Advance and evaluation in the long time series vegetation trends research based on remote sensing

CAI Bo-feng[1,2], **YU Rong**[3]

1. *Institute of Remote Sensing Applications*, *Chinese Academy of Sciences*, *Beijing* 100101, *China*;
2. *Beijing Municipal Research Academy of Environmental Protection*, *Beijing* 100037, *China*;
3. *Environmental Protection Research Institute of Guangxi*, *Guangxi Nanning* 530022, *China*

Abstract: The long time series vegetation trends (LTSVT) research based on remote sensing in large area is the core field of vegetation ecology and an important direction in the global change study. AVHRR, SPOT VGT and MODIS are currently the main data resources of LTSVT research. With volumes of remote sensing data, the analysis and evaluation methods for LTSVT study emerged as an urgent issue. Algebra calculation, Fourier transformation, PCA analysis, wavelet transform, linear trend analysis (LTA), correlation analysis (CA), *etc*., are the main methods. After the assessing and grouping of the methods, we focused on comparing the LTA and CA, which were well accepted methods, with the newly introduced Sen＋Mann-Kendall method. Our review showed Sen＋Mann-Kendall had a strong strength of errors resistance and was not constrained by the data statistical distribution.

Key words: long time series vegetation trends LTSVT, evaluation methods, Sen＋Mann-Kendall

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1 INTRODUCTION

Vegetation plays a key role in terrestrial ecosystems, and directly affects the local and global energy balance, biochemical substances cycling and water cycling. It is also the best indicator of the natural and anthropogenic effects on the environment. Long time series (over 10a) monitoring and assessment is the core field of vegetation research.

Remote sensing is proved to be the most effective tool of long time vegetation monitoring because of its advantage such as large screen area, free limitation of the geography, low cost and abundant information. The good consistency between remote sensing data makes it more and more valuable. NDVI (Normalized Deference Vegetation Index) is by far the most often used spectral index for the description of vegetation from remote sensing data (Xu *et al*., 2006; Liang, 2003; Zhao, 2003).

2 REVIEW OF LONG TIME-SERIES VEGETATION STUDY

It is widely acknowledged that large scale and long term vegetation study is one of the most important areas in the ecological and global change study (Xu *et al.*, 2007; Zhang *et al.*, 2001; Bi *et al.*, 2005; Zhao *et al.*, 2001; Li *et al.*, 2005; Fu *et al.*, 2006; Wang *et al.*, 2005; Xu *et al.*, 2003). A significant body of research has focused on this.

Sena (2000) analyzed and evaluated the vegetation behavior in Oklahoma, USA, based on the data of AVHRR-NDVI. Granados (2004) assessed the density and vigor of crop by using AVHRR-NDVI. Ricotta (1998) outlined the NPP spatial distribution by the fractal statistics of NDVI. Azzali (2000) proposed that AVHRR-NDVI time-series could be used to detect vegetation phenology. Leblon (2001) monitored the fire of north of Canada with the AVHRR-NDVI data. Weiss (2001) analyzed the human induced degradation of rangeland by AVHRR-NDVI series. Boyd (2002) detected the threat of El Niño on the rainforest of Malaysia from the AVHRR-NDVI series. Pelkey (2003) induced the long time-series trend of vegetation in habitat protection. Jia (2004) found that air temperature and surface soil temperature had a linear correlation with NDVI. Jia (2002) studied the AVHRR-NDV variability in 5a in Alaskan, USA. Jakubauskas (2002) had identified the crop species by the AVHRR-NDVI series.

Fang and Piao (2004a; 2004b; 2001, 2003) analyzed vegetation change of China between 1982—1999, and the results showed that most part of vegetation were improving while there still remained substantial difference between regions. Shi (2004) calculated the Fractional Vegetation Cover based on the AVHRR-NDVI to assess the vegetation change of Sinkiang. Chen (2002) analyzed the vegetation change from 1983—1992 of West China by the PCA of NDVI. Ma (2003, 2006) proposed

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First author biography: CAI Bo-feng (1977—), male, Ph. D candidate. He is engaged in ecological remote sensing, and over 10 papers have been published. E-mail: caibofeng@gmail.com

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the vegetation degradation of West China in the last 21 a based on the results of NDVI analysis.

The analysis methods of long time series vegetation trends (LTSVT) are becoming more and more important with quick growing of remote sensing data.

3 MAIN DATASET FOR LONG TIME-SERIES VEGETATION STUDY

The AVHRR, SPOT VGT and MODIS are the main source for time-series vegetation study. AVHRR, which is the most early used dataset, has been processed and analyzed since 1980, and SPOT VGT and MODIS have been used since 1998 and 2000 respectively. MODIS data is a milestone in meso-scale remote sensing as it substantially improved the capability of vegetation monitoring.

The original data of AVHRR, SPOT VGT and MODIS are grey value, attenuated by atmosphere and reflectivity of objects. The grey value is also affected by satellite screening breadth, earth curvature, zenith angle of sun, *etc*. These attenuation and affection would be rectified by data preprocessing including geo-referencing, radiation calibration, atmosphere calibration, cloud detection and composition. The most popularly used method of composition is Maximum Value Compositing (MVC) on 10 days cycle which could minimize the effect of cloud and atmosphere scattering.

Landsat series also accumulated more than 30a of data since its first launch in 1972. But they were still not enough for LTSVT for its lack of standard radiation calibration and cloud detection although its higher spatial resolution. So they are mostly used in LUCC. Table 1 shows the main dataset for LTSVT.

Table 1 Main data sets used to long time series vegetation trends research

Data	AVHRR				MODIS	SPOT
Spatial resolution/km	1	8	1	8	0.25,0.5, 1	1
Temporal resolution/d	10	10	10	15	16	10
Projection	Goode Interrupted Homolosine					Geographic Lon/Lat
Start time	Apr.1992—May.1996	1981—		1998—	2000—	1998—
Providers	EROS Data center	Panfinder Land		GSFC	EOS	VITO
Others					GPP (8d), LAI (8d), VCC (96d)	NPP (10d), NEP (10d), DMP (10d)

4 MAIN ANALYSIS METHODS OF LONG TIME-SERIES VEGETATION DATA

Algebra calculation, Fourier transformation, PCA analysis, wavelet transform, linear trend analysis (LTA), correlation analysis (CA), *etc*., are the main analysis methods as well as the new proposed Sen＋Mann-Kendall method.

4.1 Algebra calculation

Algebra calculation includes calculation of ratio, difference and variation. By these kinds of methods, the maximum, minimum, mean and change amplitude can be clearly expressed. Being lack of description of time series of NDVI, these methods are largely used to indicate the change characteristics of one period.

Coefficient of variation is a typical index in algebra calculation (Weiss & Marsh, 2001; Fang *et al*., 2001; Milich, 2000; Tucker *et al*., 1991). It was popular in the early vegetation study and still act a substantial role (Yan *et al*., 2003; Chen *et al*., 2004). It is calculated as follow:

$$C_{\mathrm{v}} = \frac{\sigma}{\mu} \tag{1}$$

where, C_{v} is the coefficient of variation, μ the mean value of NDVI in one period and σ the standard deviation. Coefficient of variation is a reflection of the overall data dispersion and discreteness, which was often used to represent NDVI inter/intra year fluctuation.

4.2 Principal Components Analysis (PCA)

PCA is theoretically the optimal linear scheme, in terms of least mean square error, for compressing a set of high dimensional vectors into a set of lower dimensional ones and then reconstructing the original set. PCA involves a mathematical procedure that transforms a number of correlated NDVI time series into a smaller number of uncorrelated variables reflecting different vegetation characters (Cakir *et al*., 2006; Lasaponara, 2006). Eigenvalue and eigenvectors are the key parameters calculating from covariance matrix in the PCA process.

Suppose a_{kp} represents the eigenvectors between the band k and its corresponding principal components, correlation coefficient R_{kp} can be describe as following:

$$R_{kp} = \frac{a_{kp} \times \sqrt{\lambda_p}}{\sqrt{V_{ark}}} \tag{2}$$

where $\sqrt{V_{ark}}$ is the variance of band k, λ eigenvalue.

The first principal component accounts for as much of the variability in the data as possible, and each succeeding component accounts for as much of the remaining variability as possible. So the first several bands of PCA can completely describe the characters of original datasets.

PCA showed special advantage in processing massive data sets and can detect the main fluctuation such as fire, pests and

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disease (Cakir *et al*., 2006; Lasaponara, 2006).

4.3 Fourier Transformation

Fourier transform (FT) is the frequency domain representation of the original data (Lunetta *et al*., 2006; Lhermitte *et al*., 2007; Wang *et al*., 2005).

$$F(u)=\frac{1}{N}\sum f(x)\mathrm{e}^{-\mathrm{j}\frac{2\pi}{N}ux} \tag{3}$$

where, $f(x)$ is the NDVI series, $F(u)$ FT, N length of series, x number of series, u number of series in frequency domain.

Discrete FT can detect the different amplitude of vegetation fluctuation such as yearly and monthly undulation (Olsson *et al*., 1994). FT was always used finding the inter- and intra- cycle of the vegetation fluctuation (Lhermitte *et al*., 2007; Wang *et al*., 2005).

4.4 Wavelet Transform

Wavelet transform is developed from Fourier transform. But unlike Fourier transform, the wavelet transform possesses the ability to construct a time-frequency representation of a signal that offers very good time and frequency localization. The coefficients of wavelet can be used to describe the multi-scale characters of one dataset. So the Wavelet transform was applied in the vegetation fluctuation circle detection.

$$W_f(b,x_n)=\int f(x)\left|b\right|^{-1/2}\psi\left(\frac{x-x_n}{b}\right)\mathrm{d}x \tag{4}$$

where $W_f(b, x_n)$ is the wavelet coefficients, b the scale factor, x_n the center of wavelet, $\psi(t)$ the window function also called mother wavelet. Sarkar (2004; 2007) and Li (2000) analyzed the India and USA vegetation change respectively.

Wavelet transform is new analysis method for vegetation series with high potential, but as of now it still applied as the same way as Fourier transform.

4.5 Linear Trend Analysis (LTA)

LTA is well accepted and implemented for NDVI temporal trend analysis using least squares linear regression (Weiss *et al*., 2001; Fuller, 1998; Camberlin *et al*., 2007; Rigina & Rasmussen, 1996; Tottrup & Rasmussen, 2004; Herrmann *et al*., 2005; Evans & Geerken, 2004).

$$y=a+kx_i+\varepsilon_i \tag{5}$$

$$k=\frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sum_{i=1}^{n}(x_i-\bar{x})^2}, \tag{6}$$

where $\bar{x}=\frac{1}{n}\sum_{i=1}^{n}x_i, \bar{y}=\frac{1}{n}\sum_{i=1}^{n}y_i$, x_i is the year, i and y_i is the NDVI value in the year i, a is the coefficient, ε_i the random error. k is the slope of the linear regression that represent the trend of vegetation (Weiss *et al*., 2001; Fuller, 1998; Camberlin *et al*., 2007), k>0, means vegetation was improved, and k <0, means vegetation degraded.

4.6 Correlation Analysis (CA)

Mostly the correlation analysis use the Pearson correlation coefficient to depict the trend of vegetation change (Herrmann *et al*., 2005; Evans & Geerken, 2004). The LTA and CA are much similar.

$$r_{xy}=\frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}\left(x_i-\bar{x}\right)^2\cdot\sum_{i=1}^{n}\left(y_i-\bar{y}\right)^2}} \tag{7}$$

where r_{xy} is the correlation coefficient and a normalized parameter. r_{xy}>0 means positive correlation and r_{xy}<0 means negative correlation.

Many studies concluded that the LTA or CA provided the best results in terms of interpretation and showed a consistent measure of vegetation change, regardless of the study area and period.

4.7 Sen＋Mann-Kendall analysis

Sen slope coupled with Mann-Kendall detection was proved to be the important trend analysis (Gilbert, 1987; Xu *et al*., 2003; Burn & Hag, 2002)and gradually applied in vegetation study (Fernandes *et al*., 2005; Beurs *et al*., 2005; Beurs *et al*., 2004). β, the Sen slope, is calculated as following (Burn & Hag, 2002):

$$\beta=\mathrm{Median}\left(\frac{x_j-x_i}{j-i}\right),\quad \forall j>i, \tag{8}$$

β>0 means vegetation improvement and vice versa.

Mann-Kendall was proposed by Mann to test the trend of change. Kendall and Sneyers made it much more perfect to detect the beginning and ending of the trend, and furthermore to a large range of application.

Mann-Kendall detection is defined as:

To a series of $X_t=(x_1,x_2,\cdots,x_n)$, $U_{\mathrm{MK}}=\frac{\tau}{\left[\mathrm{Var}(\tau)\right]^{1/2}}$,

where, $\tau=\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\mathrm{sgn}(x_j-x_i)$; $\mathrm{sgn}(\theta)=\begin{cases}1 & \text{if } \theta>0\\ 0 & \text{if } \theta=0\\ -1 & \text{if } \theta<0\end{cases}$; (9)

$$\mathrm{Var}(\tau)=\frac{n(n-1)(2n+5)-\sum_{i=1}^{m}t_i(t_i-1)(2t_i+5)}{18}$$

where n is the number of data in the series, m the number of tied values, t_i the number of ties for the i^{th} value.

Sen +Mann-Kendall analysis was widely used in hydrology, meteorology *etc.* (Xu *et al*., 2007; Yang *et al*., 2007; Xu *et al*., 2006a; Yue *et al*., 2002; Xu *et al*., 2006b; Jiang *et al*., 2007) and has been applied in vegetation study.

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4.8 Others

Wang (2005) ever used R/S method to study NDVI series. R/S (Jiang & Deng, 2004; Zhao & Wang, 2002) (Rescaled Range Analysis) was first developed by Hurst, a statistical method to analyze long records of natural phenomena. R/S is also a non-parameter method, and the ratio of R/S need be extracted by least squares linear regression which is lack of statistical test. Bi (2005) used wave-type time series model to simulate temporal dynamic changes of the correlation between NDVI and climatic factors. The two methods mentioned above were not the usual methods of NDVI analysis.

5 COMPARISON OF THE METHODS

The emphasis of algebra calculation is on the variation of vegetation over time rather than the temporal change feature which is most needed for evaluating an ecological project. PCA can distinguish the different vegetation fluctuation caused by different reasons, but none of its principal components could be related to one specific cause (Rigina & Rasmussen, 1996). The FT and wavelet have the same deficiency, as a consequence that they are mainly used in vegetation cycle detection (Evans & Geerken, 2006).

LTA and CA are the most popular method thanks to their simple and clear process and convincible results (Rigina & Rasmussen, 1996; Jina *et al*., 2006).

5.1 Classification and comparison

k of LTA is an absolute value which means it could vary with NDVI. So the results of LTA analysis vary greatly among regions because of their different vegetation levels. Fig. 1 shows two set of data, analyzed by LTA, the same trend resulted in different values.

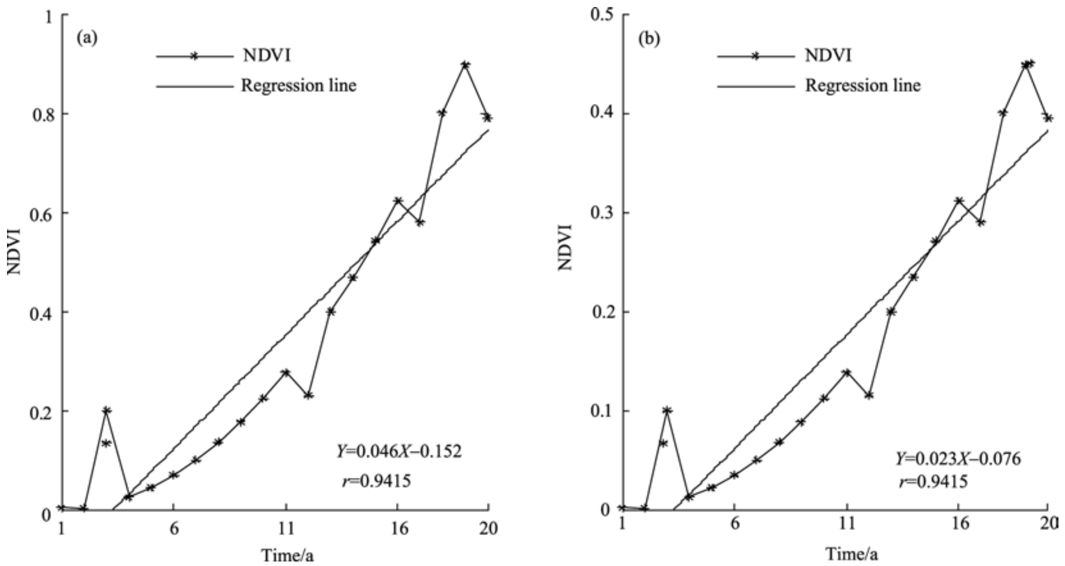

Fig. 1 Comparison between linear trend analysis and correlation analysis

LTA and CA are quite alike except that the r_{xy} in CA is a normalized value. This made CA directly measured the trend character and free of vegetation absolute value. Fig. 1 showed the results were identical although their values are not the same. β of Sen＋Mann-Kendall analysis was also a non-normalized parameter, so its significance must be tested by Mann-Kendall instead of itself.

5.2 Distribution need of dataset for the methods

The basic assumption of LTA and CA is normal distribution of dataset although most of the time it is hardly satisfied (Fernandes *et al*., 2005). No distribution of data needed was the advantage of Mann-Kendall. This made it applicable to NDVI series and had good ability to deal with gross errors and outliers.

5.3 Ability of errors resistance

The NDVI series were at its most less than 30 which is not much enough for statistical analysis and any error will greatly affect the results. Although the preprocess work had included error correction, there still remained measurement error resulted from atmosphere, position of solar zenith angle, *etc.* (Los *et al*., 1994; Chappell *et al*., 2001; Wang *et al*., 2003; Gong & He, 2004). So the errors resistance of analysis methods became very important. Wessels (2007) pointed the CA result was affected by the point in the time-series when the great change taken place.

Our simulations showed that a fixed –0.02 NDVI errors in different year will result in different correlation coefficient (Fig. 2).

Compared with CA, β of Mann-Kendall remained stability (Fig. 3). In the 20 changes, 15 results were 0.0037 which is the

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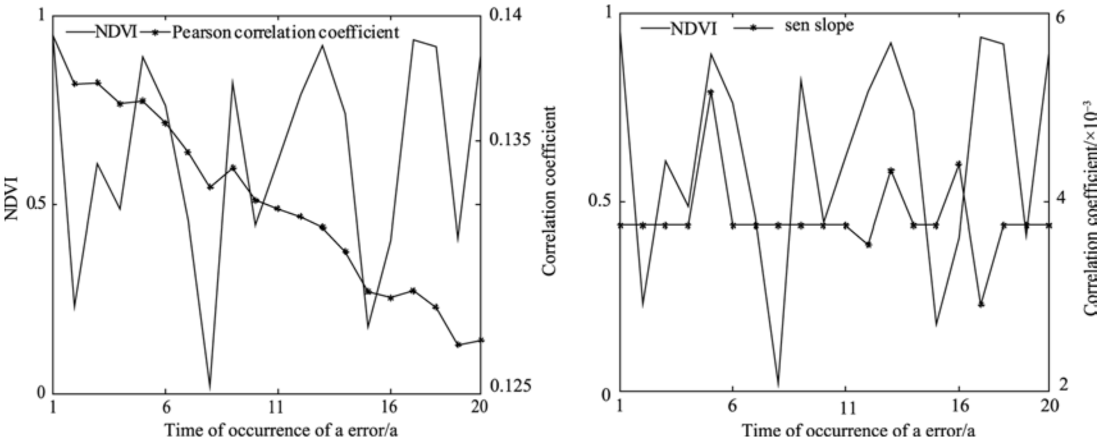

Fig .2 Effect of timing of the occurrence of a error on the correlation index and Sen

same as original data without error. This proved the Mann-Kendall had good strength in error resistance and LTA/CA would mislead because of error (Wessels, 2007).

The main reason for error resistance of Sen was that it was calculated by the data clumping and sorting process which was substantially different with LTA (Fernandes *et al*., 2005) (Table 2).

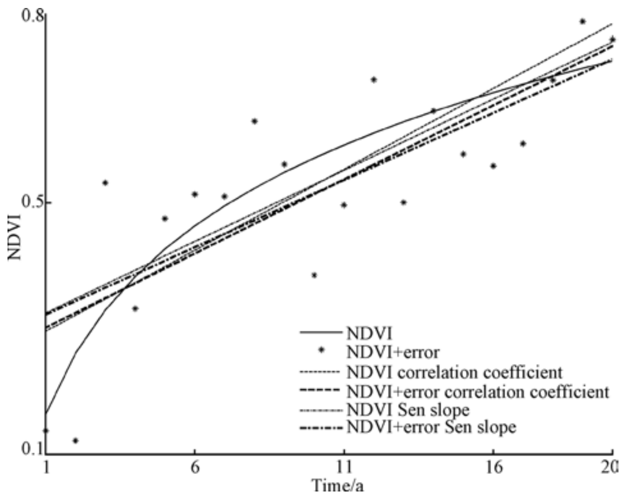

Fig. 3 Error reflectance of Sen and regression coefficients

Table 2 Comparison between Sen and regression coefficients

	NDVI	NDVI+error
LTA	0.0256	0.0234
Sen	0.0226	0.0213

6 RESULTS AND DISCUSSION

Long time series vegetation trends analysis based on remote sensing has been a hotspot of vegetation study. AVHRR, SPOT VGT, MODIS, *etc*., evidenced more and more data sources while hundreds of countries and international organization issued standard of data processing to improve vegetation study.

Nevertheless, the great difference existed between different analysis methods leads to incongruent results. LTA and CA were the well accepted methods but their deficiencies were ignorable. Sen＋Mann-Kendall fixed well the shortage of these two methods and had excellent performance in (1) data without specific distribution; (2) errors resistance. Moreover, the convincible results of Sen＋Mann-Kendall came from the solid foundation of statistic analysis and significance test. Therefore it poses great application potential in future research and deserves enough attention.

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基于遥感的植被长时序趋势特征研究进展及评价

蔡博峰[1,2]，于 嵘[3]

1. 中国科学院 遥感应用研究所，北京 100101;
2. 北京市环境保护科学研究院，北京 100037;
3. 广西壮族自治区 环境保护科学研究所，广西 南宁 530022

摘 要： 基于遥感的植被长时序变化特征是植被生态学研究的核心领域，也是全球变化研究的重点方向。AVHRR、SPOT VGT 和 MODIS 是当前研究植被长时序趋势变化的主要数据源。海量数据不断积累的同时，植被长时序趋势特征研究方法却缺乏对比评价和分析。当前常用的方法有代数运算法、傅里叶变换、主成分分析、小波变换法、回归分析法和相关系数分析法等。在对各种方法评述和分析的基础上，重点讨论和对比了主流方法中的回归分析法和相关系数分析与新兴方法 Sen＋Mann-Kendall 法。结果表明，Sen＋Mann-Kendall 能克服主流方法的不足，不需要数据服从某一特定分布，并且对数据的误差具有较强的抵抗能力。

关键词： 植被长时序趋势变化，评价方法，Sen＋Mann-Kendall

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1 引 言

植被是陆地生态系统中的重要组成部分，对区域直至全球的能量平衡、生物化学循环、水循环起着调控作用，是气候和人文因素对环境影响的敏感指标。长时序(>10a)植被监测和评价是研究植被生长和受影响特征的核心领域，也是研究陆地生态系统过程和全球变化的重要环节。遥感是当前研究区域植被长时序变化特征的核心手段，基于遥感的长时序数据具有周期短、覆盖范围广、不受地理条件限制、成本低和信息量大等特点，尤其是其数据序列的一致性好，使得其成为这一领域的核心方法。NDVI(Normalized Deference Vegetation Index)是目前卫星遥感监测植被应用最广泛的参数(徐斌等，2006; Liang, 2003; 赵英时, 2003)。

2 植被长时序研究

大尺度、长时序植被动态变化监测和评价一直是生态学研究的重要领域和全球变化研究的热点(徐兴奎等，2007; 张军等，2001; 毕晓丽等，2005; 赵茂盛等, 2001; 李震, 2005; 付新峰等, 2006; 王新明等, 2005; 徐兴奎等, 2003)。利用 NDVI 时序数据进行监测和评价植被动态变化方面作了大量工作。

Senay 等(2000)利用 AVHRR-NDVI 时序数据和土地利用数据分析和评价了美国 Oklahoma 州植被的时间和空间动态变化。Granados 等(2004)利用 AVHRR-NDVI 时序数据实现了对作物的监测，评价了作物密度和作物活力。Ricotta 等(1998)利用 AVHRR-NDVI 时序数据，建立年积累 NDVI，通过分形统计法(fractal statistics)分析和描述 NPP 的空间分布特征。Azzali 等(2000)对非洲南部(赤道以南)的 AVHRR-NDVI 时序数据进行快速傅里叶变换，从而利用幅度和相位信息研究植被的物候特征。Leblon 等(2001)使用 AVHRR-NDVI 时序数据监测加拿大北部森林的火灾。Weiss 等(2001)利用 AVHRR-NDVI 时序数据，计算了沙特阿拉伯牧场 NDVI 的变化系数，评价了近 10a 本地游牧对牧场的影响。Boyd 等(2002)利用 AVHRR-NDVI 时序数据监测厄尔尼诺现象对马来西亚热带雨林生态系统的干旱胁迫。Pelkey 等(2003)利用 NDVI 长时序数据，评价了受保护生境长期以来的植被变化，从而避免了由于植被季节波动造成的评价不确定性，最后又利用不同时间序列和空间分辨率的 NDVI 进一步进行保护地植被变化的研究。Jia 等(2004)研究了美国阿拉斯加州北部苔原的 AVHRR-NDVI 时序变化，表明空气温

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第一作者简介：蔡博峰(1977—)，男，博士生。从事生态遥感方面研究，发表论文 10 余篇。E-mail: caibofeng@gmail.com。

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度、土壤表层温度及 20cm 以下温度的奇异点和 NDVI 的奇异点的线性关系。Jia 等(2002)利用美国阿拉斯加州 5a 的 AVHRR-NDVI 时序数据研究潮湿酸性苔原(MAT)、潮湿非酸性苔原(MNT)植被空间变化情况。Jakubauskas 等(2002)利用 AVHRR-NDVI 时序数据，进行调和分析，判识作物种类。

方精云、朴世龙等(2004a; 2004b; 2001, 2003)等分析中国 1982—1999 年植被年际变化，认为大部分区域的植被有增加的趋势，近 20a 来中国植被活动在增强，但变化区域差异十分明显。师庆东等(2004)基于 AVHRR-NDVI 计算的 FVC(Fractional Vegetation Cover)，评价了 1982—2000 年新疆地区的植被变化。陈云浩等(2002)综合应用变化矢量分析和主成分分析方法研究 1983—1992 年中国陆地植被 NDVI 动态变化，研究结果表明在此期间中国陆地植被 NDVI 变化东西分异明显，东部变化幅度远大于西部，整体表现为稳中略增。马明国等(2003)得出中国西北在近 21a 植被覆盖存在普遍退化的趋势，且后 10a 变化幅度大于前 10a 变化幅度。Ma 等(2006)监测中国第二大内陆河黑河流域植被变化，表明山区和自然绿洲植被普遍退化，人工绿洲植被活动增加。

随着遥感新数据源的不断涌现，时序数据的不断累计，植被长时序变化趋势研究越来越多，而长时序数据分析方法凸显为重要的研究问题。

3 主要数据集

可用于长时序植被监测的遥感数据并不多，主要是 AVHRR, SPOT VGT 和 MODIS 数据。AVHRR 从 1980 年开始被处理和使用, SPOT VGT 从 1998 年开始提供植被数据, MODIS 从 2000 年开始接收数据。其中 AVHRR 数据是开始最早，积累时间最长的植被长时序研究的数据源。MODIS 是中尺度遥感的一个重要里程碑，大大提高了对地表植被的观测能力。

AVHRR、SPOT VGT 和 MODIS 所接收的卫星信息为灰度值，由于受大气和目标方向反射特征的影响，这些信息均有不同程度的衰减，受扫描带宽、地球曲率以及传感器扫描角和太阳天顶角差异的影响导致数据变形较大和几何畸形严重。所以在使用这些资料前必须经过严格的预处理过程。预处理过程主要包括几何精纠正、辐射定标、大气校正、云检测和合成等步骤。目前 NDVI 数据序列集主要是通过最大值合成方法(Maximum Value Compositing, MVC) 逐日合成，可以最小化云和大气散射的影响，较为常用的时间周期为 10d。Landsat 从 1972 年 7 月发射第一颗卫星到现在的 Landsat 7, Landsat 5 也一直在接收数据，从开始的 MSS 到后来的 TM、ETM+，时间序列长达三十几年。Landsat 系列虽然空间分辨率较高，但时间分辨率(16d)不足，并且对于原始数据尚未形成统一标准化的辐射定标、大气校正、云检测等过程，因而很难形成标准一致的长时序监测数据，其更多的是利用在土地利用等研究方面。

NDVI 长时序数据源的基本情况见表 1。

4 植被长时序数据主要分析方法

在利用植被指数时序数据进行植被多年动态变化分析时，常用植被长时序分析方法有代数运算法、主成分分析、小波变换法、回归分析法和相关系数分析法等，新方法有 Sen+Mann-Kendall 及其他分析方法。

4.1 代数运算

数值比较、差值运算、方差计算等可以归结到这类方法。通过这类方法可以得到诸如 NDVI 最大值、均值、最小值和变化幅度等多个特征信息。这类方法基本不涉及 NDVI 时间序列特征(即计算中没有时间变量)。因而更多的是表达植被在某一时间段中的变化幅度和波段特征。

表 1 **NDVI 长时序数据主要来源**

数据	AVHRR				MODIS	SPOT
空间分辨率/km	1	8	1	8	0.25, 0.5, 1	1
时间分辨率/d	10	10	10	15	16	10
投影	Goode Interrupted Homolosine					Geographic Lon/Lat
时序起始	1992 年 4 月—1996 年 5 月	1981—		1998—	2000—	1998—
提供单位	EROS Data center	Panfinder Land		GSFC	EOS	VITO
其他植被相关产品					GPP(8d),LAI(8d),VCC(96d)	NPP(10d),NEP(10d),DMP(10d)

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代数运算法另外一个常用方法是变异系数法(Coefficient of Variation)。变异系数主要用来表示NDVI 在一时间段内的波动特征(Weiss & Marsh, 2001; 方静云等，2001; Milich, 2000; Tucker 等，1991)。

$$C_{\mathrm{v}} = \frac{\sigma}{\mu} \tag{1}$$

式中，C_{v}是变异系数，μ是某时间段的 NDVI 平均值，σ是某时间段的 NDVI 的标准方差。变异系数是反映总体各单位值的差异程度或离散程度的指标。其含义是数据序列的标准差与其算术平均值的比值。因此变异系数在 NDVI 的分析，多用于反映年内/年际的植被波动特性。代数运算法在植被长时序变化研究的早期使用较多，当前依然发挥着重要的作用(阎福礼等,2003; 陈海等,2004)。

4.2 主成分分析

主成分分析(PCA-Principal Components Analysis)，也称为 K-L 变换，是压缩高维数据，获取主要信息的常用线性转换方法。这种方法通过从高维数据空间中产生一个合适的低维子空间，使得该子空间分布在某个空间方向可以对原数据空间进行最优描述。主成分分析方法是在统计特征基础上的多维正交线性变换，对于时间序列 NDVI 遥感数据，通过对多个连续数据提取主分量，这些主分量则对应着植被不同信息(Cakir 等, 2006; Lasaponara, 2006)。主成分分析法首先计算各波段之间的协方差矩阵，然后求出协方差矩阵的特征值(eigenvalue)和特征向量(eigenvectors)。

若以 a_{kp} 代表第 k 波段和第 k 波段主成分之间的特征向量，则第 k 波段和第 k 波段主成分之间的相关系数 R_{kp}，可以用下式表示:

$$R_{kp} = \frac{a_{kp} \times \sqrt{\lambda_p}}{\sqrt{V_{ark}}} \tag{2}$$

式中，$\sqrt{V_{ark}}$ 为第 k 波段的方差，λ为特征根。一般各波段和第一主成分(PC_1)的相关系数较高，和后面的主成分的相关系数则逐渐变小。利用主成分分析得到的各个主成分分量所含信息量不同，一般前几个主成分分量就可以反映原始数据的主要特征。

主成分分析法处理海量植被数据时有独到的优势，并且在分析长时序中植被较大变化波动(如火灾、病虫害等)有着积极的作用(Cakir 等，2006; Lasaponara, 2006)。

4.3 傅里叶变换

傅里叶变换(Fourier Transformation)可以将 NDVI 时序数据构成的时域信号变换到频域中，在频域实现对信号的分解，最后通过选取部分频率分量实现特征提取(Lunetta 等, 2006; Lhermitte 等, 2007; Wang 等, 2005)。

$$F(u) = \frac{1}{N}\sum f(x)\mathrm{e}^{-\mathrm{j}\frac{2\pi}{N}ux} \tag{3}$$

式中，$f(x)$为 NDVI 序列，$F(u)$为傅里叶变换，N 为序列长度，x 为时序序列号，u 为频域的序列号。NDVI 时序数据可以认为由包含生物学特征信息的不同频率分量对应的基波和一系列谐波叠加而成(Olsson 等, 1994)。对于年内 NDVI 时序数据，通过离散傅里叶变换可以得到不同频率分量的幅度和相位。其中零频率分量是一个常量，与基波相对应，大小等于 NDVI 的均值；第一个频率分量与第一个谐波对应，表示周期为 12 个月(36 旬)的季节性变化；第二个频率分量与第二个谐波对应，表示周期为 6 个月(18 旬)的季节性变化模式；其他每个频率对应着相应的谐波，表示了一种周期的变化模式。各个分量的信息量反映了各频率成分在整个信号中的相对权值，信息量越大，对应谐波波形起伏越大，原信号中体现出的该周期变化也越明显。

傅里叶变换在植被长时序变化研究中较为重要，尤其是研究植被年内/年际波动周期特征(Lhermitte 等, 2007; Wang 等, 2005)。

4.4 小波变换

小波变换(Wavelet Transform)是傅里叶分析的突破性进展。它同时具有时域和频域的良好局部化性质，且随着信号不同，频率成分在时空域取样的疏密自动调节，因而可以在任意尺度观察信号的任意细节并加以分析。借助小波分析理论，可以检测和提取长时序的多尺度特征，并通过小波系数表达。小波变换可以用来分析植被年际变化的周期特征。

$$W_f(b, x_n) = \int f(x)\left|b\right|^{-1/2}\psi\left(\frac{x - x_n}{b}\right)\mathrm{d}x \tag{4}$$

式中，$W_f(b, x_n)$为小波系数，b 为尺度(伸缩)因子，x_n 是小波在空间上的中心位置，为平移因子。$\psi(t)$函数是窗口函数，成为母小波或分析小波。Sarkar 等(2004a; 2007b)和 Li 等(2000)分别用小波变换来分析印度和美国的植被年际变化。

小波变换是一个很有潜力的植被长时序分析方法，但当前应用主要是在分析植被长时序波动周期，

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其使用途径和目的与傅里叶变换类似，因而受到很大局限。

4.5 回归分析

回归分析是考察多个变量之间统计联系的一种重要方法，是研究植被长时序变化趋势的重要方法(Weiss 等, 2001; Fuller, 1998; Camberlin 等, 2007; Rigina & Rasmussen, 1996; Tottrup & Rasmussen, 2004; Herrmann 等, 2005; Evans & Geerken, 2004)。对一组时间自变量 x 与 NDVI 因变量 y 数据，可以用如下的数学模型来描述:

$$y = a + kx_i + \varepsilon_i \tag{5}$$

式中是 a, k 是未知常数, ε_i 是随机误差。利用观测值($(x_i, y_i)(i = 1, 2, \cdots, n)$)可以求出未知参数 k:

$$k = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

其中，
$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i, \bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i \tag{6}$$

对于 NDVI 长时序数据，采用最小二乘法线性拟合后得到相应的线性方程，方程的斜率 k 说明像元 NDVI 值的多年度变化趋势(Weiss 等, 2001; Fuller, 1998; Camberlin 等, 2007), k>0，植被活动增强，k<0，植被活动减弱。

4.6 相关系数分析

NDVI 时序分析中的相关系数多指 Pearson 相关系数，即以 NDVI 序列和时间序列的相关系数(Herrmann 等, 2005; Evans & Geerken, 2004)表达植被长时序变换特征和趋势。相关系数法与回归分析法极其类似，其数学表示式如下:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2 \cdot \sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2}} \tag{7}$$

式中，相关系数 r_{xy} 是要素间相关程度的统计指标，x 代表时间值(年度), y 代表 NDVI, r_{xy}>0 表示正相关，反映 NDVI 呈现整体变高趋势，r_{xy}<0 表示负相关，反映 NDVI 呈现整体降低趋势，r_{xy} 的绝对值越接近 1，表示 NDVI 的变化趋势越强。r_{xy} 是一个归一化的参数。

回归分析法和相关系数法是植被长时序变化研究中最长用的主流方法，发挥着核心作用，由于两种方法较为相似，所以常常被交替或者同时使用。

4.7 Sen+Mann-Kendall 分析

Sen 趋势度和 Mann-Kendall 趋势检验能很好的结合起来，成为判断长时序数据趋势的重要方法，并且已经逐渐运用在植被长时序分析中(Gilbert, 1987; Xu 等, 2003; Burn & Hag, 2002), Sen 趋势度β(Fernandes 等, 2005; Beurs 等, 2005; Beurs 等, 2004)计算公式为:

$$\beta = \text{Median}\left(\frac{x_j - x_i}{j - i}\right), \quad \forall j > i$$
，当β>0 时，反映上升的趋势，反之则反映下降的趋势。 (8)

趋势的显著性判断需要采用 Mann-Kendall 方法完成。Mann-Kendall 法最初由 Mann 提出，仅用于检测序列的一种变化趋势。Kendall 和 Sneyers 则进一步完善了这种方法，使其能更有效地测定各种变化趋势的起始位置，并且以检测范围宽、定量化程度高而富有生命力。Mann-Kendall 趋势检验法过程如下:

对序列 $X_t = (x_1, x_2, \cdots, x_n)$ ，先确定所有对偶值 $(x_i, x_j, j > i)$ 中 x_i 与 x_j 的大小关系(设为 τ)。趋势检验的统计量为:

$$U_{\mathrm{MK}} = \frac{\tau}{\left[\mathrm{Var}(\tau)\right]^{1/2}},$$

式中:
$$\tau = \sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\mathrm{sgn}(x_j - x_i);\ \mathrm{sgn}(\theta) = \begin{cases} 1 & \text{if } \theta > 0 \\ 0 & \text{if } \theta = 0 \\ -1 & \text{if } \theta < 0 \end{cases}; \tag{9}$$

$$\mathrm{Var}(\tau) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)}{18}$$

n 是序列中数据个数，m 是序列中结(重复出现的数据组)的个数，t_i 是结的宽度(第 i 组重复数据组中的重复数据个数)。当 n>10 时, U_{MK} 收敛于标准正态分布。原假设为该序列无趋势，采用双边趋势检验，在给定显著性水平α下，在正态分布表中查得临界值 $U_{\alpha/2}$，当$|U_{\mathrm{MK}}|<U_{\alpha/2}$ 时，接受原假设，即趋势不显著; 若$|U_{\mathrm{MK}}|<U_{\alpha/2}$，则拒绝原假设，即认为趋势显著。Sen 趋势度和 Mann-Kendall 趋势检验法结合，广泛的应用于检验水文气象资料的趋势成分(徐宗学等, 2007; 杨义等, 2007; 徐宗学等, 2006a; Yue 等, 2002; 徐宗学等, 2006b; 姜逢清等, 2007)，包括水质、流量、气温和降雨序列等，并在植被长时序研究中逐渐开始应用。

4.8 其他方法

王新明(2005)等曾使用 R/S 方法研究 NDVI 序列

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的趋势特征。R/S 分析(Rescaled Range Analysis，重新标度极差分析)方法(江田汉 & 邓莲堂，2004；赵晶 & 王乃昂，2002)，是 Hurst 提出来的，通过分析多样本时间序列的自相似和长程依赖性得到赫斯特指数(H)，可以描述时间序列的变化趋势。R/S 分析法属于非参数分析法，该方法最终的赫斯特指数需要采用最小二乘法线性拟合得到，而且同样缺乏结果的有效性检验。拟和过程无疑会降低该方法研究 NDVI 长时序特征的鲁棒性。毕晓丽(2005)等采用起伏型时间序列模型拟和 NDVI 时序数据。该方法是一种用差分使序列变为符合傅里叶级数型(一组正弦和余弦曲线的组合)变化方法，其特点是最大限度的逼近 NDVI 长时序波动曲线，从而达到预期今后趋势的目的。上述 2 种方法是在 NDVI 长时序分析中极少使用的，在此不作重点论述。

5 研究方法评述

代数运算法的优点是可以直观地体现一段时期内 NDVI 的变化多少和幅度，不足在于其完全忽略了 NDVI 时序的中间变化过程，难以反映植被长时序变化趋势特征，并且结果受误差影响较大，因而使用得较少。

主成分分析能够从整个时间序列中整体地把握 NDVI 的变化特征及其影响因素。其生成的主成分图像和主成分荷载可以揭示 NDVI 的空间分布特征。主成分分析法的不足之处在其分析得到的各个主成分并没有明确的植被特征的对应(Rigina & Rasmussen, 1996)。每个主成分(PCs)试图反映降雨、温度、火灾和人类活动干扰因素中的某一种，但却难以做到一一对应并且充分的逻辑解释。傅里叶变换和小波变换性质相似，在揭示植被波动周期中发挥了重要作用，对于植被类型的遥感分类有着积极的作用，但该方法对于长时期的植被变化特征的描述并不理想(Evans & Geerken, 2006)。

上述几种方法无法参数定量评价和分析 NDVI 长时序趋势特征，因而在植被长时序变化研究中不是主要方法。回归分析法和相关系数法是当前 NDVI 时间序列分析中最主要和最常用的方法。它不仅可以定量反映多年度变化趋势，还可结合地理空间数据分析变化发生的具体空间位置。并且回归分析法和相关系数法计算过程简单、清晰，结果直观，易于解释。由于上述优点，回归分析法和相关系数法得到了广泛应用，并且被认为是分析长期植被趋势的最优方法(Rigina & Rasmussen, 1996; Jina 等, 2006)。Sen＋Mann-Kendall 分析法也是一种定量评价 NDVI 长时序变化趋势的方法，该方法在植被长时序变化研究中逐渐开始推广和使用，其特点和优势逐渐被认同和接受。以下主要对比分析回归分析法、相关系数法和 Sen＋Mann-Kendall 法。

5.1 方法归类和对比分析

回归分析计算的斜率 k 表示趋势变化的最大不足是 k 受数据本身绝对量值的影响，k 值计算中，分母中没有 NDVI，因而 k 是一个没有归一化的参数，其值会随 NDVI 绝对值大小的变化而变化，所以对于NDVI空间分布差异很大的区域，采用k表达趋势变化，然后利用统一的标准判断趋势变化的显著与否，可能忽略 NDVI 低值但变化明显的地区，凸显 NDVI 高值但变化不明显的区域。

图 1 中为随机模拟一组(20 个)NDVI，图 1(b)一组数据值是图 1(a)数据值整体除以 2，即图 1(a)、(b)两组数据 NDVI 变化趋势完全一致，但由于回归分析不仅表达变化趋势，而且和 NDVI 自身大小相关，所以两组数据的趋势值也是 2 倍关系，分别是图 1(a): 0.046 和(b): 0.023。同时，回归分析计算的回归斜率 k，缺乏显著性检验，因而对于变化趋势的等级划分主观性强，很难得到统计意义上的解释和论证。

比较回归分析法和相关系数法发现两者表达式极其相似，不同之处在于相关系数法分母多了 NDVI 值的计算，因此 r_{xy} 是一个没有量纲的归一化参数。这就使得 r_{xy} 直接度量NDVI变化趋势特征，与 NDVI 本身绝对值的大小无关。图 1(a)、(b)两图计算的相关系数法完全相同，都是 0.9415。β也是一个非归一化的参数，其趋势变化的显著性不能通过自身判断，因而通过 Mann-Kendall 基于每个像元的判断显著性水平，对于不同大小的 NDVI 序列，会有不同的显著性水平，可以更为合理、科学地衡量植被长时序的波动特征。

5.2 分析方法对数据的要求

回归分析法和相关系数法的前提假设是时序数据整体样本和误差是呈正态分布，大多数研究数据并不一定满足这一要求(Fernandes 等，2005)。Mann-Kendall 趋势检验法是一种非参数统计检验方法，其优点是不需要样本遵从一定的分布，适用于经过删检(删去低于或高于某水平的观测值)的资料，也不受少数异常值的干扰，对于测量误差(gross errors)和离群数据(outliers)有较好的规避能力，因此，在趋势检验和分析中得到了十分广泛的应用。

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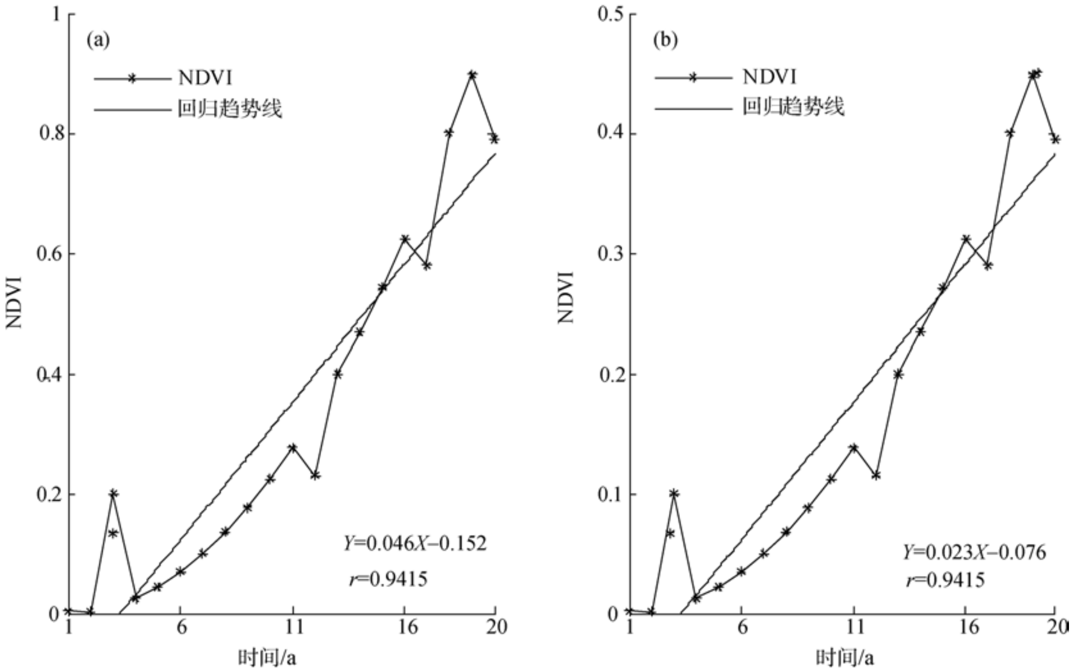

图 1 回归分析法和相关系数法

5.3 误差规避能力

当前进行植被长时序分析的数据组一般不超过 30 组，多数是十几组，这个数量在统计意义上属于少数，数据的误差会严重影响分析结果。同时 AVHRR-NDVI 数据尽管进行了许多误差消除工作，但仍存在诸多误差，大气、太阳天顶角计算误差等会影响 NDVI 对植被的真实反映(Los 等，1994; Chappell 等，2001; Wang 等，2003; Gong & He, 2004)。因而趋势分析方法对误差的反映和抵抗能力非常重要。

Wessels(2007)指出，回归分析法的结论受 NDVI 较大误差出现时间位置的影响，即同样植被波动，出现在不同的时间点上，其分析结果会有较大差异。

我们选择相关系数和 Sen 趋势度进行对比。随机模拟一组(20 个，范围：0—1)NDVI 数据，代表某一像元 20a 的 NDVI 数值，见图 2。以–0.02 的误差依次叠加到该组 NDVI 数据的不同年份上，观察相关系数和 Sen 趋势度的变化。

根据模拟计算，–0.02 的误差出现的时间不同，对趋势的影响也不同，相关系数随–0.02 的误差出现时间的延后而逐渐降低，而 Sen 趋势度却保持了较为稳定的水平，20 组数值中，有 15 次的值是一致的(0.0037)，和没有发生误差的 Sen 趋势度一致(0.0037)，说明 Sen 趋势度对误差有较好的规避能力，而回归分析法/相关系数法会形成误导和不合理的结论(Wessels, 2007)。

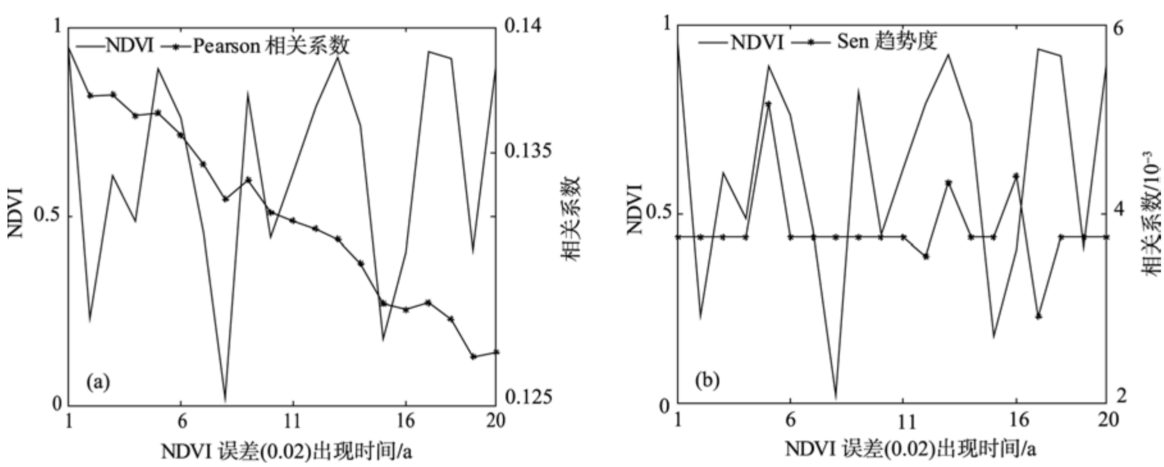

图 2 Pearson 相关系数和 Sen 趋势度对误差反映比较

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此外，回归分析法和 Sen 趋势度法是非归一化的趋势参数，但两者对于对于测量误差和系统误差的反映有很大差别。模拟一组(20 个，范围：0—1)NDVI 数据，同时模拟一组均值为 0.05，方差为 0.01 的正态分布噪声((μ, σ^2)=(0.05, 0.01))，叠加到 NDVI 数据上(图 3)。

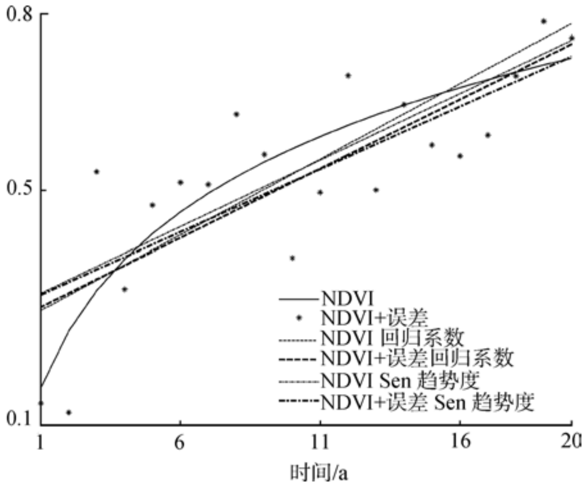

图 3 Sen 趋势度和回归系数对于误差的反映

模拟结果表明(图 3 和表 2)，回归系数对误差反映较为剧烈，而 Sen 趋势度对误差抵抗能力要优于回归系数。主要原因是 Sen 趋势度是基于聚群和排序方法来计算趋势，和回归系数基于线性最小二乘估计(linear least squares estimate)有本质区别，因而对于误差的规避能力也会有区别，而 Sen 趋势度的计算过程，在于对误差抵抗能力方面有独特优势(Fernandes 等, 2005)。

表 **2** **Sen** 趋势度和回归系数比较

	NDVI	NDVI+误差
回归系数	0.0256	0.0234
Sen 趋势度	0.0226	0.0213

6 结论与讨论

基于遥感的植被长时序动态变化分析已经成为植被生态研究的重点，也是长时序生态研究的热点问题，同时分析植被长时序动态变化和气候变化的关系成为全球变化研究的一个重要领域。AVHRR、SPOT VGT 和 MODIS 是当前研究植被长时序趋势变化的主要数据源，同时许多国家和国际组织制定了全球遥感数据接受、分析、处理从而形成标准数据集的计划，极大促进了今后植被长时序的研究工作。

但是当前研究植被长时序趋势变化的方法却差异较大，研究结果也不尽相同。回归分析法和相关系数法是当前用于研究 NDVI 长时序趋势分析的主要方法，但两种方法对长时序趋势的计算分析存在一些不足，并且数据正态分布的前提条件往往难以满足，同时这两个方法对于噪声的表现并不理想。Sen＋Mann-Kendall 方法是一种植被长时序研究的新方法，其在上述几点上优于前两种方法，即①不需要数据服从某一特定分布；②对数据的误差具有较强的抵抗能力。而且 Sen＋Mann-Kendall 方法对于显著性水平的检验也具有较为坚实的统计学理论基础，使得结果较为科学和可信。因而在今后的研究当中应该受到足够的重视和利用。

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