Increasing terrestrial vegetation activity in China, 1982—1999

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Abstract Variations in vegetation activity during the past 18 years in China were investigated using the normalized difference vegetation index (NDVI) derived from the 3rd generation time series dataset of NOAA-AVHRR from 1982 to 1999. In order to eliminate the effects of non-vegetation factors, we characterized areas with NDVI < 0.1 as "sparsely vegetated areas" and areas with NDVI ⩾ 0.1 as "vegetated areas". The results showed that increasing NDVI trends were evident, to varying extents, in almost all regions in China in the 18 years, indicating that vegetation activity has been rising in recent years in these regions. Compared to the early 1980s, the vegetated area increased by 3.5% by the late 1990s, while the sparsely vegetated area declined by 18.1% in the same period. The national total mean annual NDVI increased by 7.4% during the study period. Extended growing seasons and increased plant growth rates accounted for the bulk of these increases, while increases in temperature and summer rainfall, and strengthening agricultural activity were also likely important factors. NDVI changes in China exhibited relatively large spatial heterogeneity; the eastern coastal regions experienced declining or indiscernibly rising trends, while agricultural regions and western China experienced marked increases. Such a pattern was due primarily to urbanization, agricultural activity, regional climate characteristics, and different vegetation responses to regional climate changes.

Keywords: China, NDVI, vegetation activity, climate change, agricultural production, urbanization.

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The "opening" policies implemented in China in the past two decades have resulted in extensive changes in land use and land cover. Vegetation activity has increased through agricultural practices such as afforestation, irrigation, and intensive agricultural management[1,2]. On the other hand, vegetation coverage has decreased due to rapid urbanization, industrialization, and overgrazing[3,4]. Thus, there are conflicting reports regarding the status of China's vegetation, as no integrative analysis at the national level has yet been conducted. This study aims to explore the trends in vegetation coverage (activity) in the past two decades using a time series dataset of normalized difference vegetation index (NDVI).

At the global scale, studies based on observations of atmospheric CO_2[5,6], phenology[7,8] and land coverage change[9,10], and on carbon process models[11—13], have all indicated that vegetation activity in the Northern Hemisphere is increasing, and this leads to significant carbon sinks in these regions. This increase has been confirmed by satellite-based studies[14—21]. However, how vegetation activity has changed at the national scale in China over the past 20 years is unclear. The extended time-series, high-quality NDVI dataset derived from satellite data makes it possible to address this issue.

With a broad spatial coverage and high temporal resolution, Advanced Very High Resolution Radiometer (AVHRR) of the National Oceanic and Atmospheric Administration (NOAA) datasets have been widely used in studies of national, continental, and even global vegetation activities. The recent development of multiyear continuous NOAA/AVHRR dataset, in particular, makes large-scale time series studies possible. As an indicator of vegetation coverage and plant productivity, the NDVI has been used in analysis of vegetation activity[14—16,22—29] in the past two decades. In particular, the third-generation NOAA/AVHRR NDVI data set is widely applied in large-scale studies of vegetation activity, because the effects of solar zenith angle and stratospheric aerosol in the atmosphere have been removed, and the most problems noted in previous generations of NDVI data sets have been overcome[16,23].

In the present study, using the third-generation time-series NOAA/AVHRR NDVI dataset[16,18], the vegetation cover change over the period 1982—1999 was studied across both geographical and administrative regions. The value of NDVI is an indicator of the vegetation cover or vegetation activity, and its magnitude is contributed from two parameters, vegetation-covered area and quantity of vegetation coverage per unit area (mean NDVI). Therefore, an increase or decrease in regional vegetation activity resulting from changes in these two parameters represents an increase or decrease in vegetation productivity. The changes in both parameters over the past 20 years were examined in the current study.

It should be noted that vegetation in this study includes both natural and agricultural vegetation, without discriminating between these two types. This stems from our goal of exploring overall vegetation dynamics, as well as the difficulty in differentiating between these two types of vegetation in certain situations. For example, the differences between old-field and managed natural grasslands can rarely be discerned by satellite images.

1 Data and methods

1.1 Definitions

(i) Sparsely vegetated and vegetated areas. NDVI varies from –1 to 1. The higher the NDVI value, the higher the vegetation coverage and activity are. In regions covered by ice and snow, NDVI values usually are negative, while in desert regions, ground conditions strongly affect NDVI, leading to unstable values that cannot accurately represent vegetation status. Therefore, an NDVI threshold is commonly used to exclude those bare and sparsely vegetated areas for data analysis. A threshold of 0.05 has been used in earlier studies[14], but more recent studies set the threshold at 0.1[19,20], which is also used in the present study. That is, areas with NDVI < 0.1 were defined as “sparsely vegetated areas”, while the areas with NDVI $\geqslant 0.1$ were defined as “vegetated areas”. Only vegetated areas are analyzed in this study. Because NDVI values for a particular site vary each year due to variation of climate, the total “vegetated area” varied over the research period.

(ii) Vegetation change. Similar to “vegetation activity.” In this study “vegetation change” implies alteration in vegetated area and/or mean NDVI value.

(iii) Rate of NDVI change. The rate of NDVI change was calculated as follows:

$$\text{Rate of NDVI change (\%)} = \text{regression slope / mean NDVI value} \times 18 \times 100,$$

where regression slope represents the linear regression slope of annual or monthly average NDVI to calendar year over the period of 18 years. Mean value is the average NDVI over the 18 years. In other words, the rate of change equals the difference between final NDVI (1999) and initial NDVI (1982) divided by initial NDVI.

1.2 NDVI data set

The NDVI data used in this analysis were produced by the Global Inventory Monitoring and Modeling Studies (GIMMS) group, and were derived from the NOAA/AVHRR Land data set, at a spatial resolution of 8×8 km^2 and at 15-day intervals, for the period January 1982 to December 1999. This dataset has been corrected to remove the effects of volcanic activity and to overcome most problems noted in previous generations. It is therefore called the third-generation NDVI data set, and has been shown to be a good data source for long-term vegetation analysis[16,18—21,23].

As we used NDVI as an indicator of vegetation activity, the quality of NDVI is critical for data analysis. Therefore, we examined the suitability of this data set for analyzing vegetation activity in China. Slayback et al.[23] examined five NDVI data sets, each processed differently, for regions of the Arabian Desert. The results showed that of the five data sets, GIMMS-NDVI changed most smoothly over the period of 1982—1999, with no significant trends for either individual satellites or all satellites across the entire time period. This assessment recommends this data set for identifying patterns and dynamics of large-scale vegetation activities[23]. Furthermore, China's geographical position is within 25°N—55°N, falling within the range of satellite sensitivity. NDVI changed evenly over the 18 years, and changeover of the satellite sensor did not significantly affect overall NDVI[23]. This suggests that the GIMMS- NDVI data set can be used in identifying the long-term trends in vegetation cover and activity in China.

1.3 Climate data set

The climate data set used in this study was monthly mean temperature and precipitation over the study period (1982—1999) calculated from 680 well-distributed climatic stations across China.

1.4 Data processing

Monthly NDVI was obtained from maximum value composite (MVC) method, which minimizes cloud contamination, atmospheric effects, and solar zenith angle effects[30]. The NDVI pixels derived from the MVC method were then converted to geographic grid cells at 0.1° × 0.1° degree resolution from the original Albers equal-area projection for further analysis. The monthly NDVI values ⩾0.1 within each year were aggregated to obtain annual NDVI. The climate maps that correspond to grid cells of 0.1° × 0.1° were obtained by Kriging interpolation.

2 Results and discussion

2.1 Interannual change in vegetation coverage

An examination of distribution of China's annual NDVI in the early 1980s (3-year averaged value for 1982—1984) and the late 1990s (1997—1999) (figs. 1(a) and 1(b), respectively) revealed the following characteristics:

(1) In both periods, NDVI values across China exhibited a decreasing trend from the southeastern to the northwest, with a considerably greater NDVI in the eastern portions of the country than in the western portions. The NDVI in the northwestern desert areas was extremely low, therefore fitting our definition of sparsely vegetated areas. The favorable precipitation and temperature conditions in southern Yunnan Province and eastern Xizang (Tibet) led to correspondingly high NDVI values.

(2) Compared to the early 1980s, the NDVI values in the late 1990s for the Northeast and North- central plains, the Sichuan basin and other agricultural areas showed a significant increase. However, urbanization clearly led to a decrease in NDVI in the Pearl River and Yangtze River deltas along the eastern coast.

(3) Comparing the distribution of NDVI in these two periods, it was found that the sparsely vegetated areas (NDVI < 0.1) in northwest regions decreased to some extent by the late 1990s.

Interannual changes in NDVI across the country exhibited similar patterns. Statistical analysis showed that in the past 18 years (1982—1999) the area of vegetated regions (NDVI ⩾ 0.1) tended to increase (R^2 = 0.15, p = 0.12) at a rate of 0.98 × 10^4 km^2/year (fig. 2(a)), while sparsely vegetated areas contracted by 0.98 × 10^4 km^2/year (R^2 = 0.15, p = 0.12) (fig. 2(b)).

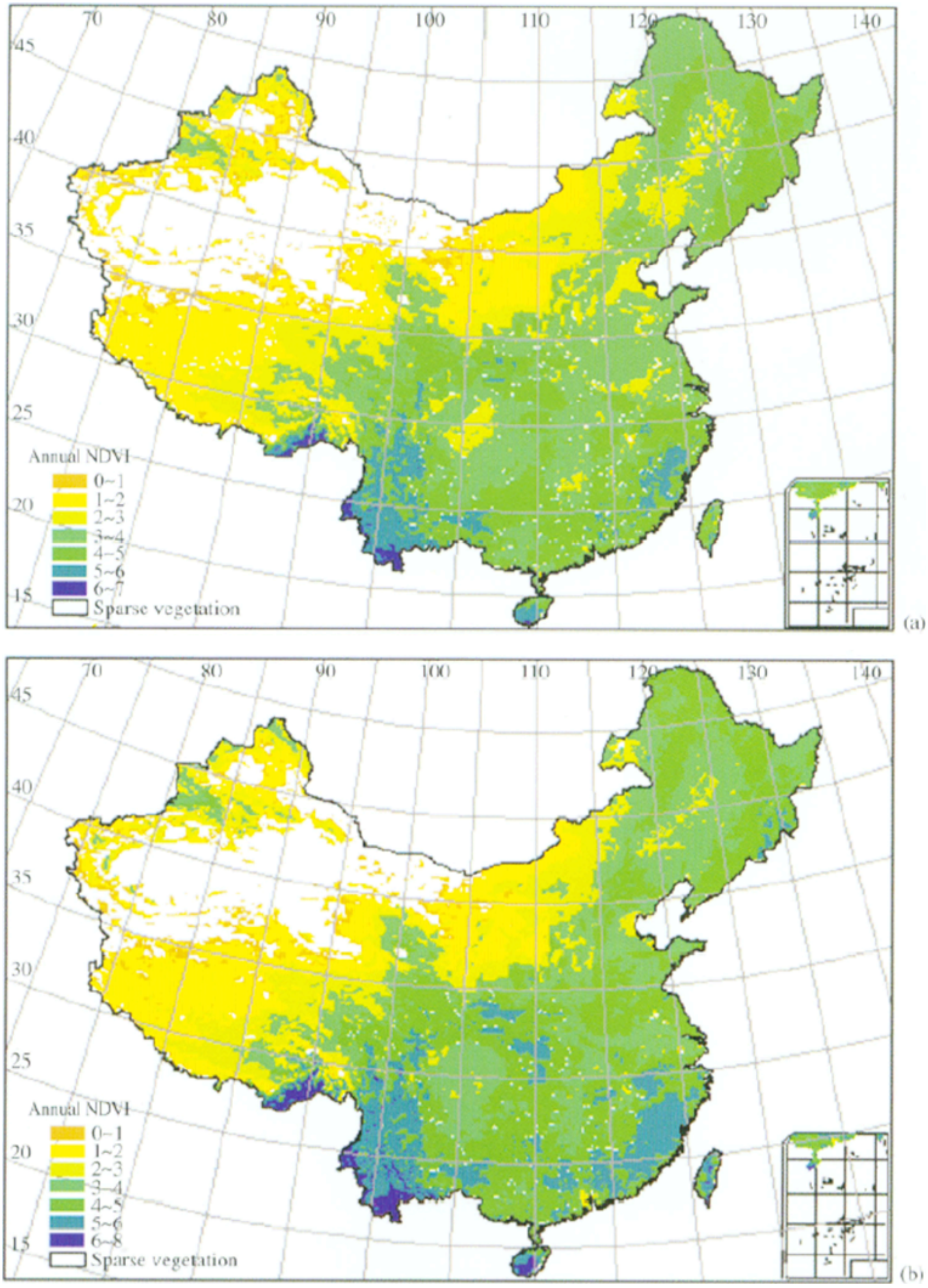

Fig. 1. Spatial distribution of three-year averaged NDVI at the early 1980s (1982—1984, (a)) and late 1990s (1997—1999, (b)).

On the other hand, area-weighted mean annual NDVI values showed a consistent increase. Both mean annual NDVI values for vegetated areas (accumulated annual NDVI for areas with NDVI $\geqslant$ 0.1 divided by total area, fig. 2(c) top) and national mean annual NDVI (accumulated NDVI values for areas with NDVI $\geqslant$0.1 divided by national land area, fig. 3(c) bottom) clearly showed an increasing trend, with a coefficient of correlation of 0.24 (p = 0.04) and 0.44 (p = 0.01), respectively. Therefore, both vegetated area

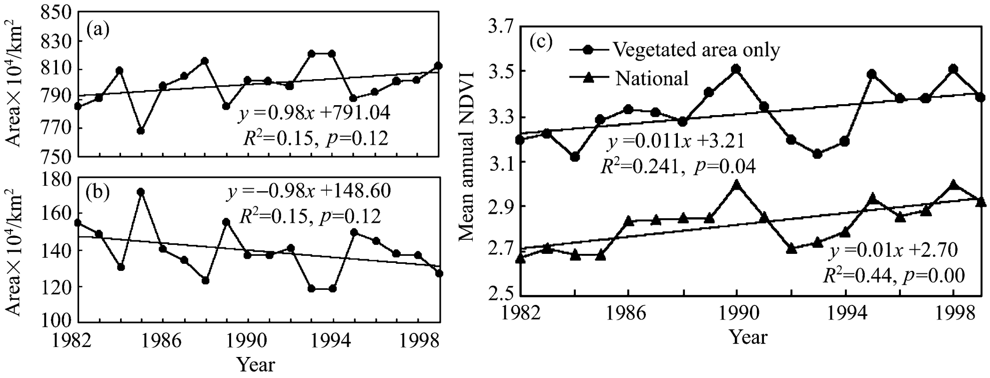

Fig. 2. Interannual variations in vegetation activity over 18 years in China. (a) Area of vegetated regions (NDVI ≥0.1), showing an evident increase; (b) area of sparsely vegetated regions, showing an evident decrease; (c) area-weighted mean annual NDVI. Mean annual NDVI values for both vegetated areas (top) and country area total (bottom) showed a marked increase.

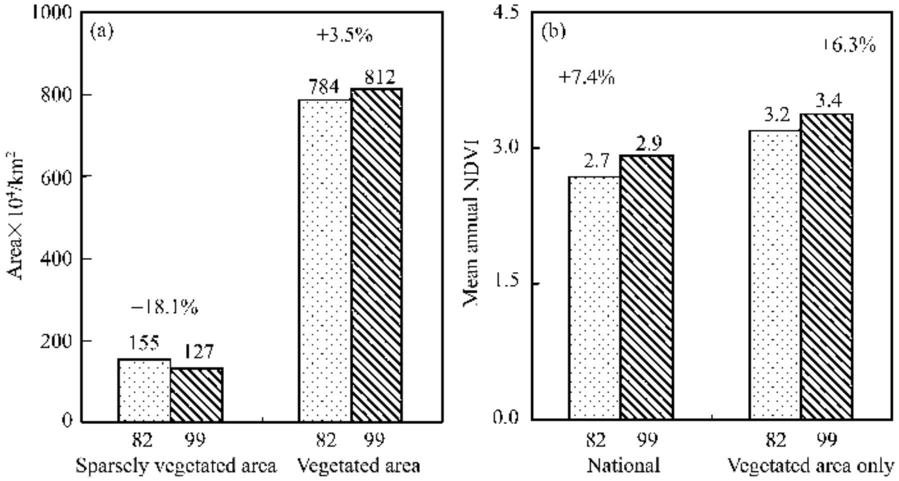

Fig. 3. Changes in vegetation coverage (a) and area-weighted mean annual NDVI (b) in China over the 18 years. (a) Sparsely vegetated area decreased by 18.1%, while vegetated area increased by 3.5% from 1982 to 1999. (b) Area-weighted mean annual NDVI increased by 7.4% country-wide and by 6.3% in vegetated areas.

and mean NDVI values per unit area increased to varying extents, demonstrating that the overall state of China's vegetation developed favorably in this period. Fig. 3 summarizes the dynamics of vegetated and sparsely-vegetated areas in the 18 years: vegetated areas increased from 784 × 10^4 km^2 in 1982 to 812 × 10^4 km^2 in 1999, an increase of 3.5%, while sparsely vegetated areas (NDVI < 0.1) decreased from 155 × 10^4 km^2 in 1982 to 127 × 10^4 km^2 in 1999, a decrease of 18.1%. In the vegetated areas, area-weighted mean annual NDVI increased from 3.2 to 3.4, a net increase of 6.3%, while national mean annual NDVI increased from 2.7 to 2.9, an increase of 7.4%.

2.2 Reasons for vegetation activity increase and influence of climate changes

Recent studies have identified two main factors leading to increase of annual NDVI in the northern hemisphere: extension of the growing season (including earlier springs and later autumns) and acceleration of plant growth[14,31]. Fig. 4(a) shows the seasonal changes in the average of monthly NDVI for China's vegetated areas from the early 1980s (1982—1984) and late 1990s (1997—1999). In terms of both growing season length and total growth of growing season (NDVI value), the late 1990s exceed the early 1980s.

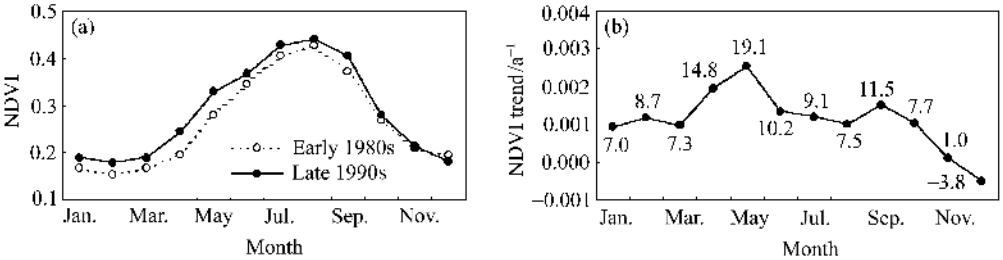

Fig. 4. Seasonal variations in vegetation activity in China. (a) Monthly average NDVI at the early 1980s (1982—1984) and late 1990s (1997—1999). (b) Seasonal changes in the trend of national average monthly NDVI from 1982 to 1999. The trend represents the slope of the regressed linear equation for monthly NDVI to the year. A positive value represents an increase, while a negative value represents a decrease.

Except for December, every other monthly NDVI value was larger in the late 1990s than in the early 1980s, especially in the first half of the year.

In order to more clearly analyze the contribution of each month and season to annual NDVI trends, fig. 4(b) shows seasonal changes in the trends of national averaged monthly NDVI over the period of 1982—1999, which is the slope for each regressed linear equation of monthly NDVI values over the year. With the exception of December, values for every month tended to increase, representing an overall increase in NDVI. The largest trends occurred in April and May, suggesting the overall increase for springtime was correspondingly the largest. NDVI values in December showed a decreasing trend. The numbers for each month in fig. 4(b) show the trend in monthly NDVI as a percentage of annual NDVI, or rather, the contribution of that month to total change in annual NDVI over the 18 years. The contribution from May was the largest, contributing to 19.1% of the total increase, followed by April (14.8%). Springtime (March to May) accounted for 41.2% of the total increase, while summer (June to August) contributed 26.8%, and autumn (September to November) 20.2%. In China, vegetation growth only occurs in the south during winter (December to February), and this season contributed only 11.9% (of which December represented −3.8%). It is evident that China's NDVI increase mainly occurred in springtime, followed by summertime. This is consistent with the results of Zhou et al.[19] and Los et al.[17], which concluded that the early advance of springtime was the major factor causing the increase in the northern hemisphere's vegetation activity.

China's NDVI increase corresponds closely with climate changes[21,29,31]. In order to analyze the relationship between NDVI and climate, fig. 5 presents the interannual variation in annual mean NDVI, temperature and annual precipitation over the period of 1982—1999. In this period, despite fluctuations, annual mean temperature increased markedly, at a rate of 0.062℃ per year. Compared to other regions of the world, this increase is notable[32]. There were relatively large fluctuations in annual rainfall, with no obvious trend.

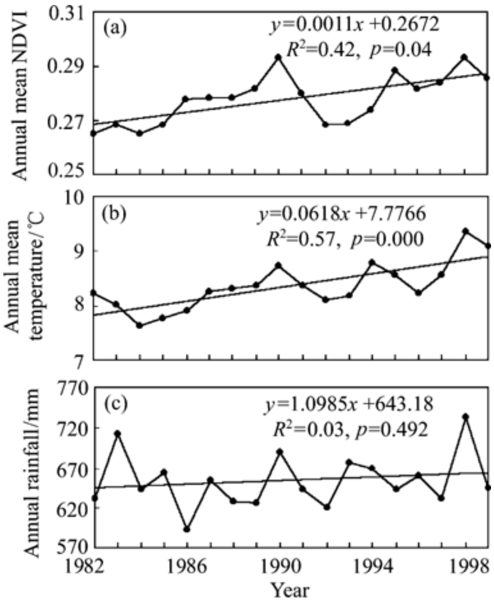

Fig. 5. Interannual variation in annual mean NDVI, mean temperature and precipitation in China from 1982 to 1999.

Compared with annual changes in climate, seasonal climate variation had an even more direct influence on vegetation growth. As shown in fig. 6, springtime contributed more to China's NDVI increase than other seasons, with a rate of increase (slope of regressed linear equation) of 0.0018 (R^2 = 0.40, p = 0.005), while the increase for summer and autumn was 0.0012 (R^2 = 0.35, p = 0.010), and 0.0009 (R^2 = 0.18, p = 0.081), respectively. There was no clear trend for winter (p = 0.287). However, the most evident increase in temperature occurred in winter, rising by 0.096℃/year, followed by a 0.062℃/year increase in springtime. Temperature increases of similar scope occurred in summer and autumn.

It is worth emphasizing that interannual variations in rainfall change with the seasons in China. As stated above, despite no obvious trends in annual rainfall, seasonal rainfall exhibited clear patterns over the 18 years: the summertime rainfall significantly increased (R^2 = 0.27, p = 0.027), while autumn rainfall clearly decreased (R^2 = 0.33, p = 0.010). There was no distinct change in spring rainfall. Overall, the reduction of rainfall in autumn might be balanced by the increase in summer, maintaining essentially the un-

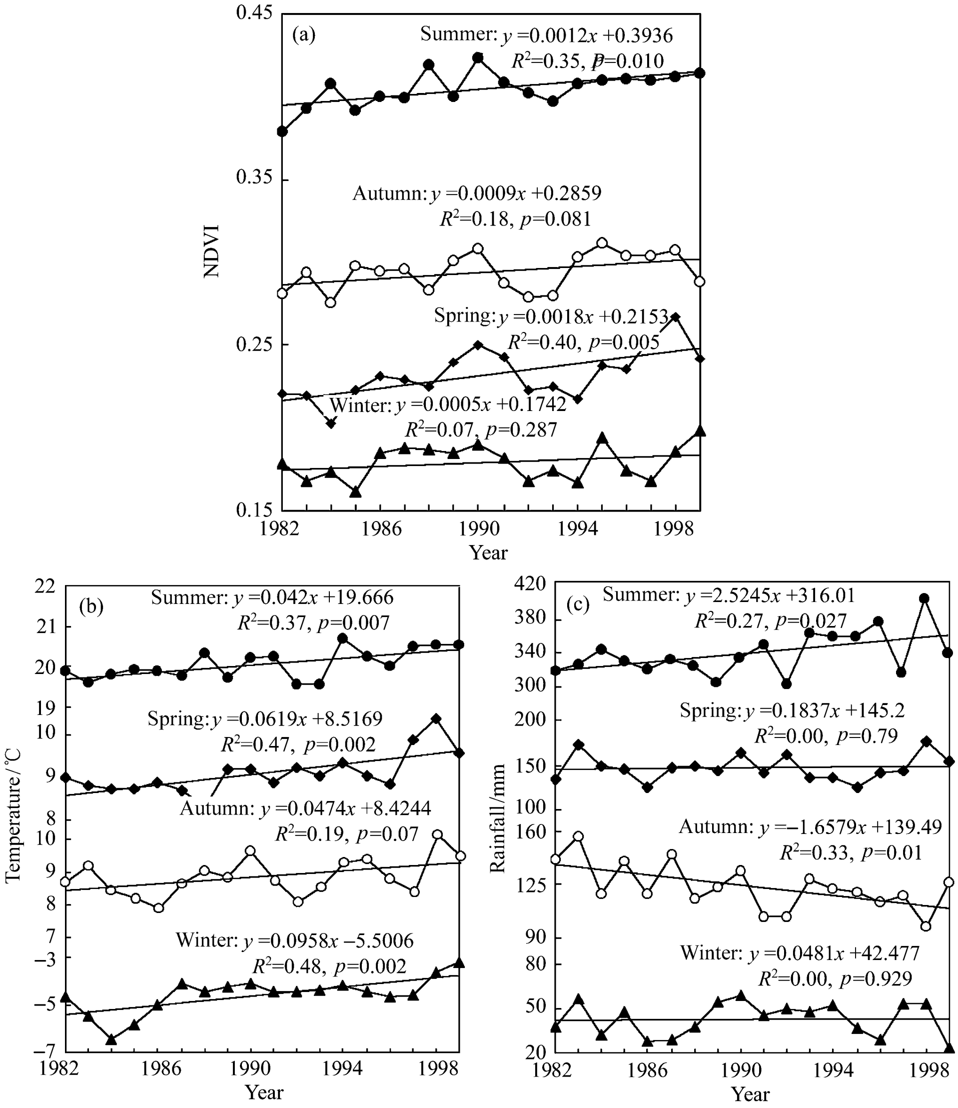

Fig. 6. Interannual variations in seasonal mean NDVI (a), seasonal mean temperature (b), and seasonal precipitation (c) in China between 1982 and 1999.

changed total rainfall for the whole year. Such a rainfall pattern has greatly contributed to the national NDVI increase. During the growing season, simultaneously increasing rainfall and temperature can undeniably enhance plant growth. This is a notable characteristic for the relationship between climate and vegetation growth in China. Furthermore, the slight decrease in rainfall during autumn, when vegetation slows or ceases growth, is likely to exert a relatively small influence on overall vegetation growth.

2.3 Spatial differences in NDVI trends and probable reasons

Despite the obvious NDVI increase at national scale, there exists a relatively large spatial heterogeneity. Fig. 8 shows spatial distribution of annual NDVI trends (fig. 7(a)) and significance levels (at 5% level, fig. 7(b)). NDVI increases clearly occurred in the major agricultural areas of east China (including the North-central plain, Northeast plain, and parts of Yangtze River regions), southern Xinjiang (mostly in the mountain and agricultural regions), and southeast Tibet and southwest Yunnan, which are influenced heavily by the southwest monsoons. NDVI tended to fall in the Yangtze River and Pearl River deltas, the Yunnan plateau, and the central Qinghai-Xizang (Tibetan) plateau. Especially worthy of note is a prominent increase of the NDVI in Tianshan Mountains of Xinjiang (fig. 7), one of the areas of the largest increase across the country. As explained below, Shi et al.[40—42] recently found that since the 1980s, the climate of the northwest China (including mountain area of Xinjiang) has been shifting from warm-arid to warm-humid. Our results support this viewpoint (fig. 7).

In order to analyze NDVI change at the provincial scale, table 1 lists mean annual NDVI, NDVI trends, and changing rate of NDVI for each province, and arranges them by magnitude of rate of change. In agreement with previous analyses, the NDVI values for southeastern coastal regions were relatively large, while those of western regions were relatively small. The mean annual NDVI in Xinjiang was only 0.74, lower than all other regions. The largest mean annual NDVI values were measured in Yunnan and Hainan Provinces, at 5.22 and 5.20, respectively. These two provinces are situated in the tropical/subtropical zone, with a high level of vegetation coverage. In addition, NDVI across the country generally decreased from southeast to northwest, with the exceptions of marked NDVI decrease due to urbanization around major metropolitan areas, such as Shanghai.

Analysis of the changing rate of averaged annual NDVI for each province revealed the following characteristics and their likely causative factors:

(1) Negative or relatively small changes (< 5%) in annual NDVI occurred in Zhejiang, Guizhou, Fujian, Guangdong, Guangxi, and Heilongjiang Provinces, as well as in Shanghai municipality. In the majority of these regions urbanization has led to reduced NDVI values. However, climate change is likely an important factor controlling the changes in Guizhou Province, since little urban growth occurred in the province during the study period. In Heilongjiang Province, a small NDVI increase is likely due to logging[33], and a devastating forest fire in 1987.

(2) Shandong, Henan, Hebei, Anhui, and other agricultural provinces experienced a relatively large NDVI increase, over 10% per year. The reforms and "opening" of China in the last 20 years have without a doubt increased the national food production in the major agricultural areas. Although grain production certainly relates to crop type, farmland area, farming intensity and other factors, it can reflect, to a high degree, the general situation of vegetation coverage[34]. The pronounced NDVI increase in China's north-central and northeast regions closely correlates with the increase in grain production in those regions. In the past 20 years, as NDVI increased in the north-central region, total grain production rose by 40%[35].

(3) The amplitude of NDVI increase was evident (> 7%) in the western provinces of Xinjiang, Gansu, Qinghai, Ningxia, and Inner Mongolia. Of these areas, the rate of increase in Xinjiang reached 26.8%. Climate change in these areas, especially an increase in summer rainfall (fig. 6(c)), is almost certainly one of the most important factors behind this change. An

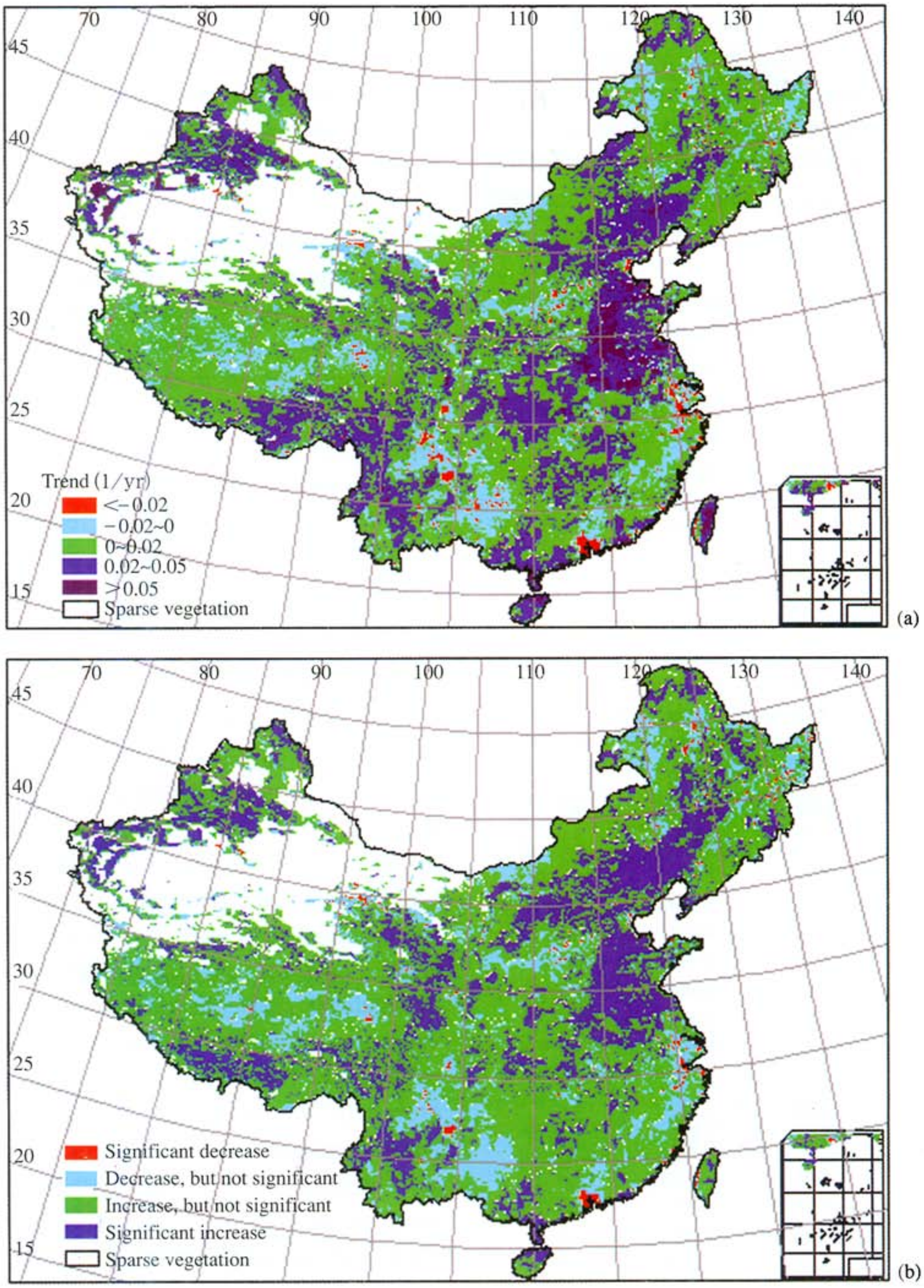

Fig. 7. Spatial distribution of the trends in annual NDVI (a) and 5% significance levels (b) over the 18 years in China.

analysis of rainfall data for the northwest regions showed a clear increase in summer rainfall in the past 20 years (r = 0.32). The synchronous change in precipitation and temperature conditions enhanced vegetation growth. In addition, artificial irrigation in parts of these regions has created artificial oases[36], further stimulating vegetation growth. The advanced springtime[21] is likely also one of the important factors for this change. The considerably large rate of NDVI increase in Xinjiang may also stem from the relatively low total NDVI values (an average annual NDVI of 0.74, table 1), and especially from low initial values. The majority of China's western regions is used for grazing, so the fact of NDVI increase indicates that the positive effects of climate changes and agricultural engineering exceed the negative effects of grazing.

Table 1 Provincial mean annual NDVI over 1982—1999, NDVI trend, rate of NDVI change (%), in descending rank of NDVI change rate

Region	Rank	Mean annual NDVI	NDVI trend	NDVI change rate (%)
Xinjiang	1	0.74	0.011	26.8
Shandong	2	3.59	0.032	16.0
Henan	3	3.86	0.031	14.5
Hebei	4	3.58	0.026	13.1
Anhui	5	3.95	0.028	12.8
Taiwan	6	4.82	0.030	11.2
Beijing	7	2.13	0.013	11.0
Hainan	8	5.20	0.031	10.7
Liaoning	9	3.72	0.020	9.7
Jiangsu	10	3.94	0.021	9.6
Gansu	11	1.98	0.010	9.1
Hubei	12	4.08	0.020	8.8
Qinghai	13	2.10	0.010	8.6
Hunan	14	4.02	0.018	8.1
Ningxia	15	2.07	0.009	7.8
Inner Mongolia	16	2.41	0.010	7.5
Shaanxi	17	3.59	0.013	6.5
Sichuan	18	4.07	0.014	6.2
Jiangxi	19	4.39	0.015	6.2
Jilin	20	3.86	0.013	6.1
Xizang	21	3.85	0.012	5.6
Shanxi	22	3.25	0.010	5.5
Yunnan	23	5.22	0.016	5.5
Tianjin	24	3.03	0.009	5.3
Guangxi	25	4.45	0.011	4.4
Guangdong	26	4.51	0.011	4.4
Heilongjiang	27	3.84	0.009	4.2
Fujian	28	4.99	0.006	2.2
Guizhou	29	4.00	0.004	1.8
Zhejiang	30	4.72	–0.003	–1.1
Shanghai	31	3.88	–0.009	–4.2

Such a large NDVI increase in China's western regions has been confirmed by a body of research. Zhong[37] analyzed land survey data, aerial photographs, and TM satellite images from the last 20 years, finding that China's deserts have been changing to grassland and oasis at an average rate of 445 km^2/year. The research of Wu[38] has also indicated that since the late 1980s, the extreme desertification in Mu Us region has been brought under control, with diminishing area undergoing desertification. According to analysis of remote sensing data, the vegetation productivity in the Inner Mongolia region has been increasing[39]. Shi et al.[40—42] analyzed historical, recent, and present-day climate changes in the northwestern regions (especially in Xinjiang), coming to an important conclusion: from the 1980s, the climate of China's northwest has increasingly altered from warm-arid to warm-humid, with increasing rainfall. This alteration has led to greater glacial melting, runoff, and rising water bodies in the northwest region, all creating favorable conditions for vegetation growth. A recent comprehensive review on the environmental developments in western China also confirmed that vegetation coverage has increased in recent a few decades[43].

3 Conclusions

As stated above, most areas in China have experienced an increase in NDVI, demonstrating that vegetation activity in China is strengthening. This disagrees with some recent reports, which assert that the situation for vegetation in China has been worsening. It is true that the vegetation in some locales within China have deteriorated due to urbanization and excessive land use (such as overgrazing). However, at the national scale, the present condition of China's vegetation coverage has improved compared to the early 1980s. This is consistent with the global situation, especially the prominent "greening" trend in the northern hemisphere[14—18,23]. For example, Zhou et al.[19] reported that in the northern hemisphere, as much as 61% of the total land area is experiencing NDVI increase from 1982 to 1999.

The trends in China's NDVI in the last 18 years exhibit the following characteristics:

(1) In the last 18 years, China's vegetation activity has tended to increase. Compared to the early 1980s, vegetated areas increased nationally by 3.5%, sparsely vegetated areas decreased in area by 18.1%, and national mean annual NDVI increased 7.4%.

(2) NDVI change exhibits relatively large regional differences. NDVI in eastern coastal regions has decreased or insignificantly increased, while that of agricultural areas markedly increased, and that of the majority of west China experienced an increasing trend.

(3) Extended growing season and more rapid growth account for the bulk of the NDVI increase in China. Climate changes, especially temperature and summer rainfall increase, are also the most important factors driving this increase.

(4) There has been a prominent increase in NDVI in agricultural areas, which almost certainly stems from the advance of agricultural technology. At the same time, the urbanization process is likely a critical factor in diminishing or obscuring the increase of NDVI in the eastern coastal areas.

(5) All the trends described above can be related to climate changes or human impact. Recent research from land surveys, remote sensing, climate change, and other fields all support our conclusion that western China is experiencing increasing NDVI. Of these, the finding of Shi et al.[40—42], indicating a climatic transformation in this region from warm-arid to warm-humid, has served as the most powerful confirmation of our conclusion.

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References

1. Zhang, P., Shao, G. F., Zhao, G. et al., China's forest policy for the 21st century, Science, 2000, 288: 2135.
2. Zang, X. S., Li, B., Shi, P. J., Development and utilization of grassland resources in southern china, Journal of Natural Resources (in Chinese), 1998, 13: 1—7.
3. Liu, J. Y., Liu, M. L., Zhuang, D. F. et al., Study on spatial pattern of land-use change in China during 1995—2000, Science in China, Ser. D, 2003, 46: 373—384.
4. Houghton, R. A., Temporal patterns of land-use change and carbon storage in China and tropical Asia, Science in China, Ser. C, 2002, 45(Supp.): 10—17.
5. Keeling, C. D., Chin, J. F. S., Whorf, T. P., Increased activity of northern vegetation in inferred from atmospheric CO_2 measurements, Nature, 1996, 382: 146—149.
6. Ciais, P., Peylin, P., Bousquet, P., Regional biospheric carbon fluxes as inferred from atmospheric CO_2 measurements, Ecol. Appl., 2000, 10: 1574—1589.
7. Bradley, N. L., Leopold, A. C., Ross, J. et al., Phenological changes reflect climate change in Wisconsin, Proc. Natl. Acad. Sci. USA, 1999, 96: 9701—9704.
8. Menzel, A., Fabian, P., Growing season extended in Europe, Nature, 1999, 397: 659—659.
9. Fang, J. Y., Chen, A. P., Peng, C. H. et al., Changes in forest biomass carbon storage in China between 1949 and 1998, Science, 2001, 292: 2320—2322.
10. Pacala, S. W., Hurtt, C. C., Baker, D. et al., Consistent land- and atmosphere-based U.S. carbon sink estimates, Science, 2001, 292: 2316—2320.
11. Melillo, J. M., McGuire, A. D., Kicklighter, D. W. et al., Global climate change and terrestrial net primary production, Nature, 1993, 363: 234—240.
12. Schimel, D., Melillo, J., Tian, H. Q. et al., Contribution of increasing CO_2 and climate to carbon storage by ecosystems in the United States, Science, 2000, 287: 2004—2006.
13. Cao, M. K., Prince, S. D., Li, K. R. et al., Response of terrestrial carbon uptake to climate interannual variability in China, Global Change Biol., 2003, 9: 536—546.
14. Myneni, R. B., Keeling, C. D., Tucker, C. J. et al., Increased plant growth in the northern high latitudes from 1981 to 1991, Nature, 1997, 386: 698—702.
15. Fang, J. Y., Piao, S. L., Field, C. et al., Increasing net primary production in China from 1982 to 1999, Frontiers in Ecology and the Environment, 2003, 1: 293—297.
16. Myneni, R. B., Dong, J., Tucker, C. J. et al., A large carbon sink in the woody biomass of Northern forests, Proc. Natl. Acad. Sci. USA, 2001, 98: 14784—14789.
17. Los, S. O., Collatz, G. J., Bounoua, L. et al., Global interannual variations in sea surface temperature and land surface vegetation, air temperature, and precipitation, J. Climate, 2001, 14: 1535—1549.
18. Tucker, C. J., Slayback, D. A., Pinzon, J. E. et al., Higher northern latitude NDVI and growing season trends from 1982 to 1999, Int. J. Biometeorol., 2001, 45: 184—190.
19. Zhou, L. M., Tucker, C. J., Kaufmann, R. K. et al., Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999, J. Geophys. Res., 2001: 106 (D17): 20069—20083.
20. Zhou, L. M., Kaufmann, R. K., Tian, Y. et al., Relation between interannual variations in satellite measures of vegetation greenness and climate between 1982 and 1999, J. Geophys. Res., 2003, 108 (D1), 10.1029/2002JD002510.
21. Piao, S. L., Fang, J. Y., Zhou, L. M. et al., Interannual variations of monthly and seasonal NDVI in China from 1982 to 1999, J. Geophys. Res., 2003, 108, No. D14, 4401, doi:10.1029/2002JD002848.
22. Paruelo, J. M., Epstein, H. E., Lauenroth, W. K. et al., ANPP estimates from NDVI for the central grassland region of United States, Ecology, 1997, 78: 953—958.
23. Slayback, D., Pinzon, J., Los, S. O. et al., Northern hemisphere photosynthetic trends 1982—1999, Global Change Biol., 2003, 9: 1—15.
24. Shi, P. J., Gong, P., Li, X. B. et al., Methods and Practice in LUCC Research (in Chinese), Beijing: Science Press, 2000, 67—96.

25. Shi, P. J., Li, X. B., Zhou W. G., Detection of vegetation response to climate change in northern china using “3s” technology, Quaternary Sciences (in Chinese), 2000, 20: 220—228.
26. Li, K. R., Chen, Y. F., Huang, M. et al., Model studies of the impacts of climate change on land cover and its feedback, Acta Geographica Sinica (in Chinese), 2000, 55 (Supplement): 57—63.
27. Piao, S. L., Fang, J. Y., Dynamic vegetation cover change over the last 18 years in China, Quaternary Sciences (in Chinese), 2000, 21: 294—302.
28. Xiang Bao, Liu Jiyuan, Relationship of East Asian land cover dynamics and interannual changes of monsoon climate, Acta Geographica Sinica (in Chinese), 2002, 57: 39—46.
29. Gong, D. Y., Shi, P. J., He, X. Z., Spatial features of the coupling between Spring NDVI and temperature over Northern Hemisphere, Acta Geographica Sinica (in Chinese), 2002, 57: 505—514.
30. Holben, B. N., Characteristics of maximum-value composite images for temporal AVHRR data, Int. J. Remote Sens., 1986, 7: 1435—1445.
31. Piao, S. L., Fang, J. Y., Chen, A. P., Seasonal dynamics of terrestrial net primary production in response to climate change in China, Acta Bot. Sin., 2003, 45: 269—275.
32. IPCC, Climate Change 2001: Impact, Adaptation, and Vulnerability, Cambridge: Cambridge University Press, 2001.
33. Wang, S. Q., Tian, H. Q., Liu, J. Y. et al., Characterization of changes in land cover and carbon storage in Northeastern China; An analysis based on Landsat TM data, Science in China, Ser. C, 2002, 45(1): 40~47.
34. Malmström, C. M., Thompson, M. V., Juday, G. P. et al., Interannual variation in global-scale net primary production: Testing model estimates, Global Biogeochem. Cycl. (in Chinese), 1997, 11: 367—392.
35. China’s Agricultural Yearbook, 1982 to 1999, China’s Agricultural Yearbook 1982 to 1999 (in Chinese), Beijing: Agriculture Press.
36. Zhang, X. S., Ecological restoration and sustainable agricultural paradigm of Mountain-Oasis-Ecotone-Desert system in the North of the Tianshan Mountains, Acta Botanica Sinica (in Chinese), 2001 43: 1294—1299.
37. Zhong D. C., The dynamic changes and trends of modern desert in China, Advance in Earth Sciences (in Chinese), 1999, 14: 230—234.
38. Wu, W., Study on process of desertification in Mu Us sandy land for last 50 years, China, Journal of Desert Research (in Chinese), 2001, 21: 164—169.
39. RunnstrÖm, M. C., Is northern China winning the battle against desertification? Satellite remote sensing as a tool to study biomass trends on the Ordos plateau in semiarid China, AMBIO, 2000, 29: 468—476.
40. Shi, Y. F., Shen, Y. P., Hu, R. J., Preliminary study on signal, impact and foreground of climatic shift from warm-dry to warm-humid in northwest China, Journal of Glaciology and Geocryology (in Chinese), 2002, 24: 219—226.
41. Shi, Y. F., Shen, Y. P., Li, D. L. et al., Discussion on the present climate change from warm-dry to warm-wet in northwest china, Quaternary Sciences (in Chinese), 2003, 23: 152—164.
42. Shi, Y. F., Shen, Y. P., Signal, impact and outlook of climatic shift from warm-dry to warm-humid in northwest China, Science & Technology Review, 2003, (2): 54—57.
43. Qin, D. H. ed., Assessment on Environment of Western China (Synopsis) (in Chinese), Beijing: Science Press, 2002.