Theoretical Paradigm and Methodology for Climate Change Impact and Risk Research: Postprint

Authors: Gao Jiangbo, Jiao Kewei, Wu Shaohong, Guo Linghui

Date: 2017-04-18T00:00:00+00:00

Abstract

Climate change, dominated by global warming, will persist throughout this century, and implementing adaptation and mitigation measures in response to climate change impacts and risks has garnered widespread international recognition. However, theories and methodologies in climate change impact and risk research remain non-standardized, leading to a lack of comparability among research findings. Based on the concepts of theoretical paradigm and constructive paradigm proposed by philosopher of science Thomas Kuhn, we systematically organize and integrate a "vulnerability-element separation-uncertainty-risk" theoretical framework for climate change impact and risk research, and summarize the corresponding methodological system that includes field observations and scientific experiments, numerical modeling and statistical methods, risk quantification assessment frameworks, among others. Climate change impact and risk research should follow the logical relationships of the "four elements" of the theoretical paradigm, comprehensively employ multiple analytical methods, and strive for comprehensiveness and systematization in relevant research, thereby enhancing the scientific rigor of climate change impact and risk research and the applicability and guiding significance of its findings.

Full Text

Preamble

ACTA ECOLOGICA SINICA
ChinaXiv Partner Journal
Vol. 37, No. 7, April 2017
DOI: 10.5846/stxb201601080052

Theory Paradigm and Methods System for Research on Climate Change Impacts and Risks

Gao Jiangbo[1], Jiao Kewei[1,2], Wu Shaohong[1], Guo Linghui[3]

[1]Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[2]University of Chinese Academy of Sciences, Beijing 100049, China
[3]School of Surveying and Land Information Engineering, Henan Polytechnic University, Jiaozuo 454000, China

Abstract

Climate change, dominated by global warming, will continue throughout the 21st century. Adaptation and mitigation measures targeting climate change impacts and risks have gained widespread acceptance from governments, scientists, and organizations worldwide. However, theories and methods for assessing climate change impacts and risks remain non-standardized, leading to incomparable results across different sectors. Drawing upon the concepts of theoretical and structural paradigms proposed by philosopher of science Thomas Kuhn, this study first proposes a theoretical paradigm for climate change impact and risk research based on the logical framework of "Vulnerability-Separation-Uncertainty-Risks." We then summarize corresponding analytical methods, including field observations, experiments, numerical models, statistical approaches, and frameworks for quantified risk assessment. Furthermore, based on the transfer logic among the four components of the theoretical paradigm, systematic research on climate change impacts and risks can be accomplished through the integrated application of diverse analytical methods. This study may help advance research on climate change impacts and risks and enhance the scientific rigor and practical guidance of related studies.

Keywords: climate change impacts; research paradigm; theoretical paradigm; analytical methods

1. Theoretical Paradigm for Climate Change Impact and Risk Research

In a broad sense, a paradigm represents an integration of research thinking and methods—a conceptual and scientific system recognized by the scientific community. Masterman summarized Kuhn' s paradigm into three aspects: first, as a belief or metaphysical speculation (philosophical paradigm); second, as a concrete scientific achievement or shared example (sociological or theoretical paradigm); and third, as a tool, method, or analogical image that demonstrates success through its own application (artificial or structural paradigm). While the primary meaning lies in the philosophical dimension, Kuhn' s originality resides in the sociological implications and constructive functions of paradigms. The sociological paradigm establishes a new relationship between applied models and metaphysics, providing pathways from general philosophical theory to practical scientific issues. This paper employs the latter two meanings—theoretical paradigm and structural paradigm—to first propose a theoretical paradigm for climate change impact and risk research. This paradigm assesses vulnerability as its foundation, focuses on separating the contribution of climate factors from other drivers of change, treats deterministic and complexity analysis as key components, and ultimately aims to project climate change risks. The relative importance of these components varies across different research stages, with earlier phases often emphasizing uncertainty less and conducting less thorough quantitative separation of impacts.

1.1 Vulnerability Assessment

Vulnerability assessment has consistently emphasized the importance of vulnerability in understanding receptor responses to climate change. The IPCC' s Fifth Assessment Report further clarified vulnerability concepts and components, including sensitivity or susceptibility to hazards and the lack of coping and adaptive capacity. Generally, higher sensitivity and weaker adaptive capacity result in greater system vulnerability. Vulnerability can be categorized as natural or social: the former reflects natural attributes of receptors, while the latter describes potential losses to social systems under climate change. System vulnerability represents the intrinsic cause of climate change impacts on natural and social systems. Vulnerability evaluation helps scientists and decision-makers understand environmental change impacts, identify vulnerable systems, and characterize vulnerability manifestations and causes. By synthesizing international vulnerability research, scholars have standardized vulnerability concepts and defined six dimensions for vulnerability assessment across natural environment and socioeconomic domains. Füssel proposed a vulnerability assessment framework, while Klein and Nicholls developed a seven-step technical route for climate change impact assessment that offers greater operability. Systematic analyses of natural ecosystem vulnerability to climate change have yielded preliminary conclusions, such as comparisons of rice yield changes under rising mean temperatures and increasing diurnal temperature ranges.

Table 1 Six domains for system vulnerability assessment [12]

Figure 1 [Figure 1: see original paper] Conceptual framework for climate change vulnerability assessment (redrawn from ref. [13])

2. Climate Factor Impact Degree Identification

Relative to system vulnerability, research on separating climate factor contributions remains generally insufficient. Climate change and human activities jointly drive dynamic changes and spatial heterogeneity across different assessment domains. The ability to isolate climate change impacts from observed trends has become a bottleneck constraining effective adaptation actions. The IPCC Fifth Assessment Report emphasizes impact attribution, noting that evidence for climate change impacts on natural systems is most comprehensive, while some impacts on human systems can also be partially attributed to climate change. In China, quantitative separation of climate versus non-climate factors has only been conducted for agricultural yield variability and water resource evolution, creating substantial uncertainty in evaluating climate change impact magnitude and scope. Studies have attributed changes in crop phenology and yields to variety shifts and climate variables, while other scholars have analyzed runoff reductions in the Haihe, Yellow River middle reaches, and Liaohe basins. Climate change often acts comprehensively on natural and socioeconomic systems, resulting in cross-cutting impact characteristics. The IPCC Fifth Assessment Report further notes that climate-related hazards affect impoverished populations directly through reduced crop yields or destroyed homes, and indirectly through food price increases and security risks. The report calls for developing cross-sectoral, integrated assessment models to enhance understanding of impact propagation chains and degree identification.

3. Uncertainty Analysis

Uncertainty sources in climate change impact and risk research include: (1) limited observational information, (2) insufficient understanding of climate change processes and receptor response mechanisms, and (3) immature core technologies and methods. The degree of certainty regarding findings on vulnerability, climate impact separation, and future risks depends on evidence quality and consistency. For basic climate facts and trends, complex system processes and feedbacks create strong uncertainties, as current climate models show large differences in simulating Earth' s radiation balance, clouds, and precipitation, making future scenario projections less reliable. In vulnerability research, adaptation creates feedbacks among system components and between systems and their environment, generating significant uncertainty and complexity. Integrated warming and CO fertilization experiments with numerical simulations reveal that while elevated CO increases photosynthetic rates and optimal temperatures for photosynthesis, high temperatures may cause yield losses and potentially force systems into reverse succession. The applicability and uncertainty of physical mechanism models require deeper investigation, including inadequate understanding of receptor adaptation processes, spatiotemporal heterogeneity, model assumptions, and constraints. Scale conversion issues exist when applying site-based models to regional scales. Walker et al. summarized uncertainties in mechanism-based simulations. When climate scenario data drive domain assessment models, uncertainties cascade like a waterfall, amplifying through complex receptor responses, data applicability, and model limitations.

4. Risk Identification and Assessment

Risk identification and quantitative assessment form the scientific basis for risk management and climate change adaptation. The IPCC Fifth Assessment Report defines risk as the probability of hazardous events or trends multiplied by their consequences, representing the combined effect of vulnerability and hazard. Analogous to natural disaster risk, climate change and extreme events serve as risk sources, while exposed socioeconomic and environmental systems constitute risk-bearing entities. Vulnerability reflects the susceptibility of these entities. Climate change risk fundamentally exhibits futurity, benefit/loss duality, and uncertainty. The IPCC report particularly notes that differences in vulnerability and exposure, caused by non-climatic factors and multiple inequities, lead to varying climate change risks. Marginalized populations are typically most vulnerable, and uncertainties in future responses are large due to human-natural system interconnections. Risk assessment methods can incorporate inconsistent impact evaluation results into risk frameworks, coupling risk evaluation with decision-making by quantitatively or qualitatively describing potential risks while fully considering uncertainties. The report highlights key risks under high vulnerability, defined as large-magnitude, high-probability, or irreversible impacts with limited potential for risk reduction through adaptation or mitigation. Current research in China remains weaker than international efforts, with most content focusing on future trend projections rather than key risk identification and quantitative assessment.

2. Methodological System for Climate Change Impact and Risk Research

Rich methodologies have emerged domestically and internationally, including experimental and statistical techniques to identify climate impacts, numerical models for future risk projection, and statistical methods for uncertainty analysis. These approaches encompass observation technologies, simulation techniques using experimental facilities, and analytical frameworks.

2.1 Observation Techniques

Advances in Earth observation technologies have achieved unprecedented coverage of land surface changes, providing high spatiotemporal resolution monitoring data. Combined with socioeconomic census data and statistics, this has shifted climate change impact research from qualitative analysis of geographic phenomena to integrated qualitative-quantitative approaches. The IPCC Fourth Assessment Report integrated nearly 30,000 data series from natural and biological systems worldwide, revealing significant changes in cryosphere, freshwater, and terrestrial ecosystems, including glacial retreat, lake expansion, earlier spring phenology, and species range shifts toward poles and higher elevations. Techniques like dendrochronology have expanded temporal scope, while experimental facilities such as Open-Top Chambers (OTC) and Free-Air CO Enrichment (FACE) have rapidly developed to reveal plant ecophysiological effects and population/community vulnerability under climate change.

2.2 Experimental Techniques

Multi-factor control experiments examining temperature, precipitation, radiation, and other variables have been widely applied. However, scaling results from typical species studies to ecosystem, landscape, or regional scales remains challenging. While observation and experimental advances have fundamentally improved mechanistic understanding, objective analyses of global climate change impacts remain limited. Most experiments focus on single-factor effects, whereas natural conditions involve complex interactions.

2.3 Climate Models and Assessment Domain Models

Numerical models in climate change impact research include climate models and domain-specific assessment models. Historical climate data can be obtained through meteorological station interpolation or proxy data reconstruction, but future scenarios rely primarily on climate models, including Global Climate Models (GCMs) and Regional Climate Models (RCMs) with dynamical downscaling. The IPCC Fifth Assessment Report employs Representative Concentration Pathways (RCPs) as scenario frameworks. Domain mechanism models are widely used for impact assessment and risk projection, including biogeochemical models (CENTURY, SIB2), dynamic vegetation models (IBIS, LPJ), distributed hydrological models (VIC, SWAT), and crop models (DSSAT, CERES). Dynamic vegetation models simulate vegetation physiology, phenology, and nutrient cycles, providing effective tools for projecting terrestrial ecosystem changes under climate change. These models have been applied to assess ecosystem vulnerability in China.

Table 2 Mechanism models for climate change impact assessment

To address uncertainties in domain mechanism models, integrated assessment methods based on regional scales offer a viable direction. Comprehensive approaches combining field surveys, multi-scenario analysis, multi-model simulation, and integration of holistic and individual perspectives can objectively reveal regional system vulnerability and adaptation mechanisms, providing scientific support for developing effective adaptation technologies.

2.4 Statistical Methods

Statistical methods for vulnerability assessment and climate attribution have become increasingly sophisticated. Parametric methods such as cluster analysis, principal component analysis, fuzzy comprehensive evaluation, and analytic hierarchy process are widely applied. Non-parametric machine learning algorithms, including artificial neural networks and rough set methods, have also emerged. Spatial analysis functions effectively express heterogeneity in climate change impacts. Statistical methods are crucial for uncertainty analysis: some uncertainties can be quantified (e.g., across model ensembles), while others require qualitative description (e.g., expert judgment). The IPCC Fifth Assessment Report employs both qualitative and quantitative uncertainty treatment, including confidence levels, probability methods, Generalized Likelihood Uncertainty Estimation (GLUE), and Bayesian modeling. Probabilistic climate scenarios from ensemble simulations can directly inform risk assessment, enabling risk-based impact evaluation. For instance, Luo et al. integrated greenhouse gas emission scenarios, climate sensitivity, and regional response uncertainties to assess climate change risks to wheat production in South Australia.

2.5 Risk Quantification Assessment Framework

Based on the three risk components—hazard, receptor vulnerability, and exposure—current quantification models fall into two categories. The first builds on traditional natural disaster risk assessment, where risk equals hazard multiplied by vulnerability and exposure. These models have clear indicators and solid research foundations but focus heavily on climatic hazards, limiting applicability when impact mechanisms, especially indirect pathways, are unclear. Such models have been applied to major meteorological and hydrological disaster risk assessment in China. The second category originates from system vulnerability, defining risk as the probability of exceeding critical vulnerability thresholds. These models first calibrate system vulnerability standards, then examine whether future climate change threatens these thresholds. This approach facilitates risk assessment when hazards are difficult to measure or impact chains are complex. Indicator system methods are commonly used, employing statistical approaches to hierarchically evaluate issues like ecosystem quality, biodiversity, and adaptation capacity.

3. Conclusions and Discussion

The theoretical paradigm for climate change impact and risk research follows the logical sequence: vulnerability assessment as the foundation, separation of climate factor influences, uncertainty analysis throughout, and dual foci on past impacts and future risks. Notably, climate change impact and risk assessment should be based on domain-specific vulnerability characteristics, but these domains often experience combined climate and human pressures. Therefore, strengthening climate impact separation is essential for scientific assessment. Due to limited understanding and analytical tools, effective differentiation of human versus non-climatic factors remains inadequate, creating substantial uncertainties in evaluating impact magnitude and scope, which constrains adaptation implementation.

Figure 3 [**Figure 3: see original paper**] Theory paradigms for climate change impact and risk research and corresponding analytical methods

During research implementation, the four paradigm elements should mutually reinforce each other, yet current studies often address only single components without fully developing the theoretical framework. For example, risk research frequently focuses solely on future projections without integrating vulnerability for quantitative assessment, while uncertainty analysis often concentrates on model performance comparisons rather than uncertainty propagation through risk formation processes. The chain-development 思路 inherent in the theoretical paradigm is essential for ensuring research completeness.

Comparative analysis across domains shows that agricultural research in China has relatively well-reflected this theoretical paradigm, employing field surveys, statistical models, and crop mechanism models for vulnerability assessment, attributing yield changes to climate trends, analyzing uncertainties through ensemble projections, and identifying key risks. Observation, experimental, and modeling methods support paradigm implementation. While observations provide validation data, they are often limited in scale. Numerical and statistical models continue developing as primary systematic research tools, though their assumptions and simplifications introduce uncertainties. Future research should adopt multi-indicator, multi-factor approaches, calibrate models with observational data, and couple mechanism models with regional climate systems to reduce uncertainties and identify ecosystem vulnerability and adaptation.

References

[1] IPCC. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. UK: Cambridge University Press, 2014.
[2] The Third National Assessment Report on Climate Change Editorial Committee. The Third National Assessment Report on Climate Change. Beijing: Science Press, 2015.
[3] Research on Adaptation Technology Framework for Climate Change. Resources and Environment, 2013, 23(5): 1-6.
[4] Impacts of Climate Change on China: Advantages and Disadvantages. Resources and Environment, 2014, 24(1): 7-13.
[5] Future Earth. Future earth initial design: report of the transition team. Paris, FRA: International Council for Science (ICSU). (2013) [2015-12-30]. http://www.futureearth.org/media/future-earth-initial-design-report.
[6] Frank DC, Esper J, Raible CC, Büntgen U, Trouet V, Stocker B, Joos F. Ensemble reconstruction constraints on the global carbon cycle sensitivity to climate. Nature, 2010, 463(7280): 527-530.
[7] Van Vuuren DP, Riahi K, Moss R, Edmonds J, Thomson A, Nakicenovic N, Kram T, Berkhout F, Swart R, Janetos A, Rose SK, Arnell N. A proposal for a new scenario framework to support research and assessment in different climate research communities. Global Environmental Change, 2012, 22(1): 21-35.
[8] Ge QS, Wang HJ, Rutishauser T, Dai JH. Phenological response to climate change in China: a meta-analysis. Global Change Biology, 2015, 21(1): 265-274.
[9] Kuhn TS. The Structure of Scientific Revolutions. Chicago: University of Chicago Press, 1962.
[10] Masterman M. The nature of a paradigm. In: Lakatos I, Musgrave

A, eds. Criticism and the Growth of Knowledge. Cambridge: Cambridge University Press, 1970: 59-89.
[11] The Rise of Complexity Paradigm and Transformation of Scientific Worldview. Journal of Peking University (Philosophy and Social Sciences Edition), 2012: 7-10.
[12] Füssel HM. Vulnerability: a generally applicable conceptual framework for climate change research. Global Environmental Change, 2007, 17(2): 155-167.
[13] Klein RJT, Nicholls RJ. Assessment of coastal vulnerability to climate change. Ambio, 1999, 28(2): 182-187.
[14] United Nations Framework Convention on Climate Change. Compendium on methods and tools to evaluate impacts of, and vulnerability and adaptation to, climate change. Bonn, Germany: UNFCCC Secretariat, 2008.
[15] Tao F, Zhang Z, Shi WJ, Liu YJ, Xiao DP, Zhang S, Zhu Z, Wang M, Liu FS. Single rice growth period was prolonged by cultivars shifts, but yield was damaged by climate change during 1981-2009 in China, and late rice was just opposite. Global Change Biology, 2013, 19(10): 3200-3209.
[16] Sensitivity and Vulnerability of Rice Production to Historical Climate Change in China. Chinese Journal of Agrometeorology, 2013, 33(2): 509-518.
[17] Hydrological Trends in the Middle Yellow River and Responses to Climate Change. Advances in Water Science, 2009, 20(2): 153-158.
[18] Wu SH, Yin YH, Zhao DS, Huang M, Shao XM, Dai EF. Impact of future climate change on terrestrial ecosystems in China. International Journal of Climatology, 2010, 30(6): 866-873.
[19] Tao FL, Zhang Z, Zhang S, Zhu Z, Shi WJ. Response of crop yields to climate trends since 1980 in China. Climate Research, 2012, 54(3): 233-247.
[20] Bao ZX, Zhang JY, Wang GQ, Fu GB, He RM, Yan XL, Jin JL, Liu YL, Zhang AJ. Attribution for decreasing streamflow of the Haihe River basin, northern China: climate variability or human activities? Journal of Hydrology, 2012, 460-461: 117-129.
[21] Re-understanding of Water Resources Issues in Northern China. Advances in Water Science, 2013, 24(3): 303-310.
[22] Latest Understanding of Climate Change Science. Advances in Climate Change Research, 2007, 3(2): 63-73.
[23] Taylor KE, Stouffer RJ, Meehl GA. An overview of CMIP5 and the experiment design. Bulletin of the American Meteorological Society, 2012, 93(4): 485-498.
[24] Research Progress on Climate Change Projection Under Different Emission Scenarios. Advances in Earth Science, 2008, 23(2): 174-185.
[25] Holland JH. Hidden Order: How Adaptation Builds Complexity. New York: Addison-Wesley, 1995.
[26] Leakey ADB, Uribelarrea M, Ainsworth EA, Naidu SL, Rogers A, Ort DR, Long SP. Photosynthesis, productivity, and yield of maize are not affected by open-air elevation of CO concentration in the absence of drought. Plant Physiology, 2006, 140(2): 779-790.
[27] Lessor RC, Ghini R. Effect of increased atmospheric CO concentration on powdery mildew and growth of soybean plants. Tropical Plant Pathology,

2009, 34(6): 385-392.
[28] Kang SZ, Zhang FC, Hu XT, Zhang JH. Benefits of CO enrichment on crop plants are modified by soil water status. Plant and Soil, 2002, 238(1): 69-77.
[29] Schimel D. Climate change and crop yields: beyond Cassandra. Science, 2006, 312(5782): 1889-1890.
[30] Prasad PVV, Boote KJ, Allen Jr LH, Sheehy JE, Thomas JMG. Species, ecotype and cultivar differences in spikelet fertility and harvest index of rice in response to high temperature stress. Field Crops Research, 2006, 95(2/3): 398-411.
[31] Reddy AR, Rasineni GK, Raghavendra AS. The impact of global elevated CO concentration on photosynthesis and plant productivity. Current Science, 2010, 99(1): 46-57.
[32] Walker WE, Harremoës P, Rotmans J, van der Sluijs JP, van Asselt MBA, Janssen P, von Krauss MPK. Defining uncertainty: a conceptual basis for uncertainty management in model-based decision support. Integrated Assessment, 2003, 4(1): 5-17.
[33] New M, Hulme M. Representing uncertainty in climate change scenarios: a Monte-Carlo approach. Integrated Assessment, 2000, 1(3): 203-213.
[34] Preliminary Discussion on Climate Change Risk Research. Advances in Climate Change Research, 2011, 7(5): 363-368.
[35] Jones RN. An environmental risk assessment/management framework for climate change impact assessments. Natural Hazards, 2001, 23(2/3): 197-230.
[36] Boyd DS. Remote sensing in physical geography: a twenty-first-century perspective. Progress in Physical Geography, 2009, 33(4): 451-456.
[37] IPCC. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report. UK: Cambridge University Press, 2007.
[38] Important Characteristics of Climate Change in China. Chinese Journal of Agrometeorology, 2005, 26(3): 170-173.
[39] Climate and Environment Evolution in China. Beijing: Science Press, 2005: 50-54.
[40] Research Progress on Impacts of Global Climate Change on Agricultural Ecosystems. Chinese Journal of Applied Ecology, 2007, 18(8): 1877-1885.
[41] Progress in Climate Change Impact Research. Chinese Science Bulletin, 2012, 42(6): 934-942.
[42] Pendall E, Bridgham S, Hanson PJ, Hungate B, Kicklighter DW, Johnson DW, Law BE, Luo YQ, Megonigal JP, Olsrud M, Ryan MG, Wan SQ. Below-ground process responses to elevated CO and temperature: a discussion of observations, measurement methods, and models. New Phytologist, 2004, 162(2): 311-322.
[43] Norby RJ, Luo YQ. Evaluating ecosystem responses to rising atmospheric CO and global warming in a multi-factor world. New Phytologist, 2004, 162(2): 281-293.
[44] Matsunami T, Otera M, Amemiya S, Kokubun M, Okada M. Effect of CO concentration, temperature and N fertilization on biomass production of

soybean genotypes differing in N fixation capacity. Plant Production Science, 2009, 12(2): 156-167.
[45] Wertin TM, McGuire MA, Teskey RO. The influence of elevated temperature, elevated atmospheric CO concentration and water stress on net photosynthesis of loblolly pine (Pinus taeda L.) at northern, central and southern sites in its native range. Global Change Biology, 2010, 16(7): 2089-2103.
[46] IPCC. Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report. UK: Cambridge University Press, 2014.
[47] Cramer W, Bondeau A, Woodward FI, Prentice IC, Betts RA, Brovkin V, Cox PM, Fisher V, Foley JA, Friend AD, Kucharik C, Lomas MR, Ramankutty N, Sitch S, Smith B, White A, Young-Molling C. Global response of terrestrial ecosystem structure and function to CO and climate change: results from six dynamic global vegetation models. Global Change Biology, 2001, 7(4): 357-373.
[48] Sitch S, Huntingford C, Gedney N, Levy PE, Lomas M, Piao SL, Betts R, Ciais P, Cox P, Friedlingstein P, Jones CD, Prentice IC, Woodward FI. Evaluation of the terrestrial carbon cycle, future plant geography and climate-carbon cycle feedbacks using five Dynamic Global Vegetation Models (DGVMs). Global Change Biology, 2008, 14(9): 2015-2039.
[49] Zhao DS, Wu SH. Vulnerability of natural ecosystem in China under regional climate scenarios: an analysis based on eco-geographical regions. Journal of Geographical Sciences, 2014, 24(2): 237-248.
[50] Uncertainty and Treatment Methods in Climate Change Impact Assessment Based on Model Simulation. Chinese Science Bulletin, 2011, 56(8): 547-555.
[51] Naylor RL, Battisti DS, Vimont DJ, Falcon WP, Burke MB. Assessing risks of climate variability and climate change for Indonesian rice agriculture. Proceedings of the National Academy of Sciences, 2007, 104(19): 7752-7757.
[52] New M, Lopez A, Dessai S, Wilby R. Challenges in using probabilistic climate change information for impact assessments: an example from the water sector. Philosophical Transactions of the Royal Society A, 2007, 365(1857): 2117-2131.
[53] Luo QY, Bellotti W, Williams M, Cooper I, Bryan B. Risk analysis of possible impacts of climate change on South Australian wheat production. Climatic Change, 2007, 85(1/2): 89-101.
[54] Risk Analysis of Extreme Climate Events and Insurance Adaptation Mechanisms in China. Beijing: Science Press, 2014: 78-80.
[55] Risk Patterns and Prevention of Major Meteorological and Hydrological Disasters in China. Beijing: Meteorological Press, 2008: 25-28.
[56] Jones RN, Mearns L. Assessing future climate risks. In: Lim L, ed. Adaptation Policy Frameworks for Climate Change: Developing Strategies, Policies and Measures. Cambridge, UK: Cambridge University Press, 2004: 119-143.
[57] Progress in Coastal Vulnerability Assessment Under Climate Change. Acta Ecologica Sinica, 2012, 32(7): 2248-2258.
[58] History and Dynamics of Physical Geography Development. Journal of Central China Normal University (Natural Sciences), 2003, 37(2): 269-272.

[59] Progress in Identifying Climate Change Contributions to Agricultural Yields Using Statistical Models. Acta Geographica Sinica, 2012, 67(3): 337-345.
[60] Probabilistic Prediction and Uncertainty Analysis of Climate Change Impacts on Wheat Biomass. Acta Geographica Sinica, 2012, 67(9): 1213-1222.
[61] Ye LM, Xiong W, Li ZG, Yang P, Wu WB, Yang GX, Fu YJ, Zou JQ, Chen ZX, Van Ranst E, Tang HJ. Climate change impact on China food security in 2050. Agronomy for Sustainable Development, 2013, 33(2): 363-374.
[62] Vulnerability and Adaptation of Forest Ecosystems to Climate Change. Journal of Natural Resources, 2007, 43(11): 138-145.

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