Postprint: Differential Analysis of NDVI Variation Trends Across Different Slope Gradients in the Taihang Mountains

Authors: Li Wei, Tan Minghong

Date: 2017-11-09T00:00:00+00:00

Abstract

Slope in mountainous areas has significant impacts on soil erosion and vegetation growth. Analyzing the differences in NDVI variation trends across different slopes helps understand vegetation responses to various slopes and deepens the comprehension of influencing mechanisms of vegetation change. Based on MODIS data and DEM data, this study employs the growing season mean NDVI as the characteristic indicator, uses pixel-based trend analysis method and slope-based regression analysis method to analyze vegetation changes in the Taihang Mountain region from 2000 to 2015, and conducts a systematic analysis of the relationship between vegetation change trends and slope. Simultaneously, this study adopts the land use transfer matrix to analyze the area and direction of land type conversion across different slopes between 2000 and 2010, and explores the influence of land use change on vegetation variation across different slopes. The results show that: (1) During the study period, vegetation in the Taihang Mountain region experienced overall improvement, with vegetation improvement areas accounting for 93.5% of the total region area. (2) The NDVI increasing trend was most pronounced in the central and western regions (within Shanxi Province), while decreasing trends occurred in some mid-low altitude areas in the eastern and southern parts, mainly concentrated in the low mountain and hilly areas adjacent to the North China Plain in the east. (3) Areas with larger slopes exhibited higher growing season mean NDVI values. (4) The relationship between vegetation change trend (y) and slope (x) is nonlinear and can be expressed by a quadratic function: y= 0.311x2+8.098x+28.027. (5) When slope ranges from 7° to 15°, the vegetation improvement trend is most significant, followed by slopes of 15° to 20°. The mean NDVI change trend for slopes of 7° to 20° is 15.8% and 29.8% higher than that of >20° areas and 7° areas, respectively. (6) From 2000 to 2010, in low (0°-7°), medium (7°-20°), and high slope (>20°) areas, the total area of cropland, forestland, and grassland all decreased, primarily converting to construction land and water bodies. However, NDVI change trends in all three slope ranges were positive, with the most pronounced increase in medium slope areas, followed by high slope areas and low slope areas. (7) NDVI change trends are less affected by land use type and area, and are primarily influenced by the combined effects of intrinsic biochemical conditions, natural environmental conditions, and human disturbance (land use intensity, etc.). Based on these results, this study holds significant importance for the rational utilization of land resources and ecological environment protection across different slopes in the Taihang Mountain region.

Full Text

Preamble

Chinese Journal of Eco-Agriculture, Apr. 2017, Vol. 25, No. 4: 509–519
Collaborative Journal of ChinaXiv
DOI: 10.13930/j.cnki.cjea.160781

Li W, Tan M H. NDVI variation tendency under different slopes in Taihang Mountain[J]. *Chinese Journal of Eco-Agriculture*, 2017, 25(4): 509–519

NDVI Variation Tendency Under Different Slopes in Taihang Mountain*

LI Wei[1,2], TAN Minghong[1,3]
(1. Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences / Key Laboratory of Land Surface Pattern and Simulation, Beijing 100101, China;
2. College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100190, China;
3. International College, University of Chinese Academy of Sciences, Beijing 100190, China)

Abstract: Slope gradient in mountainous areas critically influences soil erosion and vegetation growth, serving as a key determinant of site conditions for vegetation. Analyzing the variation tendency of NDVI (Normalized Difference Vegetation Index) across different slope gradients in the Taihang Mountains not only helps understand how vegetation responds to slope gradients under long-term adaptation but also deepens comprehension of vegetation change mechanisms. Based on MODIS data and DEM data, this study employed pixel-scale trend analysis and slope-related regression analysis to investigate vegetation changes in the Taihang Mountain region from 2000 to 2015, using the mean NDVI during the growing season as the primary indicator. After selecting approximately 1,000 typical samples across the study area, we explored the relationship between vegetation greenness changes and slope gradient through regression analysis. Meanwhile, land use transition matrices were used to analyze the transfer area and direction of different land use types across various slope gradients between 2000 and 2010, examining how land use changes affected vegetation dynamics under different slopes. The results showed that: (1) Vegetation in the Taihang Mountains generally improved during the study period, with vegetation-improving areas accounting for 93.5% of the total study area. (2) The most significant NDVI increase occurred in the central and western regions (especially within Shanxi Province), while decreasing trends appeared in patches of medium and lower elevations in the eastern and southern parts, mainly concentrated in the eastern hilly areas adjacent to the North China Plain. (3) Areas with steeper slopes exhibited higher average growing-season NDVI values. (4) The relationship between vegetation change trend (y) and slope (x) was non-linear and best represented by a quadratic function: $y = -0.311x^2 + 8.098x + 28.027$. (5) The most pronounced vegetation improvement occurred on slopes of 7°–15°, followed by 15°–20°. The mean NDVI change trend in the 7°–20° slope range was 15.8% and 29.8% higher than that in slopes >20° and 7°, respectively. (6) From 2000 to 2010, the total area of arable land, forestland, and grassland decreased across low (0°–7°), medium (7°–20°), and high slope (>20°) zones, primarily converting to construction land and water bodies. However, NDVI change trends were positive across all three slope ranges, with the most obvious increase in medium-slope areas, followed by high-slope and low-slope areas. (7) NDVI change trends were less affected by land use type and area, being mainly influenced by the combined effects of biochemical conditions, natural environmental factors, and human disturbance (such as land use intensity). These results are significant for the rational utilization of land resources and ecological environmental protection across different slopes in the Taihang Mountains.

Keywords: Taihang Mountain; slope; vegetation; NDVI; land use; trend analysis

Introduction

Mountainous areas constitute approximately 67% of China' s total land area, characterized by complex ecological environments. Environmental changes and ecological carrying capacity in mountainous regions have long been important research directions in geography and ecology. Mountain vegetation serves as a critical link between atmosphere, soil, and water, and represents an important indicator of mountain ecological conditions and global environmental change. The Normalized Difference Vegetation Index (NDVI) has become one of the primary indices for characterizing vegetation conditions in recent years. Previous studies have utilized this index to analyze vegetation cover characteristics, inter-annual variation patterns, and spatial variability. Numerous studies have shown that global vegetation has exhibited an improving trend in recent years, particularly significant in mid-to-high latitudes of the Northern Hemisphere. Piao et al. found that China' s NDVI showed a clear increasing trend during the 1980s and 1990s using NOAA-AVHRR data. Liu and Gong reported that China' s surface vegetation greenness was comprehensively improving and desertification was decreasing from 2000–2010 based on MODIS data. Additionally, influencing factors of NDVI changes have attracted increasing scholarly attention, with both domestic and international researchers conducting in-depth analyses of climatic factors (temperature and precipitation) using MODIS and AVHRR data sources. Thavorntam et al. found that temperature was an important factor affecting vegetation productivity in evergreen broadleaf forests in northeastern Thailand. More recently, scholars have begun focusing on human activity impacts, considering them decisive in many regions. In summary, existing research has analyzed spatiotemporal vegetation cover changes and emphasized climate conditions and human activities as primary influences.

However, analyses of natural factors have concentrated mainly on temperature and precipitation, while macro-scale analysis specifically examining slope effects remains relatively scarce. In mountainous areas, slope gradient plays a crucial role in soil erosion and determines vegetation site conditions (such as soil moisture and thickness), significantly affecting vegetation growth. Existing slope-related research has primarily focused on differences in vegetation types or landscape patterns under various topographic conditions (elevation, slope, and aspect), and on how different slope criteria affect farmland abandonment and reforestation. Xu et al. studied topographic distribution differences of vegetation types in the Xiaohegou Nature Reserve in Sichuan, finding that vegetation structure changed correspondingly as slope gradient increased. Tang et al. demonstrated the maximum slope for reforestation in the loess hilly region through field observations and rainfall simulation experiments. Ding et al. examined how slope gradient affected vegetation recovery on abandoned land in Hainan Province by measuring community composition and structure in secondary forests on hillslopes. Jin et al. found that slope significantly influenced natural vegetation succession on abandoned farmland in the Loess Plateau. These studies have revealed slope' s role in vegetation recovery to some extent, but simple slope classification comparisons cannot effectively reveal the relationship between slope and vegetation change trends. Furthermore, while some scholars have touched upon slope effects when discussing vegetation change factors, they have not systematically analyzed slope as a primary factor. Therefore, current analysis of vegetation change differences across slope gradients remains incomplete.

The Taihang Mountains, located in the transitional zone between China' s Loess Plateau and North China Plain, serve as an ecological barrier for the Beijing-Tianjin-Hebei metropolitan area and the North China Plain, and represent one of China' s regions with severe soil erosion. As a typical rocky mountainous area in northern China, it features low soil moisture content, thin soil layers, and acute human-land conflicts. Over the long term, slope gradient largely determines vegetation growth conditions and recovery capacity. Investigating how slope affects vegetation change mechanisms is crucial for alleviating human-land conflicts in the Taihang Mountains. However, how slope influences vegetation spatial distribution during long-term adaptation remains unclear, and few studies have separately analyzed differences in vegetation condition changes under various slope conditions. This study addresses this topic by employing trend line analysis to examine vegetation changes in the Taihang Mountains from

2000–2015 and macroscopically analyzing vegetation change conditions across different slopes. Additionally, regression analysis was used to propose a mathematical relationship between vegetation change and slope gradient. Combined with land use transition matrix analysis, this research examines how land use changes affected vegetation under different slopes. These findings provide reference for future ecological construction and rational land resource utilization in the Taihang Mountains, helping to understand vegetation adaptation to slope gradients and the mechanisms underlying vegetation change.

1.1 Study Area Overview

The Taihang Mountains are located between 34°71 –40°34 N and 110°60 – 115°62 E, covering approximately 127,000 km² as a transitional zone and geographical boundary between the Loess Plateau and North China Plain. The average elevation ranges from 1,500–2,000 m, with the highest peak being Xiaowutai Mountain at 3,099 m. The region features four distinct seasons and a warm temperate semi-humid continental monsoon climate. Vertical vegetation differentiation is pronounced, with natural vegetation types including evergreen broadleaf forest, coniferous-broadleaf mixed forest, coniferous forest, shrubland, shrub-grassland, and alpine meadow. The Taihang Mountains span four provincial-level administrative regions: Henan, Hebei, Shanxi, and Beijing, as shown in Figure 1 [Figure 1: see original paper].

1.2 Data Sources and Preprocessing

This study utilized three data types: NDVI data, DEM data, and land use data. NDVI data were derived from the MOD13Q1 vegetation index product provided by NASA' s LAADS Web platform (https://ladsweb.nascom.nasa.gov/data/search.html), with a spatial resolution of 250 m, temporal resolution of 16 days, and time span from 2000–2015. The NDVI product was processed from Terra satellite Level-3 MOD13Q data through mosaicking, projection conversion, and masking, with monthly NDVI values obtained using the maximum value composition method. April–October represents the plant growing season in the Taihang Mountains; this study calculated the annual mean NDVI during the growing season using monthly NDVI values from April–October, resulting in 16 annual growing-season NDVI mean images for 2000–2015. DEM data were SRTMDEM data for China, obtained from the Geospatial Data Cloud platform of the Computer Network Information Center of the Chinese Academy of Sciences (http://www.gscloud.cn), with a spatial resolution of 90 m. Using ArcGIS Spatial Analyst, a slope distribution map for the Taihang Mountains was calculated with slope units in degrees. Land use data for 2000 and 2010 were obtained from the 5-year interval terrestrial ecosystem spatial distribution dataset (1990–2010) published by the Global Change Research Data Publishing and Repository System, with a spatial resolution of 100 m.

2.1 Sample Selection and Slope Classification

Within the Taihang Mountains, 1,000 sample points were randomly and uniformly selected. To reduce random error and spatial variation effects, circular sample areas with a 3 km radius were created (Figure 2 [Figure 2: see original paper]), ensuring no overlap between sample areas. Samples falling within construction land were removed, resulting in 921 samples included in the regression model. NDVI change trends and mean slope conditions were statistically analyzed for each sample area to establish a regression model examining the relationship between slope and vegetation change trends. To understand NDVI changes under different slopes, this study referenced the slope classification standard of Zhang et al. and adapted it to the Taihang Mountains context, dividing slopes into seven grades: 0°-3°, 3°-7°, 7°-10°, 10°-15°, 15°-20°, 20°-25°, and >25°.

2.2 Trend Line Analysis

This study analyzed NDVI change trends during the study period using regression slope, with time (n) as the independent variable and NDVI values regressed pixel-by-pixel. The regression equation slope indicates the variable' s change trend: a negative slope suggests decreasing vegetation, while a positive slope indicates increasing vegetation. The expression is:

$$y_{NDVI} = \frac{\sum_{j=1}^{n}(x_j - \bar{x})(j - \bar{j})}{\sum_{j=1}^{n}(j - \bar{j})^2}$$

where y_{NDVI} represents the NDVI change trend (i.e., the slope of the interannual variation curve), n is the number of study years (16), and x_j is the growing-season NDVI value in year j. Using ArcGIS Map Algebra raster calculator tools, vegetation change trend data for 2000–2015 were calculated and summarized.

2.3 NDVI Change Trend and Slope Regression Analysis

This study statistically analyzed NDVI change trends across samples in the Taihang Mountains using ArcGIS zonal statistics as table to compile NDVI change trend and slope data by sample unit, establishing a regression model between NDVI change trends and slope to analyze their relationship.

2.4 Land Use Transition Matrix

Land use transition matrices were used to analyze land use changes across different slopes in the Taihang Mountains and reveal the impact of land use changes on vegetation conditions. The transition matrix reflects the dynamic conversion process between land use types at the beginning and end of the study period, including conversion areas and directions. Its mathematical expression is:

$$A = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1n} \\ A_{21} & A_{22} & \cdots & A_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ A_{n1} & A_{n2} & \cdots & A_{nn} \end{bmatrix}$$

where A represents area, n is the number of land use types, and i, j represent land use types at the beginning and end of the study period, respectively. A_{12} indicates the area converted from type 1 to type 2, and A_{53} represents the area converted from type 5 to type 3.

3.1 Interannual Variation Characteristics of NDVI by Slope

To reveal slope effects on NDVI changes, mean NDVI values were calculated by slope grade to analyze interannual variation, as shown in Figure 3a [Figure 3: see original paper]. Overall, NDVI values across all slope grades showed upward trends during the study period, with four distinct peak growth periods: 2001–2004, 2006–2008, 2011–2012, and 2013–2015. Mean annual NDVI values also differed across slopes, with smaller slopes generally showing lower NDVI values. Figure 3b shows the slope values of fitted curves for interannual NDVI variation by slope grade. Generally, NDVI across all slopes exhibited increasing trends during the study period, indicating vegetation recovery. NDVI change trends first increased then decreased with slope gradient, with the most obvious vegetation improvement occurring on slopes of 7°–20° (Figure 3b).

3.2 Spatial Distribution of NDVI Change Trends

The 16-year mean growing-season NDVI for 2000–2015 was calculated pixel-by-pixel, and the interannual change slope for each pixel was derived using Equation (1) to represent NDVI change trends (Figure 4 [Figure 4: see original paper]). The results show that 93.5% of the study area exhibited increasing NDVI (green areas in the figure), indicating overall vegetation improvement, particularly pronounced in the central and western regions (within Shanxi Province). Decreasing trends (red areas) appeared in medium and lower elevation zones in the eastern and southern parts, mainly concentrated in the eastern hilly areas adjacent to the North China Plain.

3.3.1 Regression Analysis

The scatter plot of NDVI change trends versus slope for 921 samples (Figure 5 [Figure 5: see original paper]) reveals a quadratic function relationship. Using the 2000–2015 NDVI change trend as the dependent variable and slope as the independent variable, a regression model was established. The model F-value was 212.820, significant at the 0.001 level. The regression model revealed the relationship between slope and NDVI change trend, with both slope and its quadratic term significantly affecting NDVI change trends at the 0.001 level. The curve' s goodness-of-fit was 0.315. The relationship is expressed as:

$$y = -0.311x^2 + 8.098x + 28.027$$

where y is the NDVI change trend and x is the slope gradient. NDVI increase trends reached maximum values at approximately 13° slope. When slope was less than 13°, NDVI change trends increased with slope, indicating that vegetation improvement trends gradually increased with slope in this range. When slope exceeded 13°, vegetation improvement trends began to weaken with increasing slope.

3.3.2 Differences in NDVI Change Trends Across Slope Grades

To differentiate NDVI change trends across slope grades, statistics were compiled by slope grade (Table 1). Based on mean values across slope ranges, the most pronounced NDVI change trends occurred on slopes of 7°–15°, followed by 15°–20°. Areas with slopes exceeding 20° and below 7° showed relatively smaller NDVI change trends. Specifically, the mean NDVI change trend in the 7°–20° slope range was 15.8% and 29.8% higher than that in slopes >20° and 7°, respectively. Regarding standard deviation, values decreased with increasing slope, indicating that NDVI change trend distribution became more concentrated with steeper slopes. In contrast, lower slope areas exhibited greater NDVI change trend fluctuations because, while gentle slopes favor vegetation growth, they also experience more frequent human activities that significantly impact vegetation change trends.

3.4 Land Use Change and Its Impact on NDVI Across Different Slopes

Land use is the most direct factor affecting vegetation change. This study briefly analyzed causes of vegetation changes across different slopes from a land use change perspective. Since 15°–20° represents the critical slope for China' s Grain-for-Green Program, and considering the differences in NDVI change trends across slopes shown in Table 1, this study merged the classified slope ranges into three zones for land use change analysis (Table 2 and Table 3): low slope (0°–7°), medium slope (7°–20°), and high slope (>20°).

Table 2 shows NDVI change trends and land use type areas and changes across slope grades from 2000–2010. Overall, NDVI across all slopes showed increasing trends, most pronounced in medium-slope areas. Arable land area decreased across all slope ranges, grassland area decreased slightly, and unused land and other land types decreased minimally. Forestland, water bodies, and construction land areas increased.

To explore conversion areas and directions of land use types, land use transition matrices were used to analyze changes from 2000 to 2010 across slope grades. Table 3 shows that in low-slope areas, decreased arable land was primarily converted to construction land, with 73.74% converting to construction land, 16.39% to water bodies, 5.99% to forestland, and 3.89% to grassland. In medium-slope areas, decreased arable land converted 41.41% to grassland, 26.87% to water bodies, 19.86% to construction land, and 11.86% to forestland. In high-slope areas, decreased arable land converted 43.45% to grassland, 25.40% to water bodies, and 18.85% to forestland.

Due to irrigated agriculture development, crops grew well during the growing season. Therefore, land use types reflecting vegetation conditions included arable land, forestland, and grassland. In low-slope areas (<7°), 转出 areas of arable land, forestland, and grassland were 73,799 hm^2, 3,464 hm^2, and 8,557 hm^2, respectively, while 转入 areas were 7,118 hm^2, 6,793 hm^2, and 3,393 hm^2, respectively, resulting in a total vegetation area decrease of 68,516 hm^2. Arable land and grassland decreased significantly, while forestland, construction land, and water bodies increased substantially. In medium-slope areas (7°–20°), 转出 areas were 10,428 hm^2, 2,317 hm^2, and 8,579 hm^2, respectively, with 转入 areas of 114 hm^2, 3,190 hm^2, and 4,875 hm^2, respectively, resulting in a vegetation area decrease of 13,145 hm^2. Similar to low-slope areas, arable land and grassland decreased while forestland, construction land, and water bodies increased, though change magnitudes were much smaller. In high-slope areas (>20°), 转出 areas were 1,236 hm^2, 1,363 hm^2, and 2,368 hm^2, respectively, with 转入 areas of 14 hm^2, 787 hm^2, and 812 hm^2, respectively, resulting in a vegetation area decrease of 3,354 hm^2. All three vegetation types decreased to varying degrees, mainly converting to construction land and water bodies. Additionally, unused land and other land types had small transfer areas and low transfer rates across all three slope ranges, primarily converting to construction land and grassland.

Overall, the total area of arable land, forestland, and grassland decreased across all three slope ranges, mainly flowing to construction land and water bodies. However, Table 2 shows that NDVI change trends were positive across low, medium, and high slope ranges, with the most obvious increase in medium-slope areas, followed by high-slope and low-slope areas. This indicates that NDVI change trends were not significantly affected by land use type and area changes. Vegetation changes were primarily influenced by the combined effects of biochemical conditions, natural environmental factors, and human disturbance.

4 Conclusions and Discussion

Based on MODIS data, this study analyzed vegetation index (NDVI) changes across different slopes in the Taihang Mountains. The findings reveal that mean annual NDVI values increased with slope gradient, with better vegetation conditions on steeper slopes. Slope is an important factor affecting soil erosion and directly influences water distribution and accumulation. Different slopes produce varying degrees of soil erosion, differentially impacting vegetation growth. Wang et al. found that soil erosion on arable land with slopes >20° was relatively severe. Since the 21st century, China' s Grain-for-Green Program has explicitly prohibited cultivation on slopes >25°, significantly reducing soil erosion and restoring vegetation conditions in this range. Tang et al. demonstrated that slopes >25° should be prohibited for cultivation in the loess hilly region, with critical slopes ideally controlled below 15°–20°. Therefore, high-slope areas are dominated by natural vegetation and reforestation lands, with reduced soil erosion and less human disturbance, resulting in higher NDVI values compared to gentle-slope areas.

Through trend line analysis, this study found that NDVI across all slope ranges in the Taihang Mountains showed increasing trends from 2000–2015, covering 93.5% of the region. Zhang et al. indicated that post-Grain-for-Green, farmland abandonment mainly occurred on slopes >8°, concentrated in areas >15°. Differently, since arable land in the Taihang Mountains is primarily distributed in areas <15°, farmland abandonment concentrated in medium and low slope ranges. This study' s results show that vegetation improvement was most significant in medium-slope areas from 2000–2015. On one hand, apart from reforestation, farmland abandonment can promote vegetation recovery. Since 2000, large-scale rural labor outmigration has sharply reduced the agricultural workforce in mountainous areas, with severe abandonment on steep, low-productivity farmland, leading to obvious vegetation improvement through natural recovery. On the other hand, population decreased in the 7°–20° range, reducing human disturbance. The Taihang Mountains' elevation map shows that higher altitude areas generally have steeper slopes. Population outmigration occurred mainly in high-altitude, steep-slope areas, while population increased in low-altitude, gentle-slope river valleys and low-lying areas. In summary, the direct effects of reforestation and abandonment, combined with indirect effects of reduced human activity intensity due to population outmigration, made vegetation recovery most significant in medium-slope areas with concentrated farmland and population distribution.

Furthermore, a quadratic function relationship existed between slope and NDVI change trends during the study period. Using 13° as the threshold, vegetation improvement trends became more obvious with increasing slope when slope was <13°, reaching maximum at 13°, then weakening with further slope increase. Similar patterns have been qualitatively described but lacked mathematical verification.

From the land use transition matrix perspective, land use type and area changes had minimal impact on vegetation change trends. During the first decade of the 21st century, arable land and grassland decreased while forestland, water bodies, and construction land increased. Decreased arable land in low-slope areas mainly converted to construction land, while in medium and high-slope areas it mainly converted to forestland and grassland. NDVI change trends across the three slope grades followed the pattern: medium slope > high slope > low slope, indicating that gentle-slope areas experienced the greatest urbanization impact and relatively weaker vegetation improvement. In terms of total vegetation area (arable land, forestland, and grassland), all three slope ranges showed decreases, with low-slope reductions being 5.2 and 20.4 times those of medium and high-slope areas, respectively. This demonstrates that while land use type and area changes had some influence, they did not play a significant role. On one hand, although vegetation area decreased, the reduction represented a small proportion of total vegetation area (Table 2), with minimal impact at the regional scale. On the other hand, vegetation changes were more strongly influenced by land use intensity, such as reduced grazing intensity and logging, which improved forestland and grassland quality.

Overall, vegetation changes result from the combined effects of vegetation biochemical characteristics, natural environmental conditions (temperature, precipitation, slope, etc.), and human disturbance (land use intensity, population pressure, etc.). Fang et al. found that temperature rise, increased summer precipitation, and intensified agricultural activities may be the main drivers of NDVI increase. Cai et al. analyzed the significance of climate and population factors in vegetation changes. These studies indicate that vegetation change is influenced by complex and diverse factors, representing a comprehensive effect. For example, improved living standards and energy structures in mountainous areas reduced fuelwood demand, while increased irrigation area and improved climate conditions enhanced farmland quality. These aspects require further research.

This study focused on vegetation condition changes across different slopes in the Taihang Mountains, mathematically demonstrating vegetation change trends on different slopes and clarifying their relationship. While previous research on natural influencing factors of vegetation change has focused mainly on temperature and precipitation, this study complements that work by specifically analyzing slope effects, which is crucial for understanding vegetation change factors. However, this study did not address the mechanisms through which slope influences vegetation change. Future research should strengthen investigation into the internal mechanisms of slope effects on vegetation.

References

[1] Liu Z J, Yu X X, Li L, et al. Vulnerability assessment of eco-environment in Yimeng Mountainous area of Shandong Province based on SRP conceptual model[J]. *Chinese Journal of Applied Ecology*, 2011, 22(8): 2084–2090

[2] Wang M W, Xu H. Research review of karst mountain eco-environmental geological problems and sustainable development in Yunnan[J]. *Ecological Economy*, 2014, 30(9): 185–187

[3] Sun H Y, Wang C Y, Niu Z, et al. Analysis of the vegetation cover change and the relationship between NDVI and environmental factors by using NOAA time series data[J]. *Journal of Remote Sensing*, 1998, 2(3): 204–210

[4] Xin Z B, Xu J X, Zheng W. Impact of climate change and human activities

in vegetation cover change on the Loess Plateau[J]. *Science in China Series D: Earth Sciences*, 2007, 37(11): 1504–1514

[5] Wei Z F, Wang D G, Zhang C, et al. Response of vegetation cover to climate change and human activities in Northwest China during 1999–2010[J]. *Journal of Desert Research*, 2014, 34(6): 1665–1670

[6] Wang Z H, Li S M, Liu L Y, et al. Hierarchical land cover classification based on MODIS NDVI time-series[J]. *Remote Sensing Technology and Application*, 2013, 28(5): 910–919

[7] Wang H S, Huang J F. Study on characteristics of land cover change using MODIS NDVI time series[J]. *Journal of Zhejiang University: Agriculture & Life Science*, 2009, 35(1): 105–110

[8] Li Y C, Chen J, Gong P, et al. Study on land cover change detection method based on NDVI time series datasets: Change detection indexes design[J]. *Journal of Basic Science and Engineering*, 2005, 13(3): 44–58

[9] Zheng D. Issues on land degradation and eco-reconstruction in northeast arid region of China[J]. *Chinese Journal of Nature*, 2007, 29(1): 7–11

[10] Li X B, Chen Y H, Zhang Y X, et al. Impact of climate change on desert steppe in northern China[J]. *Advance in Earth Sciences*, 2002, 17(2): 254–261

[11] Chen X Q, Wang H. Spatial and temporal variations of vegetation belts and vegetation cover degrees in Inner Mongolia from 1982 to 2003[J]. *Acta Geographica Sinica*, 2009, 64(1): 84–94

[12] Zhang H B, Tang H J, Yang G X, et al. Changes of spatial-temporal characteristics based on MODIS NDVI data in Inner Mongolia grassland from 2000 to 2008[J]. *Transactions of the CSAE*, 2009, 25(9): 168–175

[13] Wang J, Li B L, Yu W L. Analysis of vegetation trend and their causes during recent 30 years in Inner Mongolia Autonomous Region[J]. *Journal of Arid Land Resources and Environment*, 2012, 26(2): 132–138

[14] Myneni R B, Tucker C J, Asrar G, et al. Inter-annual variations in satellite-sensed vegetation index data from 1981 to 1991[J]. *Journal of Geophysical Research: Atmospheres*, 1998, 103(D6): 6145–6160

[15] Ramakrishna R, Nemani C D, Keeling H H, et al. Climate-driven increases in global terrestrial net primary production from 1982 to 1999[J]. *Science*, 2003, 300: 1560–1563

[16] Piao S L, Fang J Y. Seasonal changes in vegetation activity in response to climate changes in China between 1982 and 1999[J]. *Acta Geographica Sinica*, 2003, 58(1): 119–125

[17] Piao S L, Fang J Y. Dynamic vegetation cover change over the last 18 years in China[J]. *Quaternary Science*, 2001, 21(4): 294–302

[18] Fang J Y, Piao S L, He J S, et al. Vegetation activities are enhancing in the past 20 years[J]. *Science in China Series C: Life Sciences*, 2003, 33(6): 554–565

[19] Liu S, Gong P. Change of surface cover greenness in China between 2000 and 2010[J]. *China Science Bulletin*, 2012, 57(16): 1423–1434

[20] Mao D H, Wang Z M, Luo L, et al. Correlation analysis between NDVI and climate in Northeast China based on AVHRR and GIMMS data sources[J]. *Remote Sensing Technology and Application*, 2012, 27(1): 77–85

[21] Gu Z H, Chen J, Shi P J, et al. Correlation analysis of NDVI difference series and climate variables in Xilingole Steppe from 1983 to 1999[J]. *Acta Phytoecologica Sinica*, 2005, 29(5): 753–765

[22] Qi S H, Wang C Y, Niu Z, et al. SVI and VCI based on NDVI time-series dataset used to monitor vegetation growth status response to climate variables[J]. *Progress in Geography*, 2004, 23(3): 91–99

[23] Thavorntam W, Tantemsapya N. Vegetation greenness modeling in response to climate change for Northeast Thailand[J]. *Journal of Geographical Sciences*, 2013, 23(6): 1052–1068

[24] Lü Y H, Zhang L W, Feng X M, et al. Recent ecological transitions in China: Greening, browning, and influential factors[J]. *Science Reports*, 2015, 5: 1–8

[25] Lu Y, Fu B, Wei W, et al. Major ecosystems in China: Dynamics and challenges for sustainable management[J]. *Environmental Management*, 2011, 48: 13–27

[26] Li A, Wu J G, Huang J H. Distinguishing between human-induced and climate-driven vegetation changes: A critical application of RESTREND in inner Mongolia[J]. *Landscape Ecology*, 2012, 27: 969–982

[27] Cai H Y, Yang X H, Wang K J, et al. Is forest restoration in the Southwest China karst promoted mainly by climate change or human-induced factors?[J]. *Remote Sensing*, 2014, 6: 9895–9910

[28] Wang Y F, Li M S, Lu Y D, et al. Analysis of definition of slope gradient criterion for farmland to forest[J]. *Scientific and Technical Information of Soil and Water Conservation*, 2004, 6(1): 25–27

[29] Xu X, Wu Y, Liao Y M. Topographic variation of vegetation types in Xiaohegou Nature Reserve of Sichuan Province[J]. *Acta Botanica Boreali-Occidentalia Sinica*, 2006, 26(3): 572–578

[30] Wang R, Pan W B. Topographic differences for vegetation types in Wuyishan National Nature Reserve, Fujian Province[J]. *Journal of Zhejiang Forestry College*, 2007, 24(6): 731–735

[31] Kong N N, Zeng H, Li S J. Study on the topographic variation pattern of vegetation distribution in Wolong Nature Reserve, Sichuan Province[J]. *Acta Scientiarum Naturalium Universitatis Pekinensis*, 2002, 38(4): 543–549

[32] Tang K L, Zhang K L, Lei A L. Analysis of the maximum slope for returning farmland to forest in loess hilly-gully region[J]. *Chinese Science Bulletin*, 1998, 43(2): 200-203

[33] Ding Y, Zang R G, Jiang Y X. Effect of hillslope gradient on vegetation recovery on abandoned land of shifting cultivation in Hanan Island, South China[J]. *Journal of Integrative Plant Biology*, 2006, 48(6): 642-653

[34] Jin L, Du X G, Hou F J, et al. Effects of hillside slopes on plant community succession of re-natural farmland in the Loess Plateau[J]. *Patacultural Science*, 2007, 24(7): 66-71

[35] Zha X, Tang K L. Study on comprehensive control model of small watershed eco-environment in water and wind crisscrossed erosion zone[J]. *Journal of Natural Resources*, 2000, 15(1): 97-100

[36] Liu H, Lyn B. Study on development and utilization of a microscale basin: A case study in the Niujiaohe River of Taihang Mountains[J]. *Geographic Research*, 2012, 31(6): 1050-1056

[37] Gu W M, Liu J T. Spatial analysis of hilly catchment based on digital drainage network extraction information[J]. *Journal of China Hydrology*, 2009, 29(4): 34-36

[38] Liu Y M. A study on ecological environment change and its driving force in mountain area —Taking Hebei Taihang Mountain for a case[D]. Shijiazhuang: Hebei Normal University, 2008

[39] Zhang X P, Li R, Yang Q K, et al. Study of land-use/farming converting change their slope gradient differentiation on the middle scale research site using remote sensing data[J]. *Chinese Agricultural Science Bulletin*, 2005, 21(8): 388-392

[40] Li S J, Sun Z G, Tan M H, et al. Effects of rural-urban migration on vegetation greenness in fragile areas: A case study of Inner Mongolia in China[J]. *Journal of Geographical Sciences*, 2016, 26(3): 313-324

[41] Qiao W F, Sheng Y H, Fang B, et al. Land use change information mining in highly urbanized area based on transfer matrix: A case study of Suzhou, Jiangsu Province[J]. *Geographical Research*, 2013, 32(8): 1497-1507

[42] Zhu H Y, Li X B. Discussion on the index method of regional land use change[J]. *Acta Geographica Sinica*, 2003, 58(5): 643-650

[43] Xu N, Zhang G L, Liu Z Y. Spatial-temporal variability of land use with terrain gradient in Taihang Mountain, Hebei Province[J]. *Chinese Journal of Eco-Agriculture*, 2013, 21(10): 1284-1292

[44] Ma Q X, He S L. To probe into the problems of arable land wasting and its quality declining in rural areas at present[J]. *Journal of China Agricultural Resources and Regional Planning*, 2002, 23(4): 22-24

[45] Zhang X F. Analysis of vegetation cover change and its influence factors in Bashang area[D]. Yantai: Ludong University, 2016

[46] Jiang Y, Zhang Y P, Yang Y G, et al. Impacts of grazing on the system coupling between vegetation and soil in the alpine and subalpine meadows of Wutai Mountain[J]. *Acta Ecologica Sinica*, 2010, 30(4): 837-846

Note: Figure translations are in progress. See original paper for figures.