Quantitative assessment of ecosystem vulnerability to climate change: methodology and application in China

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Abstract

Understanding how ecosystem vulnerability in response to climate change is generated and distributed is an important topic; however, quantitative assessments of the vulnerability process remain relatively rare. The Intergovernmental Panel on Climate Change (IPCC) regards ecosystem vulnerability as sensitivity or susceptibility to harm, lacking the capacity to cope and adapt. Through analysis of the concept of vulnerability, we propose a response-based quantitative method to assess ecosystem vulnerability, integrating the concepts of sensitivity and adaptability. This method was applied to assess ecosystem vulnerability in China from 1981 to 2050. The results indicated that vulnerability would develop in nearly 30% of the terrestrial ecosystems of China. Vulnerability would be severe in the grassland and desert ecosystems, distributed mainly in the Tianshan Mountain and the Inner Mongolia Plateau. As the effects of sensitivity and adaptability to temperature and precipitation differ, obvious regional differences exist between the ecosystem vulnerability zones in China. For example, the effects of climate warming would be severe in the northwest of the Loess Plateau, with the vulnerability caused mainly by high sensitivity to warming. However, the vulnerability in the southeastern part would be caused mainly by low adaptability to increasing precipitation. Compared with previous research, our method emphasizes the critical role of adaptability, which enhances the scientifcity and reasonableness of assessing ecosystem vulnerability, and enriches the methodology adopted under the IPCC framework. However, as we did not consider fully the autonomous adaptation mechanism in ecosystem vulnerability, this aspect should be combined with other factors in future study.

1. Introduction

Climate change is an essential external factor that causes internal variation in vulnerability, so the ecosystem vulnerability to climate change is an important aspect in research on global change, attracting extensive attention from the international community (Füssel and Klein 2006, Lindner et al 2010, IPCC 2014). The fourth assessment report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) proposes a carefully articulated and precise definition: ‘Vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity’ (IPCC 2007). The IPCC emphasizes the importance of vulnerability in response to climate change and is committed to developing a widely accepted, precise, and operational framework for vulnerability. Various concepts and components relevant to the meaning of vulnerability were clarified in the IPCC AR5, adding that it ‘embraces a variety of concepts and elements
including sensitivity or susceptibility to harm and lack of capacity to cope and adapt’ (IPCC 2014). Adger (2006) and Dlamini (2011) contend that scientific assessment of the effects of climate change on ecosystems and the identification of ecosystem vulnerability form the basis of coping with climate change.

Currently, studies on ecosystem vulnerability are based mainly on the comprehensive index system, threshold, and process trend, which focus on the conceptual framework of the ecosystem vulnerability assessment model (Cutter and Finch 2008, Gonzalez et al 2010). The results are therefore relative or related only to patterns and horizontal contrast (Malone and Engle 2011, Hansen et al 2014, Dong et al 2015). However, assessments based on the mechanism and process related to the meaning of vulnerability remain rare (IPCC 2014). Moreover, there is lack of guidance on managing climate change response and adaptation mechanisms, as the structure and functions of the ecosystem are complex at large spatiotemporal scales. As it is difficult to conduct research on the effects of climate change, vulnerability, and adaptability by employing the ecosystem process model, the adaptation and mitigation strategies in response to such change are based simply on qualitative research (United Nations Framework Convention on Climate Change 2008). Accordingly, quantitative assessment of the essence of ecosystem vulnerability is vital in the research on climate change (Antwi-Agyei et al 2012).

According to the IPCC definition, vulnerability refers to the stress of sensitivity and the adaptive capacity of a system to climate change. Together, higher sensitivity and weaker adaptability create a vulnerable system (IPCC 2014). Sensitivity is described as the degree to which a system is directly or indirectly affected by or is responsive to climate stimuli, including the frequency, intensity, and variability of the average climate (Beaugrand 2015). Adaptability can be considered a response measure to external changes to cope with potential losses and to maintain a stable system (Brooks et al 2005, Keenan 2015). Similarly, the variation trend of ecosystem variability is a measure of its deviation from the steady state over time. If the trend of variability were reduced or unchanged, the ecosystem would remain relatively stable and could adapt to such change. However, if the system were unable to adapt to the effects of climate change, it would become highly vulnerable (Verbesselt et al 2016). According to the IPCC framework, sensitivity determines the potential effects of climate change on the ecosystem, whereas adaptability is the potential to adjust the sensitivity to maximize the ability to moderate or cope with the detrimental effects of such change (Giupponi and Biscaro 2015). Accordingly, the concepts of sensitivity, adaptive capacity, and vulnerability are interrelated and are applied widely in research on global change.

Quantitative assessment of vulnerability, based on the response process, is important in determining the response process of the ecosystem (Füssel 2007). Therefore, analyzing relative variation, such as differences in ecosystem variability, could be an effective assessment method. Such method would be more indicative of the stability of the ecosystem than an average method and could better reflect ecosystem vulnerability (Minnen et al 2002). As regards the meaning of the IPCC term vulnerability, the sensitivity and adaptability of ecosystems are defined based on the rate of variation and the variability of ecosystem functions, respectively. Accordingly, this study constructed a quantitative assessment method of vulnerability based on the response process of the ecosystem. We applied the method to assess the spatial pattern and characteristics of terrestrial ecosystem vulnerability in China over 70 years, from the past (1981) to the future (2050).

2. Materials and methods

2.1. Climate databases and pretreatment

Two climate databases were used in this study, with one containing data from the meteorological stations nationwide. These data are available from the China Meteorological Science Data Service Sharing Network. After eliminating the stations with missing data, we collected the monthly temperature and precipitation data from 652 meteorological stations for the period 1981 to 2015. Subsequently, these data were interpolated into 0.5° spatial resolution by using Ausplin 4.2 (http://fennerschool.anu.edu.au/research/products). The other database we used contains the monthly temperature and precipitation data provided by the National Climate Center of the China Meteorological Administration (CMA). This database includes historical simulation (1981–2005) and projected data (2006–2050) under the RCP8.5 (Representative Concentration Pathways) emission scenario. The database for China was simulated by using Beijing Climate Center Climate system model version 1.1 (BCC-CSM1.1), which had a good effect in most parts of East Asia (Xin et al 2013, 2018) and could meet the data needs of this study. Subsequently, the data were interpolated into 0.5° spatial resolution. Owing to the deviation between historical simulation data and observation data, the climate projected data for 2006–2050 had to be calibrated by using the month-by-month deviation data of the historical simulation and the interpolated station data from 1981 to 2005 (Leng and Tang 2014, Räty et al 2014):

\[ T_{pi} = T_{ai} + (T_{ai} - T_{hi}), \]
\[ P_{pi} = P_{ai} \cdot \left(\frac{P_{ai}}{P_{hi}}\right), \]

where \( T_{ai} \) is the average temperature of the 0th month, obtained from the meteorological stations (1981–2005); \( T_{hi} \) is the average temperature of the 0th month, obtained from the historical simulation (1981–2005); \( T_{pi} \) is the average temperature of the 0th month, obtained from the projected data before correction; and \( T_{ai} \) is the average temperature of the 0th month, obtained from
the projected data before correction from 2006 to 2050. \( P_n \) is the total precipitation of the 8th month, obtained from the meteorological stations (1981–2005); \( P_{n0} \) is the total precipitation of the 8th month, obtained from the historical simulation (1981–2005); \( P_n \) is the total precipitation of the 8th month, obtained from the projected data before correction; and \( P_n \) is the total precipitation of the 8th month, obtained from the projected data before correction from 2006 to 2050. Our calculations indicated that the deviation of the actual temperature interpolation from the historical simulation during 1981–2005 was in the range of −2 K to 5 K, and the precipitation deviation was −40% to 16%.

Moreover, this study utilized the RCP8.5, a high greenhouse gas emission scenario that excludes any specific climate mitigation targets. The aim was to explore fully the response of ecosystem sensitivity and adaptive capacity to climate change within a larger changing range, to highlight the vulnerability process to reflect the superiority of the methodology proposed in this study, and to assess the ecosystem vulnerability at the maximum emission intensity. This is an important basis for the selection of "no-regret" measures and the promotion of greenhouse gas emission reductions.

### 2.2. Simulated NPP database

Net primary productivity (NPP) reflects the efficiency of vegetation fixation and transformation of light energy for organic matter, and is related to vegetation growth and development. NPP is reflected relatively in the structure, function, and habitat characteristics of the ecosystem, and its distribution and dynamics are controlled by climatic factors (Michaletz et al. 2014). Therefore, NPP could be used as a research object relevant to the vulnerability of the terrestrial ecosystem response to climate change. In this study, the NPP database from 1981 to 2050, with spatial resolution of 0.5°, was simulated by using the Lund–Potsdam–Jena dynamic global vegetation model (LPJ-DGVM). The data imported into the model were obtained from the climate scenario information provided by the National Climate Center of the CMA. Furthermore, soil texture data were imported from the United Nations Food and Agriculture Organization that include information on mineral grain proportions in the top soil and the geographical distribution of various soil texture types. Subsequently, the soil data were resampled to 0.5° spatial resolution by using ArcGIS 10.3.

The LPJ-DGVM is applied widely in vegetation dynamics and biogeochemistry (Sitch et al. 2003). The model can simulate the stomatal conductance, photosynthesis, respiration, foliage and leaf litter, resource competition, tissue turnover, and soil microbial decomposition process-based on the canopy energy balance, the distribution of photosynthates in plants, and the soil–water balance. Subsequently, the carbon cycle, CO₂ and moisture flux, photosynthetic rate, primary productivity, and carbon storage of vegetation could be calculated. A study by Gao et al. (2017) expounded the modification and operation of the model. Specifically, the LPJ-DGVM was improved by adding shrub and cold grass PFTs, which were parameterized based on various inventory and observational data in accordance with the characteristics of ecosystems to improve the simulation in China (Zhao et al. 2015). The NPP simulated by the modified model was validated with the data of observed sites in China, where the correlation coefficient \( R^2 = 0.64, p < 0.01 \) was higher than that of the original LPJ-DGVM data \( R^2 = 0.10 \) used by Ni (2003). Subsequently, a 1000 year model spin-up was run to approach equilibrium relevant to vegetation cover and carbon pools for the terrestrial ecosystem. Finally, the LPJ-DGVM was driven by the climate database to simulate the NPP. The simulation results were verified from the spatial distribution pattern and the varying range of vegetation types. The historical simulation reflected the spatial distribution of the NPP downturn from southeast to northwest China, which agrees with the moderate-resolution imaging spectroradiometer NPP datasets. In addition, the statistical analyses showed that the difference between the average LPJ-DGVM-simulated NPP and the observations was smaller for needle-leaf evergreen deciduous forests and grasslands. However, tropical broadleaf evergreen/monsoon and broadleaf evergreen forests showed a relatively larger deviation compared with that from the observations.

### 2.3. Vegetation type map

The vegetation type dataset (1:1 000 000) was provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn). The distribution of 11 vegetation type groups and 54 vegetation types, and the patterns of horizontal and vertical zonality were reflected in detail (figure S1 is available online at stacks.iop.org/ERL/13/094016/mmedia), and were consistent with the corresponding classification of PFTs in LPJ-DGVM in China. Therefore, the dataset was considered suitable for the data needs of the current study.

### 2.4. Theoretical analysis of ecosystem vulnerability to climate change

Climate change (especially changes in hydrothermal conditions) is an important external driver in the ecosystem response process. Appropriate warming and increasing precipitation can promote the photosynthetic rate and other vegetation activity. However, when the climate change reaches a certain magnitude or rate, it will have an adverse effect on the ecosystem, and exhibit a nonlinear pattern (figure 1). With the increasing rate or magnitude of temperature before (A), vegetation photosynthesis would weaken but respiration would be enhanced gradually. Subsequently, with the acceleration of evapotranspiration, the drought trend of the ecosystem would become increasingly obvious. Consequently, the hydrothermal
factors drive the increasing of the ecosystem sensitivity (the slope of the response curve), whereas the sensitivity variation rate (the rate of slope) would show a trend of first increasing and subsequently decreasing. The direction of the variation rate is consistent with the sensitivity (both are negative). When the hydrothermal conditions improve after (A), which could meet the self-regulation needs of the ecosystem, the system sensitivity will decrease gradually with increasing precipitation that enhanced the photosynthesis. Although the trend was similar to that in the previous stage, the variation direction of the sensitivity rate was the opposite (turned to positive) of the sensitivity trend. This observation indicated that at that time the ecosystem reflected higher adaptive capacity to offset the adverse effects of warming on the ecosystem to a certain extent and reduce the level of vulnerability. Therefore, the response trend would gradually slow down and, over time, the ecosystem could adapt or could be restored even (A–C). However, if the hydrothermal conditions failed to meet the demands of vegetation activity, the adverse effects on the ecosystem would become increasingly vulnerable (A–D). Moreover, when the rate or magnitude of climate change exceeded the regulation capacity of the ecosystem (B), the severity of the adverse effects would increase and the ecosystem would collapse or could reverse the succession (B–E), dissociating from the original ecology response law. Therefore, the vulnerability assessment system established in this study does not consider the processes that involve changes in vegetation types, such as ecosystem succession.

The analysis of the ecosystem response trend to climate change indicated that the ecosystem vulnerability was attributable mainly to the adverse effects of such change. Therefore, the study regions were restricted to areas where NPP has been decreasing over a period of time. In addition, the ecosystem vulnerability was a specific response process to the interaction of sensitivity and adaptability within the system. For example, in areas with relatively high sensitivity, the downturn of the ecosystem could be slowed down by improved hydrothermal conditions, which would lead to adaptability gradually increasing and ecosystem vulnerability still being low. However, areas with lower sensitivity do not necessarily have superior adaptation capability; therefore, integrating sensitivity and adaptability was important in the quantitative assessment of ecosystem vulnerability.

Ecosystem vulnerability could be characterized as a function of sensitivity and adaptability (IPCC 2007) and, in this study, sensitivity was defined as the ratio of the NPP variation rate and the climate change rate:

\[
S = \lim_{\Delta T \to 0} \left( \frac{\Delta N/N}{\Delta C/C} \right) = \frac{\partial N}{\partial C} \cdot \frac{C}{N},
\]

where \( S \) is dimensionless and represents ecosystem sensitivity to climatic factors; \( N \) is the NPP (g C m\(^{-2}\)); and \( C \) represents climatic factors, including the temperature (K) and precipitation (mm). The greater absolute value of \( S \) indicates higher sensitivity and that climatic factors significantly affect NPP.

Based on the meaning of adaptability, it could be defined as the ratio of the sensitivity variation rate and the climate change rate:

\[
A = \lim_{\Delta T \to 0} \left( \frac{\Delta S/S}{\Delta C/C} \right) = \frac{\partial S}{\partial C} \cdot \frac{C}{S},
\]

Figure 1. Theoretical process of ecosystem response to climate change.
equation (3) into (4) to obtain:

\[
A = 1 + C \frac{\partial^2 N / \partial C^2}{\partial N / \partial C} - \frac{\partial C}{N} \cdot \frac{C}{N}
\]

\[
= 1 + C \frac{\partial^2 N / \partial C^2}{\partial N / \partial C} - S_f,
\]

where A represents ecosystem adaptability to climatic factors. A greater absolute value of A implies lower adaptability and that climatic factors significantly affect ecosystem sensitivity.

To quantify ecosystem vulnerability to temperature change, this study conducted normalization with S and A, according to their distinct characteristics, by using the maximum-minimum standardized treatment, making the scopes 0–1 before calculating vulnerability:

\[
S_N = \begin{cases} 
\frac{\text{max}(S) - S}{\text{max}(S) - \text{min}(S)}, & S < 0 \\
0, & S > 0
\end{cases}
\]

\[
A_N = \frac{|A|}{\text{max}(|\text{max}(A)|, |\text{min}(A)|)},
\]

where $S_N$ represents the normalized coefficient of ecosystem sensitivity, 0 indicates no sensitivity, and 1 indicates the highest sensitivity. $A_N$ is the normalized coefficient of ecosystem adaptability, 0 indicates the highest adaptability, and 1 indicates the lowest adaptability. Accordingly, ecosystem vulnerability to climate change can be expressed as:

\[
V = S_N \cdot A_N,
\]

where $V$ is the coefficient of ecosystem vulnerability, with a range from 0 to 1. A higher value of $V$ (that is, higher sensitivity and lower adaptability) indicates higher ecosystem vulnerability.

This formula for vulnerability assessment integrated the two vital components of sensitivity and adaptability, which reflect the range and rate characteristics of climate change within the ecosystem. Based on local climate and vegetation activity, this study used this process-based quantitative method to analyze the vulnerability pattern and the dominant factors. Subsequently, we conducted an in-depth study on the vulnerability process to clarify the characteristics, causes, and varying trends of vulnerability in different vegetation types and regions in China. As considering the adaptive capability of ecosystems is difficult for assessment models, we based sensitivity, adaptability, and vulnerability on the analysis of ecosystem response to climate change.

3. Results

3.1. Ecosystem vulnerability pattern

The pattern of the NPP variation trend and ecosystem vulnerability to temperature and precipitation variation in China during the study period are illustrated in figure 2. With climate change, NPP would have an adverse effect over the entire period on approximately 28.1% of the areas in China distributed mainly in the warm temperate, subtropical, and tropical zones. We therefore selected these areas as targets for our ecosystem vulnerability assessment. The regions with relatively high ecosystem vulnerability to warming were located in the Tianshan Mountain, Inner Mongolia Plateau, Yunnan–Guizhou Plateau, and from the Poyang Lake plain to the northeast of the Guangdong and Guangxi hills. Temperature was the most obvious driving force on the ecosystem in these areas, resulting in more serious adverse effects. The regions of relatively low vulnerability would be located in the midstream of the Nenjiang River basin, the Loess Plateau, the west of the Huanghuai Plain, and the Yangtze River delta. Furthermore, the distribution pattern of ecosystem vulnerability to precipitation variation was basically the same as that to warming, except for some parts of the north of the Loess Plateau, which indicates the consistency of the external driving forces of hydrothermal factors on the ecosystem. However, the overall distribution of vulnerability to precipitation variation was less concentrated than that to warming because of its spatial discontinuity.

The assessment of vulnerability in the past (1981–2015) and future (2016–2050) periods (figure 3) indicated that regions with ecosystem vulnerability to climate change over the past 35 years constituted 35.5% of the areas in China, mainly concentrated in the south; however, the vulnerability in most regions (East, Central, and South China) showed a low level. The ecosystem vulnerability to warming was much higher than that to precipitation variation from the Junggar Basin–Qilian Mountains–Sichuan Basin to the Yunnan–Guizhou Plateau. Excessive warming accelerated the evapotranspiration and further formed a drought trend, thereby inhibiting vegetation activity. In the future period, the areas of ecosystem vulnerability to climate change would be reduced by 22.9% and would show a trend of moving northwards compared with the past. Ecosystem vulnerability in the cold-temperate zone, the Inner Mongolia Plateau, the Loess Plateau, and the North China Plain had increased significantly, indicating that the precipitation variation could not meet the demand for vegetation activity, and formed hydrothermal combinations that were beneficial to the ecosystem with warming; therefore, the vulnerability to precipitation was higher than was that to temperature in most of these regions.

3.2. Dominant factors of ecosystem vulnerability

According to the calculation formula of ecosystem vulnerability, the factors with a greater value of the normalized coefficient between sensitivity and adaptability in the same region would contribute more to ecosystem vulnerability. The spatial distribution of ecosystem vulnerability to different climatic factors in China for the study period indicated that the areas
Figure 2. Spatial patterns of the NPP trend (a), ecosystem vulnerability to warming (b), and precipitation variation (c) in China from 1981 to 2050. The blank regions of (b), (c) where NPP increased or no change during the study period are not applicable to the vulnerability assessment of this study. The same below.

Figure 3. Spatial patterns of eco-vulnerability to climate change in China from 1981 to 2015 (a: temperature; b: precipitation) and 2016 to 2050 (c: temperature; d: precipitation).
with higher vulnerability to precipitation variation than to warming would be approximately 61.3% of the total region of vulnerability. These areas were distributed mainly in the south of the Loess Plateau, the west of the Huanghuai Plain, the west and northeast of the Yangtze River Plain, and some parts of the southeast coast (figure 4(a)). The humid areas had a relatively limited warming range, but ecosystem sensitivity to precipitation variation caused a strong response within the system and contributed more to the vulnerability in the northeast of the Yangtze River Plain and some parts of the south coast. The decreasing precipitation in the former region affected the water use by vegetation, whereas the increasing precipitation in the latter reduced the absorption of solar radiation by vegetation by the varying amount of cloud cover. However, ecosystem adaptability to precipitation variation could hardly cause the response within the system, and the ability of the ecosystem to maintain its existing state was poor. Low adaptability to precipitation variation was an important aspect of ecosystem vulnerability in the south of the Loess Plateau and the west of the Huanghuai Plain (figure 4(b)). In addition, the areas of higher vulnerability to warming were located in the Tianshan Mountain, the northwest of the Loess Plateau, the Inner Mongolia Plateau, and some parts of the Yunnan–Guizhou Plateau (figure 4(a)). The areas with higher vulnerability to warming, mainly contributed by low adaptability, would be located in some regions of the Yunnan–Guizhou Plateau, where poor hydrothermal conditions were predicted in the future. The adverse effects of warming would be severe on vegetation activity in most other regions; therefore, high sensitivity to warming would be a significant aspect of ecosystem vulnerability (figure 4(b)).

3.3. Analysis of vulnerability in vegetation types and typical regions

The assessment results on the different vegetation types show that the vulnerability of cold grasses to climate change was at a relatively high level, followed by temperate grasses, and desert (figure 5). Ecosystem vulnerability to warming was higher than to precipitation variation, mainly because the adverse effects of warming on these vegetation types were more obvious, causing higher levels of sensitivity. However, at the same time, a certain degree of adaptability would be produced to offset the adverse effects of warming. In addition to temperate needle-leaved evergreen forest, ecosystem vulnerability to precipitation variation was higher than to warming for other forest types, and tropical broadleaved evergreen forest and subtropical forests were more sensitive to climate change than other forest types. Moreover, a larger temperature increase would result in a higher level of sensitivity for cold-temperate needle-leaved deciduous forest and temperate needle-leaved forest, whereas tropical broadleaved evergreen forest and subtropical forests were more sensitive to precipitation variation than to warming. Ecosystem adaptability to warming was higher than to precipitation variation for the forest types, except for the tropical broadleaved evergreen forest, and was more obvious in areas with higher temperatures.

We selected four typical regions for in-depth analysis (figure 6) in accordance with various characteristics of ecosystem vulnerability in China. The middle of the Inner Mongolia Plateau (R1) and the northwest of the Loess Plateau (R3) are located in the temperate arid and semiarid regions, and the dominant vegetation type is temperate grasses, which would have high vulnerability to temperature. The value of NPP would be low and would decrease rapidly with warming in R1, indicating that ecosystem vulnerability caused by low adaptability to warming would continue to increase and the environment would deteriorate further in this region. However, the decreasing trend of NPP would be slowing down gradually with warming in R3, indicating that the strong ecosystem adaptability to warming could relieve the high sensitivity to climate change.

![Figure 4](image_url)

Figure 4. Spatial distribution of the higher eco-vulnerability between temperature and precipitation (a), and higher normalized coefficient between SN and AN for each eco-vulnerability (b) in China from 1981 to 2050.
a certain degree. Subsequently, the vegetation would start to adapt to the warm and dry environment, and ecosystem vulnerability could decrease in future.

Ecosystem vulnerability to precipitation variation was higher than to warming in the region of the southeast coast (R2) and the southeast of the Loess Plateau (R4). The R2 area is located in the subtropical and tropical transition region, and the zonal vegetation are broadleaf evergreen and tropical broadleaved monsoon forests. Regional differences in the sensitivity and adaptability were distinct in this region. From the relationship between NPP and the precipitation variation, the trend of NPP would decrease first and subsequently increase with the decreasing precipitation, indicating that precipitation variation could form a more favorable hydrothermal combination with warming at a certain time to promote vegetation activity in the future, with ecosystem adaptability increasing. With the adverse effects of climate change counteracted (ecosystem sensitivity decreased gradually to zero) in this region, the NPP started to increase. The R4 is located in the warm temperate sub-humid areas and the vegetation type here is mainly temperate broadleaf deciduous forest. It would be difficult for
precipitation variation to cause the adaptability response in the region as a significant reason for ecosystem vulnerability; therefore, the downturn of NPP was accelerating gradually with the decreasing precipitation. Under future warming conditions, the reduced of precipitation would accelerate the drought trend and could exceed the regulatory capability of the ecosystem, causing more serious damage.

4. Discussion

After in-depth analysis of the concept of vulnerability, which integrates sensitivity and adaptability, we constructed a quantitative assessment method of vulnerability, based on ecosystem processes. Comparing previously obtained results that used methods such as index evaluation, and comparative and quantitative assessments (Zhao and Wu 2014, Xu et al. 2016, Yuan et al. 2017), the spatial distribution pattern of ecosystem vulnerability in China indicated by the present study was mainly similar. However, the degree of ecosystem vulnerability varied in several regions. Wu et al. (2017) evaluated ecosystem vulnerability for the same period and climate scenario by using the standard deviation method, based mainly on the downward trend of NPP. Therefore, they considered only the effect of ecosystem sensitivity on vulnerability. Although their assessment result is similar to the vulnerability pattern found in our study, the degree of vulnerability in several regions differed. For example, we found that the vulnerability of meadow grassland would be higher than that of typical grassland in the middle of the Inner Mongolia Plateau, and the vulnerability of tropical and southern subtropic areas would be higher than that of the middle sub-tropic areas. Our study considered the combined effects of sensitivity and adaptability, enhancing the scientificity and reasonableness of the ecosystem vulnerability assessment. Our method did not focus only on the adverse effects of climate change but considered also the variation rate of such adverse effects. This reflected the key role of ecosystem adaptability in vulnerability assessment.

The vulnerability of the ecosystem showed spatial heterogeneity. Most of the Inner Mongolia Plateau is located in regions subject to high vulnerability to warming, from the northeast to southwest, followed by the distribution of meadow grassland, typical grassland, and desert steppe. Although the ecosystem sensitivity to warming of the typical grassland in the central part would be slightly lower than that of the meadow steppe in the northeast, its adaptability would be much lower. This implied that the vulnerability of typical grassland would be higher than that of meadow steppe. As regards the ecosystem vulnerability of subtropical broadleaf evergreen forest, the Yunnan–Guizhou Plateau would have higher vulnerability to warming, whereas vulnerability to precipitation variation would have a significant effect in most parts of the Poyang Lake plain. However, the lower adaptability to climate change of these areas contributed more to the ecosystem vulnerability. In addition, ecosystem sensitivity and adaptability to each climatic factor would be different, resulting in the spatial heterogeneity of ecosystem vulnerability being the response of the different vegetation types to climate change in the northwest and southeast of the Loess Plateau. Overall, the vegetation types reflected spatial differences in temperature and moisture, leading to spatial heterogeneity of ecosystem vulnerability. Accordingly, the hydrothermal combination in the different regions was an important factor in the spatial heterogeneity of ecosystem vulnerability.

The interaction between the ecosystem and the climate system is extremely complex. Temperature and precipitation have a significant impact on the ecosystem; therefore, a reasonable combination of water and heat affects vegetation activity positively. Moreover, the response of ecosystems to moisture change would be associated closely with temperature warming in the future (Piao et al. 2014). Our study considered only the vulnerability to warming and precipitation variation separately. However, in future systematic and comprehensive vulnerability analysis, this aspect could be combined with the effects of various other climatic factors on the ecosystem. Furthermore, the effects of non-climatic factors, such as land use, have become increasingly important in ecosystem vulnerability. From the perspective of the human-environment relationship, the difference between the effects of climate change and non-climatic factors on ecosystems could be crucial in vulnerability studies (Janssen et al. 2007, Li et al. 2016).

Based on a previous method to assess ecosystem vulnerability, our study highlighted the theoretical connotation and the enhancement of ecosystem adaptability, proposing a more scientific and intuitive qualitative assessment method. However, this method did not consider fully the effects of the autonomous adaptation mechanism on ecosystem vulnerability. The ecosystem is more conducive to its own activity, while adapting to environmental conditions, and such autonomous adaptive capacity is therefore an important component of ecosystem adaptability (Smit and Wandel 2006, Barnosky et al. 2017). Accordingly, in future study on ecosystem vulnerability, this aspect should enhance the understanding of the interaction among the different factors. This is particularly relevant to further exploration of the methods of the ecosystem adaptation mechanism, as well as mathematical expressions, in order to obtain a comprehensive reflection of the effects of climate change and non-climatic factors on ecosystems.

5. Conclusions

Based on the IPCC definition of vulnerability, this study constructed a process-based quantitative assessment method to determine ecosystem vulnerability by
analyzing sensitivity and adaptability. The method focused on the trend of ecosystem variability, which characterizes adaptability and highlights its crucial role in vulnerability assessment. Our novel method enhanced ecosystem assessment by understanding the existing adaptation mechanism. We obtained acceptable results by applying our assessment method to determine the vulnerability of the terrestrial ecosystem in China to climate change.

The NPP in China, simulated by the global dynamic vegetation model, was used as the assessment object of ecosystem vulnerability. As indicated by considering the current climate conditions up to the RCP8.5 climate scenario (1981–2050), approximately 30% of the regions in China would be affected by ecosystem vulnerability, of which about 61% would be relatively vulnerable to precipitation variation. Compared with the past 30 years, the future ecosystem vulnerability areas showed a trend of moving northwards. The Tianshan Mountain, the Inner Mongolia Plateau, and the subtropical region from the Yunnan–Guizhou Plateau to the Poyang Lake plain would be more susceptible to the adverse effects of climate change, and ecosystem vulnerability would be higher there. High sensitivity to warming would contribute significantly to the vulnerability of desert and grassland, whereas the vulnerability of forest and temperate shrubs could be attributed mainly to relatively lower adaptability to precipitation variation than that to warming. Our study indicated that ecosystem adaptability plays a crucial role in regulating sensitivity. Our results showed spatial heterogeneity in ecosystem vulnerability in the different regions of the country. Therefore, quantifying adaptability is an important aspect of assessing ecosystem vulnerability.

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