Change trend analysis of the time-series shadow-eliminated vegetation index (SEVI) for the Wuyishan Nature Reserve with the Sen+Mann-Kendall method

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Abstract. In order to reveal the characteristics of spatial distribution and dynamic change of the forest in the Wuyishan Nature Reserve from 2000 to 2019, the recently proposed shadow-eliminated vegetation index (SEVI) and the method of Sen+Mann-Kendall were used together in this study. The results show a trend of “decreasing first and then increasing” of vegetation cover change of the Reserve during the sub-periods of 2000-2011 and 2012-2019, but, as a whole, the vegetation cover of the Reserve was improved during 2000-2019, with 43.76% slight improvement and 55.18% significant improvement, approximately.

1. Introduction

As an important ecosystem, the vegetation plays a crucial role in the substance circulation and energy transformation on earth[1]. In order to protect the vegetation resource and biodiversity, the nature reserve has become an effective strategy[2]. The monitoring and analysis of nature reserve vegetation are a vital measure to assess the regional vegetation protection effectiveness and human activity disturbance[3]. It is particularly important to use the time series analysis method to evaluate the vegetation cover change in a period. In mountain areas, the forest nature reserve has been studied in recent years, e.g., the Wuyishan Nature Reserve[4]. However, the topographic shadow effect, which locates in the rugged terrain, including self and cast shadows[5], is a dominant obstacle in obtaining accurate vegetation information through remote sensing[6-8]. A recently proposed shadow-eliminated vegetation index (SEVI) was used to evaluate the trend of vegetation cover and landscape fragmentation change in the Wuyishan Nature Reserve during 2000-2019[9]. The combination of Sen trend degree and Mann-Kendall trend test has become an important method to judge the trend of temporal data, and has been applied in the temporal change analysis of vegetation cover[10-11]. To further reveal the forest change trend of the nature reserve geographically, the Seni+Mann-Kendall (SMK) method was used to analyse the time-series SEVI change of the Wuyishan Nature Reserve in the period from 2000 to 2019.

2. Data and methods

2.1. Study area and data

The Wuyishan Nature Reserve is located in the Fujian province in Southeast China with geographical boundaries of 117°24′14″–117°50′31″E and 27°34′56″–27°55′22″N (Figure 1). The elevation of the
Reserve ranges from about 280 to 2158 meters with an average of 1150 meters, and the terrain slope is from 0° to 72.69° with an average of 28.23°. The forest coverage in the Reserve reaches to 96.30%, forming the largest and best-preserved subtropical forest ecological system in Southeast China. It is the birthplace of the upper reaches of the Minjiang River. What is more, the Reserve is known for its rich biodiversity and becomes a paradise for many cherished animals and plants, including some ancient and relict plant species that only appeared in China but rarely found elsewhere in other countries[12].

Figure.1 Study area. Yellow rectangle is the sample area used for adjustment factor calculation.

The time series of Landsat and HJ-1 multispectral images with spatial resolution of 30 meters from 2000 to 2019 were used in this study. It was so difficult to find cloud-free images on the same day of each year during the study period for the generally cloudy sky conditions in the Reserve. So, we especially selected the images acquired during the clear-sky wintertime, such as December, January, and February (DJF). At last, a total of fourteen Landsat images (2000-2005, 2007, 2009-2011, 2014-2017) and four HJ-1 images (2012-2013, 2018-2019) were selected, however no cloud-free images were available in 2006 and 2008. The remote sensing images and ASTER GDEM V2 in this study were obtained from the United States Geological Survey (https://earthexplorer.usgs.gov/) and China Centre for Resource Satellite Data and Application (http://www.cresda.com/CN/).

2.2. Method
The data processing included image pre-processing, the SEVI calculation and normalization, and the SMK trend analysis of the SEVI (figure 2). The image pre-processing covered geometric correction, radiometric calibration, atmospheric correction, and area clipping of the reserve boundary.
2.2.1. SEVI calculation.

The SEVI, calculated from the reflectance of the red and near-infrared bands, can remove the self and cast shadows drastically. The fundamental principles of the SEVI include the terrain radiative transfer model[13] and the band-ratio model.

\[
SEVI = RVI + f(\Delta) \times SVI
\]

(1)

\[
RVI = B_{\text{air}} / B_r
\]

(2)

\[
SVI = 1 / B_r
\]

(3)

Where \( RVI \) is the ratio vegetation index, \( SVI \) is the shadow vegetation index, \( f(\Delta) \) is an adjustment factor, \( B_{\text{air}} \) is the reflectance of the near-infrared band and \( B_r \) is the reflectance of the red band.

The time series of SEVI in the Wuyishan Nature Reserve were calculated using Formula (1), and the \( f(\Delta) \) values were determined by the optimal algorithm of coefficient of correlation (r-algorithm).

\[
r_1 = \frac{\sum_{i=1}^{n} (x_i - \overline{x})(y_{i1} - \overline{y}_1)}{\sqrt{\sum_{i=1}^{n} (x_i - \overline{x})^2 \cdot \sum_{i=1}^{n} (y_{i1} - \overline{y}_1)^2}}
\]

(4)

\[
r_2 = \frac{\sum_{i=1}^{n} (x_i - \overline{x})(y_{i2} - \overline{y}_2)}{\sqrt{\sum_{i=1}^{n} (x_i - \overline{x})^2 \cdot \sum_{i=1}^{n} (y_{i2} - \overline{y}_2)^2}}
\]

(5)

\[
f_{\text{opt}} = \arg \min (|r_1 - r_2|), f(\Delta) \in (0.001, 1.000)
\]

(6)

Where \( r_1 \) is the coefficient of correlation between SEVI and \( RVI \), \( r_2 \) is the coefficient of correlation between SEVI and \( SVI \), \( x_i \) is the pixel value of SEVI, \( y_{i1} \) is the pixel value of RVI, \( y_{i2} \) is the pixel value of \( SVI \), \( n \) is the number of pixels in the selected slopes and \( f_{\text{opt}} \) is the optimized adjustment factor.
2.2.2. **SEVI normalization.**
These calculated SEVI were normalized to 0.00-1.00 for quantifying the vegetation growth variability (Formula 7).

\[ x' = \frac{(x - x_{\text{min}})}{(x_{\text{max}} - x_{\text{min}})} \quad (7) \]

where \( x' \) is the normalized SEVI, \( x \) is the SEVI, \( x_{\text{max}} \) is the maximum SEVI from the image erased noise, and \( x_{\text{min}} \) is the minimum SEVI of naked rock in the Reserve.

2.2.3. **Vegetation cover trend Analysis.**
The Sen trend degree \( \beta \) is calculated by the following formula:

\[ \beta = \text{Median} \left( \frac{x_j - x_i}{j - i} \right) \quad (\forall j > i) \quad (8) \]

where \( i \) and \( j \) are the independent variables, representing the annual numbers; \( x_i \) and \( x_j \) are the SEVI value of the \( i \) year and \( j \) year; \( \beta \) is trend degree, its value is used to judge the rise or fall of the vegetation cover change in time series. When \( \beta \) is greater than 0, the vegetation cover is increasing from year \( i \) to year \( j \); on the contrary, it is decreasing.

Mann-Kendall\[14-15\] trend test process is to determine the size relationship(set as \( Z \)) between \( x_i \) and \( x_j \) in all dual values \((x_i, x_j, j > i)\) of the sequence \( X = (x_1, x_2, \ldots, x_n) \). The check statistic \( Z \) is calculated by the following formula:

\[
Z = \begin{cases} 
\frac{S - 1}{\sqrt{\text{VAR}(S)}} & (S > 0) \\
0 & (S = 0) \\
\frac{S + 1}{\sqrt{\text{VAR}(S)}} & (S < 0)
\end{cases} 
\]

\[ S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(x_j - x_i) \text{sgn}(x_j - x_i) = \begin{cases} +1 & (x_j - x_i > 0) \\
0 & (x_j - x_i = 0) \\
-1 & (x_j - x_i < 0) 
\end{cases} 
\]

\[ \text{VAR}(S) = \left( n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5) \right)/18 
\]

where \( Z \) is the standardized test statistic; \( S \) is the test statistic; \( n \) is the number of serial samples; \( m \) is the number of repeated data sets in the sequence; \( t_i \) is the number of duplicate data in group \( i \). At a given significance level, the critical value \( Z_{1-\alpha/2} \) is found in the normal distribution table, when \( |Z| \leq Z_{1-\alpha/2} \), the trend is not significant; when \( |Z| > Z_{1-\alpha/2} \), the trend is significant. In this paper, the significance level \( \alpha = 0.05 \), \( Z_{1-0.05/2} = Z_{0.975} = 1.96 \).

The research result of reference[16] shows that there were two significant different mean levels of patch density about 40.67/km² in the period of 2000-2011 and about 18.69/km² in the period of 2012-2019. Therefore, the SMK change trend analysis covers not only the period of 2000-2019, but also the sub-periods of 2000-2011 and 2012-2019.
3. Results

3.1. Time-series SEVI result
The result of normalized SEVI from 2000 to 2019 (lack images of 2006 and 2008) shows the vegetation cover distribution of the Wuyishan Nature Reserve (figure 3).

Figure 3 The normalized SEVI maps of the Wuyishan Nature Reserve from 2000 to 2019 (lack images of 2006 and 2008).
3.2. Vegetation change area
The result of Sen+Mann-Kendall analysis during 2000-2019 shows that the areas with slight vegetation improvement and significant vegetation improvement covered approximately 43.76% and 55.18% of the Wuyishan Nature Reserve area, respectively (figure 4a). During the sub-period of 2000-2011, the areas with slight vegetation degradation covered approximately 55.05% of the Reserve area and the areas with slight vegetation improvement covered approximately 38.69% of the Reserve (figure 4b). While, the area with slight vegetation degradation covered approximately 20.48% of the Reserve area and the slight vegetation improvement area covered approximately 69.26% of the Reserve from 2012 to 2019 (figure 4c).

3.3. Vegetation change distribution
During the period of 2000-2011, the vegetation area with severely degraded was mainly located in the southwest of the Reserve, while the vegetation area with significantly improved was mainly lie in the north of the Reserve (figure 5a). From 2012 to 2019, the area with significant vegetation improvement was mainly located in the east of the Reserve (figure 5b). Therefore, the areas with vegetation improvement (including the slight and significant improvement) covered approximately 98.94% of the Reserve during the period of 2000-2019 (figure 5c).

4. Discussion

4.1. The trend of vegetation cover change
The vegetation in the Wuyishan Nature Reserve showed a trend of “decreasing first and then increasing” during the entire period of 2000-2019. The vegetation cover of the Reserve mainly showed a slight
degradation trend during 2000-2011, but a slight improvement trend during 2012-2019. It might be due to the implementation of the new environmental protection laws and regulations in about 2011.

4.2. The Sen+Mann-Kendall method
The method of Sen+Mann-Kendall analysis combines the Sen trend degree and the significance test of the Mann-Kendall, and has no requirements for data normalized distribution. It can reduce the interference of data noise and improve the accuracy of test result to some extent. So, it is a useful method to evaluate the time-series change of vegetation cover.

4.3. Comparison with previous result
Previous study[16] has shown that the mean value of SEVI in the Wuyishan Nature Reserve from 2000 to 2019 was an overall upward trend, which is consistent with the results of the trend analysis in this paper. The patch density of the Reserve dropped sharply in 2012, from about 40.67/km² of patch density in the sub-period of 2000-2011 to about 18.69/km² in the sub-period of 2012-2019, which is consistent with the results of this paper.

5. Conclusions
The results from this study show that the vegetation cover of the Wuyishan Nature Reserve had a whole trend of improvement during 2000-2019, but with a slight degradation during 2000-2011 and a slight improvement during 2012-2019, respectively. In general, the Sen+Mann-Kendall method combined with the shadow-eliminated vegetation index can analyse the trend of vegetation cover change with high accuracy in the rugged nature reserve.

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