Vegetation coverage dynamics and its response to urbanization in the Taihu Lake Basin during 1998~2010

Hu Qingfang¹*, Wang Leizhi¹, Wang Yintang¹, Li Lingjie¹, Liu Yong¹, Cui Tingting¹

¹State Key Laboratory of Water Resources and Hydraulic Engineering Science, Nanjing Hydraulic Research Institute, Nanjing 210029, China

*Corresponding author’s e-mail: hqf_work@163.com

Abstract. Based on the DMSP/OLS nighttime lighting data, the temporal and spatial evolution patterns of urbanization in Taihu Lake Basin from 1992 to 2010 were illustrated. In the meantime, the dynamic change characteristics of vegetation cover in Taihu Lake Basin from 1998-2010 were revealed according to the annual maximum ten-day normalized vegetation NDVI index and the corresponding vegetation coverage rate of SPOT in 1km × 1km resolution. Subsequently, the temporal and spatial response characteristics of vegetation cover factor to urbanization were also identified. The results showed that the urbanization process of the Taihu Lake Basin has been accelerated substantially since the beginning of the 1990s, and the intensity of nighttime and human activity has continuously increased. The urban built-up area has expanded extensively in the eastern part of the basin. Although the annual maximum ten-day normalized vegetation index NDVI and vegetation coverage in the whole basin over the past more than 10 years did not exhibit significant decline or class difference, there were significant negative temporal correlations of the annual maximum NDVI index and the vegetation coverage with the light intensity in the surrounding area and the corridors of main communication. As a result, the vegetation coverage in Puxi, Pudong, Yangcheng-Dianmao, and WuchengXiYu exhibited continued downward trends. At the same time, there was a close relationship between the spatial pattern of vegetation coverage and the pattern of urbanization in Taihu Lake Basin. On the spatial scale of 1km × 1km, there were significant negative correlations between NDVI and light intensity in the whole basin except for the Taihu Lake area over all the investigated years. Since the rapid urbanization of the Taihu Lake Basin has a significant effect on vegetation cover characteristics, it is necessary to reinforce the ecological protection, restoration and other measures to scientifically respond and prevent changes in vegetation cover caused by the ecological environment and hydrological risks.

1. Introduction

The vegetation cover condition, closely related to the basin hydrological cycle, is a major and critical factor reflecting the characteristics of the underlying surface of the basin. Vegetation affects the surface water circulation and its accompanying material and energy transfer processes through various mechanisms, such as the canopy interception, evapotranspiration, and infiltration into the root zone, and even has a particular impact on the local precipitation. Therefore, researchers around the world have conducted extensive studies on the interaction between vegetation cover and the water cycle. In particularly, Normalized Difference Vegetation Index (NDVI), an important indicator of vegetation growth status, has been widely used in the detection of vegetation change, estimation of vegetation
productivity, analysis of hydrological effect, dynamic monitoring of drought, and so on. For example, according to the NDVI during 1981 to 1999, vegetation activity in the middle latitudes of the northern hemisphere exhibited a significant increasing trend. Based on this finding, Tucker et al. believed that this phenomenon should be attributed to climate warming[1]. Park et al. analyzed the NDVI changes of growing seasons in the northern part of Eastern Asia from 1982 to 2006 and found that the vegetation activity in the mid-1990s was a turning point, in which the vegetation activity increased first and then decreased[2]. Krishnaswamy et al. demonstrated the consistency of vegetation dynamics with climatic factors in the mountainous areas of 30° N ~ 30° S from 1982 to 2006 by using the monthly NDVI data[3]. Pettorelli et al. also reviewed the important role of NDVI in the analysis of global vegetation changes[4]. In China, Piao[5], Chen Xiaqiu[6], Chen Fujun[7], Tian Tian[8] and many other researchers have studied the temporal and spatial variations of vegetation coverage in different regions and periods, as well as their relationships with hydrothermal factors by analyzing NDVI data. He Changgao employed NDVI data to evaluate the hydrological effects on soil and water conservation projects[9]. Qi Shuhua et al. studied the feasibility of using NDVI and surface temperature products to assess the national drought distribution and conducted a preliminary verification by measuring the soil water content[10]. Ge Xiaoguang et al. revealed the significant impact of Heihe River water on the vegetation development of the Ejin oasis by using NDVI data on the regional scale[11]. By investigating the arid and semi-arid areas in the Yellow River Basin, Shao Weimei systematically studied the correlation between NDVI and water cycle elements, such as evapotranspiration and surface runoff[12]. Liu Hui et al. established the time series logistic model of NDVI and explored the applicability of this model for phenological identification by studying the Inner Mongolia Plateau grassland area[13].

However, most of the current studies focus on the detection of large-scale vegetation cover state changes and their responses to precipitation, temperature, and other climatic factors, only a small number of studies analyzed the effects of human factors on the vegetation pattern and their potential ecological and hydrological effects[14-16]. However, human activities, represented by urbanization, have become increasingly important to the underlying surface characteristics of watersheds, including vegetation cover. As the economy, population size and density continue to increase, the impact of urbanization on vegetation coverage may even dominate at a certain time and space. The change of urban vegetation cover will not only have a direct impact on the ecological pattern of urban landscape but also change the retention, infiltration, dissipation and storage characteristics of surface water, thus resulting in a chain effect on urban drainage and waterlogging and water resources management. Therefore, it is helpful to understand the urban ecology, hydrological processes, and their control mechanisms deeply, and to provide a scientific basis for the optimization of urban vegetation and low-impact development model by studying the dynamic change of surface vegetation cover in the process of urbanization and elucidating the influence of vegetation cover change on the urbanization.

Located in the southeastern region of China, Taihu Lake Basin includes numerous central cities, such as Shanghai, Suzhou, Wuxi, and Changzhou, as well as many medium-sized and small cities, which is always the most highly populated and economically developed region. Since the 1990s, the process of urbanization in the Taihu Lake Basin has been significantly accelerated and has become one of the most urbanized areas in China. However, there are a few systematic studies on the response of the vegetation coverage factor to the urbanization in Taihu Lake Basin. In this work, the nighttime light data were employed to analyze the spatial and temporal evolution pattern of urbanization in Taihu Lake Basin since the 1990s (see the literature[17] for nighttime light data extraction and application), and then the dynamic changes of vegetation cover in the basin were identified based on NDVI data. On the basis of these results, the influence of urbanization on vegetation cover factor was elucidated. These research results will provide a foundation for further revealing the impact of vegetation change on the hydrological cycle of Taihu Lake Basin, optimizing the pattern of urban land use, and reducing the risk of urban flooding.
2. Research Area and Data

2.1. Research Area
Taihu Lake Basin is situated in the southern of Yangtze River, northern of Hangzhou Bay, western of the East China Sea. The total area of the basin is about 36895 km², which is the economic center of the Yangtze River Delta and crosses the provinces of Jiangsu, Zhejiang, Shanghai, and Anhui. By the end of 2010, the total population of the Taihu Lake Basin was 57.24 million, with an average population density of about 1550 people/km²; the total basin GDP was 429.5 billion yuan, accounting for 10.8% of the country, and the per capita GDP was about 2.5 times of the national average. The urban system, consisting of mega, big, medium and small cities and towns, has been highly developed in Taihu Lake Basin. The average urbanization rate of the river basin was 47.2% and 74.7% in 1990 and 2010, respectively. (The urbanization rate in Shanghai was 88.4% in 2010).

The water system and the main geographical elements of Taihu Lake Basin are shown in Figure 1. The entire basin is divided into eight subzones, including Pudong, Puxi, Yangcheng-Dianmao, WuChengXiYu, Lake West, Western Zhejiang, Hangzhou-Jiaxing-Huzhou, and Lake District. Among them, Pudong, Puxi, Yangcheng-Dianmao, WuChengXiYu District, Hangzhou-Jiaxing-Huzhou District are mainly plains with dense river network. Lake West district has both plains and hills while the western Zhejiang is a mountainous area. Lake District is primarily the Taihu Lake and shore belt.

Figure 1. Water drainage sub-areas and geographical elements in the Taihu Lake Basin

2.2. Data

2.2.1. NDVI Data. NDVI is defined as the ratio of the difference between the reflectivity of the near-infrared and the visible infrared bands to the reflectance sum of the two bands. This index is the best indicator of vegetation growth status and plant coverage. The NDVI of the water body is generally less than 0 while the NDVI of the rock and the bare soil is about 0. The NDVI of vegetation coverage area is more than 0. Moreover, the vegetation coverage increases with the increase of NDVI. NDVI used in this work was adopted from the SPOTVGT database with the time resolution of ten days, the spatial resolution of 1km × 1km, and the time series of 1998 to 2010.

2.2.2. Nighttime Light Data. The USG Defense Meteorological Satellite Program (DMSP) is equipped with a sensor - the Operational Linescan System (OLS) that works at night to detect low-intensity lights from urban areas and even small-scale residential areas. Thus, it can be used to distinguish urban and rural areas efficiently. Numerous studies have confirmed that DMSP/OLS nighttime light data is suitable for dynamic monitoring of urbanization processes and human activity intensity [18]. The DMSP/OLS data used in this work was adapted from the fourth edition of the non-radiative calibration nighttime average light intensity data released by the National Geographic Information Center in 2010, with a spatial resolution of 1 km × 1 km and a series of time from 1992 to 2012. In order to solve the data errors caused by overlapping data in different years and different
sensors in different years, we conducted the annual and inter-annual corrections of the original data and removed the light noise. The specific methods are shown in the literature [19].

3. Study Methods

3.1. Urbanization Indicators
Based on DMSP/OLS night light raster data, the average light intensity index in a certain range can be calculated as a primary indicator of the urbanization level and human activity intensity in Taihu Lake Basin on different spatial scales. At the same time, the distribution of urban built-up area in the basin at different years was obtained by using the light index threshold to analyze the pattern of urban spatial evolution.

The Average Light Intensity (ALI) is defined as the ratio of the light mean value to the maximum pixel brightness value for each pixel in a certain spatial range:

$$\text{ALI} = \frac{\sum_{i=1}^{n} (DN_i \times n_i)}{N_L \times DN_{\text{max}}}$$  \hspace{1cm} (1)

In the formula (1), DN_i represents the luminance value of i-level pixel; n_i represents the pixel number of i-th level; DN_{max} is the luminance value of the maximum pixel (DN_{max} = 63), and N_L is the total number of light pixels in the area.

The urban built-up area is an important factor reflecting urbanization. Because of the lack of spatial information, the traditional urban built-up area statistics cannot meet the requirements for the analysis of urban spatial pattern. Moreover, the night light information not only can quantitate the urban built-up area but also can determine its spatial distribution range, in which the critical process is to determine the optimal lighting threshold (DN_t). The pixels with light brightness greater than or equal to DN_t correspond to the urban areas; otherwise, they correspond to non-urban areas. In this work, DNT is determined by using the statistical data of the large and medium-sized cities in the Taihu Lake Basin. The detailed method is according to the literature procedure[20].

3.2. Vegetation Coverage Index
Since there are four distinct seasons in the Taihu Lake Basin, the precipitation, heat, and sunlight are unevenly distributed through the year. Accordingly, the vegetation growth also has significant seasonal changes. In this work, the maximum ten-day normalized vegetation NDVI index (MNDVI) is used as an indicator of vegetation growth in the year. In the meantime, the fraction ratio of vegetation coverage (Fraction ratio of vegetation coverage, fc) was calculated based on NDVI:

$$f_c = \frac{(\text{NDVI}_\text{veg} - \text{NDVI}_{\text{soil}})}{(\text{NDVI}_{\text{soil}} - \text{NDVI}_{\text{veg}})}$$  \hspace{1cm} (2)

In the formula (2): NDVI_{veg} and NDVI_{soil} are NDVI values of net vegetation cover and nude pixels in the study area, respectively. According to the value of fc, the vegetation coverage status can be further divided into different grades.

3.3. Correlation Analysis Method
This paper reveals the influence of urbanization on the vegetation coverage in Taihu Lake Basin from aspects of time and space. In terms of time series, the dynamic correlation between MNDVI and fc with ALI during the years of 1998-2010 was analyzed for the whole basin and subzones with 1km × 1km grid scale. Moreover, the differences in the correlation between vegetation cover factor and light intensity in different spatial locations were also analyzed for comparison. In the spatial aspect, the spatial correlations between the vegetation cover factor and the light intensity were analyzed for the whole basin and subzones with 1km × 1km grid scale to elucidate the response of the vegetation coverage pattern of the Taihu Lake Basin to the corresponding urbanization pattern.
4. Results and Analysis

4.1. Urbanization Evolution Pattern of Taihu Lake Basin

Figure 2 shows the ALI value of the Taihu Lake Basin during the years of 1992 ~ 2012 and the urban built-up area according to the light intensity of the Basin. As shown in Figure 2, the average light intensity index of the Taihu Lake Basin continuously increased from 1992 to 2012, in which the ALI values in 1992 and 2012 were 0.15 and 0.53, respectively. With increasing ALI, the urban built-up area within the basin correspondingly expanded substantially. Specifically, the total area of Taihu Lake Basin increased from 642 km² to 5783 km² from 1992 to 2010, and their ratios to total basin area increased from 1.74% to 13.0%. These results indicate that there is a significant increase in the intensity of human activities such as the rapid progress of the urbanization process and the corresponding land development. The period after 2000 is the acceleration phase of urbanization, in which the increasing rates of the average river light intensity index and built-up area were significantly higher than those in the years before 2000. From a spatial point of view, urbanization has obvious heterogeneity. According to Figure 3, the urbanization of the Taihu Lake Basin has two prominent features. First, there is an outward expansion characteristic from the central cities, such as Shanghai, Suzhou, and Wuxi; secondly, there is a linear expansion characteristic centered on corridors of main communication and rivers, such as the Grand Canal and the Beijing-Shanghai Railway.

According to the lighting intensity index and the urban district, the most rapidly developed urban areas in Taihu Lake Basin are Pudong, WuChengXiYu, and Yangcheng-Dianmao during the years of 1992 ~ 2012. These three districts together with the early urbanized Puxi area have the highest level of urbanization in the basin in 2012. The total built-up areas in these four districts in 2012 were 4555 km², accounting for 78.8% of the whole basin, especially there was a large-scale urban or urban zone in the southern Jiangsu and Shanghai. On the other hand, the urbanization process in the western part of the Taihu Lake Basin, such as Lake West, Western Zhejiang, and southern Hang-Jia-Hu, was relatively slow, in which the average light intensity index and the ratios of the urban area were significantly lower than those in the eastern part of the Taihu Lake Basin.
4.2. Dynamic changes of vegetation coverage in Taihu Lake Basin

Figure 4 shows the average MNDVI and their corresponding fc distributions of the Taihu Lake Basin and the respective districts from 1998 to 2010. Figure 5 shows the spatial distribution of MNDVI and fc in Taihu Lake Basin in 1998 and 2010 (1 km × 1 km resolution, Water was masked). These two figures reflect the change of the spatial pattern of vegetation cover in Taihu Lake Basin over more than 10 years. The vegetation coverage in western Zhejiang and Lake West areas were significantly better than other areas in the basin. Similarly, MNDVI and fc in western Zhejiang and Lake West were also apparently higher than those in other areas. The MNDVI and fc of Hangzhou-Jiaxing-Huzhou area were greater than the average of the basin, whereas the MNDVI and fc of Pudong, Puxi, WuChengXiYu, and Yangcheng-Dianmao were lower than the average of the basin, especially in the Puxi area. These results are consistent with the conclusion of the study on the vegetation cover change in the Taihu Lake Basin by Di Ji et al. [21]

Figure 4. Dynamics of maximum ten-day NDVI and the fraction ratio of vegetation coverage during 1998–2010 for the whole Taihu Lake Basin and its sub-areas
Figure 5. Maximum ten-day NDVI and the fraction ratio of vegetation coverage in 1998 and 2010 in the Taihu Lake Basin

At the same time, the change characteristics of MNDVI and fc in Taihu Lake Basin from 1998 to 2010 were analyzed on the grid scale of 1km × 1km. Comparing the data of 2010 with those of 1998, the number of grid cells with more than 0.10 reduction in MNDVI and fc were 8587 and 9012, respectively. In contrast, the number of grid cells with more than 0.1 increase in MNDVI and fc were 844 and 1740, respectively (These grid units were mainly lake or river shoreline after analysis). According to the criteria for vegetation coverage rate, fc <0. 2. 2 <fc <0. 4, 0. 4 <fc <0. 6, 0. 6 <fc <0.8 and fc> 0.8 (5 grades: lower, low, average, high, higher), in the year of 1998, the ratios of grid units with fc values of higher, high, average, low, and lower accounted for 41.0%, 52.3%, 4.0%, 1.8%, and 0.8% of the total land area in Taihu Lake Basin, respectively. In contrast, in the year of 2010, the ratios of grid units with fc values of higher, high, average, low, and lower accounted for 34.8%, 45.6%, 15.1%, 4.2%, and 0.3% of the total land area in Taihu Lake Basin, respectively. Therefore, the main change characteristic of the vegetation coverage in the Taihu Lake Basin is that the number of grid cells corresponding to higher and high vegetation coverage grades decreased and converted into the average grade, whereas the ratios of grid cells corresponding to low and lower vegetation coverage grades changed slightly.

4.3. Response Analysis of Vegetation Coverage on Urbanization

The impact of urbanization on vegetation coverage in Taihu Lake Basin was further analyzed from aspects of time and space. Figure 6 shows the scatter plot of MNDVI, fc and ALI in the entire basin and representative subzones from 1998 to 2010. In the entire basin, as shown in Figure 6 (a), the correlation coefficients of MNDVI and fc with contemporaneous ALI in the Taihu Lake Basin from 1998 to 2010 were -0.37 and -0.32, respectively. Apparently, the MNDVI and fc are decreased by the influence of urbanization on a watershed scale, but the negative correlation does not pass the p = 0.05 significance test.
Figure 6. Scatters for the maximum ten-day NDVI and the fraction ratio of vegetation coverage versus average lighting intensity during 1998~2010 for the whole Taihu Lake Basin and its sub-areas.

There was a significant negative correlation between the vegetation cover factor and the contemporaneous ALI in the Pudong, Puxi, WuChengXiYu, and Yangcheng-Dianmao districts from 1998 to 2010 (as shown in Figure 6 (b), only the Pudong area was listed but no other three subzones due to the limited space). The correlation coefficients between MNDVI and ALI of these four subzones were -0.87, -0.80, 0.63, and 0.71, respectively, and the correlation coefficients of fc and ALI of these four subzones were -0.84, -0.71, -0.68, and -0.57, respectively. Moreover, all these correlations passed the p = 0.05 significance test. This result showed that the vegetation coverage was considerably interfered by human activities and vegetation index and vegetation coverage continuously decreased in these areas, with growing economic and social development and progressing urbanization. According to the results of linear regression, for each increment of 0.10 in ALI, the mean MNDVI and fc decreased by about 0.04 and 0.05 in Pudong District, respectively. The corresponding values for Puxi, Yangcheng-Dianmao, and WuChengXiYu were 0.05 and 0.05, 0.03 and 0.02, and 0.02 and 0.02, respectively. There was also negative correlations between MNDVI, fc and ALI in Hangzhou-Jiaxing-Huzhou and Lake area, but not meet the significant level of p = 0.05 (as shown in Figure 6 (c), only the area of Hangzhou-Jiaxing-Huzhou was listed but not the Lake area). In contrast, the time correlation coefficients between MNDVI, fc and ALI in western Zhejiang and western Lake were positive but did not the significant level of p = 0.05 (as shown in Figure 6 (d)), only the area of western Zhejiang was listed but not the western Lake).

At the same time, the response of vegetation cover factor to the light index was analyzed at the grid scale of 1km × 1km. Figure 7 shows the distribution of grids with time correlation coefficient between MNDVI, fc and ALI from 1998 to 2010. It can be clearly seen that the vegetation cover factors in the different spatial location of the Taihu Lake Basin had significant differences in response to urbanization. According to the statistics, the number of grids with significant negative correlations between MNDVI, fc and light intensity were 7470 and 6875 (p = 0.05), respectively, accounting for the total land area in Taihu Lake Basin 22.1% and 20.3%, respectively. The comparison of Figure 7 (a) with Figure 3 shows that this type of grid units are mainly distributed in the surrounding areas of large
and medium-sized cities and along the main road, which is mainly attributed to large-scale land development and other human activities in the urbanization process. This result also shows that the overall response trend of vegetation coverage to the urbanization of the Taihu Lake Basin is that the higher degree of urbanization and intensity of human activities result in a worse vegetation cover. It should also be noted that there are a few grids having positive correlations between the MNDVI, fc and the light intensity (which are 2249 and 1595 grids, accounting for 6.7% and 4.7% of the total land area, respectively). According to Figure 7 (b), such grids are mainly distributed in the western Zhejiang and Lake West areas, and some are located on the shore of Taihu Lake or Huangpu River. The former may be mainly due to rocky soil and water conservation, vegetation conservation, rehabilitation and other measures, whereas the latter may be attributed to the lands adjacent to the beach or artificial green space. This finding has been disclosed in the previous studies [13-14]. This indicates that although the vegetation coverage factor in the Taihu Lake Basin is mainly negatively correlated with the intensity of human activities in the process of urbanization, measures such as active ecological protection or restoration in the process of urbanization can significantly improve the quality of vegetation cover in some areas.

Figure 7. Distribution for the grids in which maximum ten-day NDVI is substantially correlated with lighting intensity in time during 1998~2010 within the Taihu Lake Basin

In this work, the spatial correlation between MNDVI and light intensity in Taihu Lake Basin from 1998 to 2010 was also analyzed. Figure 8 shows the spatial correlation coefficients between MNDVI and light intensity in the entire basin and each subzone. It can be seen from the graph that there was a significant negative correlation between MNDVI and DN in the Taihu Lake Basin, and the linear correlation coefficients between MNDVI and light intensity ranged from -0.71 to -0.64. This indicates that in general the spatial pattern of vegetation coverage in the Taihu Lake Basin is closely related to the spatial pattern of the urbanization level. In each year from 1998 to 2010, in general, the higher the degree of urbanization is, the poorer the growing state of the vegetation in the economically developed areas is. In contrast, and the relatively low degree of urbanization in the economically underdeveloped areas displayed a relatively better vegetation cover. Except for the lake area, there are significant negative correlations between the vegetation cover factor and the light intensity in each subzone. Among them, Puxi, WuChengXiyu, and Pudong District have highest negative correlations and followed by western Zhejiang, Hangzhou-Jiaxing-Huzhou, and Yangcheng-Dianmao. Therefore, the spatial correlation between vegetation cover factor and light intensity in Taihu Lake Basin is obviously different from the temporal correlation.
Conclusions

In this paper, DMSP/OLS nighttime light data were used to analyze the spatial and temporal evolution of urbanization in Taihu Lake Basin since the 1990s. Based on SPOT/NDVI data, the dynamic changes of vegetation coverage were identified with the annual maximum ten-day normalized vegetation NDVI index and the corresponding vegetation coverage rate. Based on these results, the spatial and temporal responses of vegetation cover factors to urbanization in Taihu Lake Basin from 1998 to 2010 were further elucidated. The main conclusions are as follows:

1. From 1992 to 2012, with increasing average nighttime light intensity index of the Taihu Lake Basin, the urban built-up area expanded significantly, and the urbanization process was accelerated substantially. In time series, the period after 2000 is the acceleration phase of urbanization. From the perspective of spatial, the built-up area has the characteristics of the outer circle expansion centered on Shanghai and other large cities and the linear expansion characteristics of corridors centered on main communication or rivers. Pudong, WuchengXiYu and Yangcheng-Dianmao exhibited a more rapid urbanization progress, whereas West Zhejiang, Lake West and Hangzhou-Jiaxing-Huzhou had a relatively slow urbanization.

2. In the whole basin scale, MNDVI and fc in 2010 were slightly lower than those in 1998, but there was no continued decline or class difference over more than 10 years. Among all subzones in the basin, MNDVI or fc of Puxi, Pudong, Yangcheng-Dianmao, and WuchengXiYu exhibited a sustained downward trend in 1998-2010 while and MNDVI or fc of West Zhejiang, Lake West and Hangzhou-Jiaxing-Huzhou hardly changed. At the grid scale, the main change of vegetation coverage in Taihu Lake Basin is that the grid units with high vegetation coverage converted into those with average vegetation coverage.

3. From 1998 to 2010, the spatial response of vegetation cover factor to the urbanization in Taihu Lake Basin had an obvious spatial heterogeneity. The grid area with MNDVI or fc having a significant negative correlation with the intensity of the light index accounted for more than 20% of the total land area, which were mainly distributed around the city and along the traffic arteries, leading to the continuous decline of fc in Pudong, Puxi, Yangcheng-Dianmao, and WuchengXiYu. However, there was also a positive correlation between the MNDVI or fc with the intensity of the light index in a few grid cells located in the riverside shoreline of the western Zhejiang, Lake west and other subzones, which is mainly attributed to soil and water conservation, vegetation restoration or artificial greening, and so on.
From the perspective of spatial, the vegetation coverage pattern of Taihu Lake Basin had a close response to the pattern of urbanization. The global spatial correlation coefficient of MNDVI or fc and DN was between -0.71 and -0.64 on the 1km × 1km grid scale. In the same year, the higher degree of urbanization and the intensity of human activities are, the lower the growing status of vegetation is. In contrast, the relatively low degree of urbanization and the higher the intensity of human activities resulted in a relatively healthy vegetation growth. Except for the Lake area, there was a significant negative correlation between vegetation cover factor and light intensity in other subzones.

In general, the response of vegetation coverage dynamics to the urbanization in Taihu Lake Basin from 1998 to 2010 showed a certain complexity because of geographical conditions and differences in production activities, but adverse impacts of urban vegetation coverage in the eastern part of the basin were quite prominent. With the continuation of the urbanization process in the Taihu Lake Basin, the quality of vegetation coverage may continue to decline in more areas. Therefore, it is necessary to scientifically assess the ecological and hydrological risks of vegetation degradation in Taihu Lake Basin, and strengthen the scientific management and ecological restoration of land use.

Acknowledgments
The authors appreciate the financial support from the following projects: National Natural Science Foundation of China (51109136, 51479118); Ministry of Water Resources of the public welfare industry research special funds project (201501014); China Academy of Engineering major consulting research project (2015-ZD-07-02-01); National key research and development projects (2016YFC0400902).

References
[1] Tucker C J, Slayback D A, Pinzon J E, et al. Higher northern latitude normalized difference vegetation index and growing season trends from 1982 to 1999. International journal of biometeorology, 2001, 45(4): 184-190.
[2] Park H S, Sohn B J. Recent trends in changes of vegetation over East Asia coupled with temperature and rainfall variations. Journal of Geophysical Research: Atmospheres (1984–2012), 2010, 115(D14).
[3] Krishnaswamy J, John R, Joseph S. Consistent response of vegetation dynamics to recent climate change in tropical mountain regions. Global change biology, 2014, 20(1): 203-215.
[4] Pettorelli N, Vik J O, Mysterud A, et al. Using the satellite-derived NDVI to assess ecological responses to environmental change. Trends in ecology & evolution, 2005, 20(9): 503-510.
[5] Piao S, Mohammat A, Fang J, et al. NDVI-based increase in growth of temperate grasslands and its responses to climate changes in China. Global Environmental Change, 2006, 16(4): 340-348.
[6] Chen X, Wang H. Spatial and Temporal Variations of Vegetation Belts and Vegetation Cover Degrees in Inner Mongolia from 1982 to 2003. Acta Geographica Sinica, 2009, 1: 010. (in Chinese)
[7] Chen F, Shen Y, Hu Q, et al. Responses of NDVI to climate change in the Hai Basin. Journal of Remote Sensing, 2011, 15(2): 401-414. (in Chinese)
[8] Tian T, Li S, Chen, M, et al. Analysis on vegetation index's long time series dynamics of Yalong River basin. Journal of Hydroelectric Engineering, 2012, 31(2):159-164. (in Chinese)
[9] He C, Dong Z, Shi J, et al. Distributed simulation of hydrological response to water and soil conservation measures. Advances in Water Science, 2009, 20(4): 584-589. (in Chinese)
[10] Qi S, Li G, Wang C. Study on Monitoring Drought in China with MODIS Product. Advances in Water Science, 2005, 16(1): 56-61. (in Chinese)
[11] Ge X, Xue B, Wan L, et al. Modelling of lagging response of NDVI in Ejina Oasis to moff in the lower reaches of Heihe River. Scientia Geographica Sinica, 2009, 29(6): 900-904. (in Chinese)
[12] Shao W. Study on the interaction between vegetation and hydrological cycle in the non-humid regions of China. Beijing, Tsinghua University. (in Chinese)

[13] Liu H, Hu H, Hu H, et al. Applicability of logistic model for phenology detection based on remote sensing data. Journal of Hydroelectric Engineering, 2015, 34(6):88-94. (in Chinese)

[14] Wenjie W, Wenming S, Xiaoman L. Research on the relation of the urbanization and urban heat island effect changes in Beijing based on remote sensing. Research of Environmental Sciences, 2006, 19(2): 44-48. (in Chinese)

[15] Han G F, Xu J H. Spatio-temporal correlation between urbanization and vegetation vigor in the Delta of Yangtze River. Ecol Sci, 2008, 27(1): 1-5. (in Chinese)

[16] Li X, Ren Z, Zhang C. Spatial-temporal variations of vegetation cover in Chongqing city (1999-2010): impacts of climate factors and human activities. Scientia Geographica Sinica, 2013, 33(11): 1390-1394. (in Chinese)

[17] Wang X. Urban expansion in China over the past 30 years detected using DMSP/OLS nighttime light data. Nanjing University, 2013. (in Chinese)

[18] Yang M, Wang S, Zhou Y, et al. Review on Applications of DMSP/OLS Night-time Emissions Data. Remote Sensing Technology and Application, 2011, 26(1): 45-51.

[19] Liu Z, He C, Zhang Q, et al. Extracting the dynamics of urban expansion in China using DMSP-OLS nighttime light data from 1992 to 2008. Landscape and Urban Planning, 2012, 106(1): 62-72.

[20] Cao L, Li P, Zhang L. Urban Population Estimation Based on The DMSP/OLS Night-time Satellite Data—A Case of Hubei Province. Remote Sensing Information, 2009, 1: 83-87. (in Chinese)

[21] Ji D, Zhang H, Shen W, et al. The response relationship between underlying surface changing and climate change in the taihu Basin. Journal of Natural Resources, 2013(1):51-62. (in Chinese)