 1) developed land as the forest plantation and agricultural lands, and 2) secondary swamp forest and swamp bush. Different typical pattern of these ecosystems represented different environmental characteristics such as peat depth. Moreover, the abrupt changes in the secondary swamp forest and swamp bush in peatlands ecosystem, by either peat-fire or human factors, especially located at very deep peat soil, have numerous consequences relevant to the environmental changes.

Regional shifts in temporal vegetation dynamics, including the actual changes in the peatland and temporary changes of land cover, have numerous consequences relevant to the environment as well as changes in carbon and nitrogen storage, land degradation and loss of biodiversity. Determining the change of temporal vegetation dynamics is the first step in understanding their implications, for example, long-term crop production, and environmental, agricultural and economic sustainability. An understanding of temporal vegetation dynamics to explain the mechanisms and pathways of dynamics change of peatland ecosystem is important because of the relationship between ecosystem characteristics and socio-economic attributes of the land.

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