ADVANCES IN CLIMATE CHANGE RESEARCH 2(4): 203–210, 2011
www.climatechange.cn
DOI: 10.3724/SP.J.1248.2011.00203

REVIEW

Research Progress in Agricultural Vulnerability to Climate Change

Shengcai Tao[1,2,3], Yinlong Xu[1,2], Ke Liu[1,2], Jie Pan[1,2], Shiwei Gou[1,2]

[1] *Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences, Beijing* 100081, *China*

[2] *Key Open Laboratory of Agro-Environment and Climate Change, Agriculture Ministry of China, Beijing* 100081, *China*

[3] *Meteorological Bureau of Shenzhen Municipality, Shenzhen* 518040, *China*

Abstract

With the deepening of climate change research, more attention has been paid to vulnerability to climate change. Compared with water resources, forests and other natural ecosystems, agriculture is more vulnerable to climate change, thereby scientifically assessing agricultural vulnerability to climate change is of great significance to the formulation of rational and effective adaptation strategies. In this paper, the authors give a comprehensive review of the research from the perspective of the definition of climate change vulnerability and agricultural vulnerability to climate change, research topics, and evaluation methodologies. Existing problems in current research, including scenario application, methods, and uncertainties, are analyzed, and meanwhile, a vision of the direction for future research in assessment of agricultural vulnerability is also presented.

Keywords: climate change; vulnerability; agriculture

Citation: Tao, S., Y. Xu, K. Liu, et al., 2011: Research progress in agricultural vulnerability to climate change. *Adv. Clim. Change Res.*, **2**(4), doi:10.3724/SP.J.1248.2011.00203.

1 Introduction

Global climate change has become a major environmental problem affecting the future survival and the development of mankind, and it has attracted widespread attention of governmental organizations and academic community in the world. Agriculture is one of the sectors most sensitive to climate change, and any degree of climate change will bring potential or significant impact to agricultural production and related processes. Climate change has impacted agriculture of China significantly, and it will inevitably have a huge impact on agricultural production in the future. Even though the impact will vary by locations, as a whole it will be mainly adverse [*ECCNARCC*, 2007]. At present, assessment of climate change vulnerability is still a relatively new field of study. Although IPCC developed a dedicated research program specifically for assessment of climate change research, research work thus far indicates feasible methods to evaluate (especially in a quantitative way) different natural systems, human systems and for specific purposes are still lacking [*Xu and Ma*, 2009].

Since the 1990s, with the deepening of research on climate change impact on agriculture and adaptation, the vulnerability of agro-ecosystems and agricultural production to climate change has become the focus of study of scientists around the world. China is a large

Received: 25 July 2011
Corresponding author: Yinlong Xu, xuyl@ami.ac.cn

agricultural country located in a fragile ecological zone, strengthening the evaluation of agricultural vulnerability to climate change bears more practical significance [*NCCCCTO and MCCA21th*, 2004]. By studying the impact of climate change on agriculture and the agricultural vulnerability to climate change in different regions, it is of great significance for proactively adapting to climate change, developing effective adaptation measures and ensuring sustainable agricultural development, and also for providing a scientific basis for decision-making. In addition, scientific and reasonable evaluation of the vulnerability will provide meaningful results for risk analysis of climate change. Therefore, the evaluation of agricultural vulnerability to climate change is not only necessary, but it also is an important part of the research of climate change impact and adaptation. Through reflecting current knowledge and progress in the research of climate change vulnerability and agricultural vulnerability to climate change issues around the world, the authors hope to provide a meaningful reference for related studies in the future.

2 Vulnerability to climate change

2.1 *Definition of vulnerability to climate change*

The term vulnerability is widely used in different disciplines, because of the differences in their study objects and knowledge background, the understanding and definition of vulnerability can be very different. Vulnerability was originally used in the field of disaster studies to represent the extent of the injury. Later, with the growing influence of climate change issues, the concept was introduced to the field of climate science, and the IPCC First Assessment Report provided a preliminary elaboration of it. In 1996, the IPCC Second Assessment Report gave the definition of sensitivity and vulnerability. In 2001, the IPCC Third Assessment Report clearly defined the relationship among climate change sensitivity and adaptation and vulnerability with Eq. (1).

$$\text{Vulnerability} = f(\text{Exposure}, \text{Sensitivity}, \text{Adaptive capacity}) \tag{1}$$

Exposure refers to the extent and the characteristics as a system exposed to significant climate variability; sensitivity refers to the degree of influence as a system stimulated by climate-related factors, including the adverse and beneficial effects; adaptive capacity refers to ability of making profit and avoiding loss as the natural and man-made system affected by actual or expected climatic stimuli and their impacts. Vulnerability refers to the degree to which a system is susceptible to or unable to cope with adverse effects of climate change (including climate mean, variability, and extremes), and it is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity [*McCarthy et al.*, 2001]. This definition has been generally accepted by the academic community [*ECCNARCC*, 2007].

In 2007, the IPCC Fourth Assessment Report still used the definition in the Third Report, and provided a comprehensive description of the latest knowledge of climate change vulnerability and mitigation acquired by the international scientific community. The meaning of vulnerability to climate change is still evolving and marching toward perfection.

2.2 *Research progress in vulnerability to climate change*

The study of vulnerability started early abroad, general conceptual models for vulnerability have emerged in the field of climate change studies [*Kelly and Adger*, 2000; *Downing*, 2001; *Turner et al.*, 2003; *Yohe et al.*, 2003]. *Adger* [2006] summarized the process in the vulnerability research (Table 1). *Smit et al.* [2006] reviewed the state of human communities' adaption to global change (especially climate change), and their vulnerability and adaptive capacity under this background. *Hahn et al.* [2009] used the livelihood vulnerability index to assess vulnerability to climate change in some regions of Mozambique.

The assessment of vulnerability to climate change in China started later than abroad, and the studies have focused on areas such as natural ecosystems, agriculture (crop) production, and water resources [*Tang et al.*, 2000; *Yin and Wang*, 2004; *Li et al.*, 2005; *Pan*,

Table 1 Research process of vulnerability

Vulnerability approach	Objectives
Vulnerability to famine and food insecurity	Developed to explain vulnerability to famine in the absence of shortages of food or production failures. Described vulnerability as a failure of entitlements and shortage of capabilities
Vulnerability to hazards	Identification and prediction of vulnerable groups, critical regions through likelihood and consequence of hazard. Applications in climate change impacts
Human ecology	Structural analysis of underlying causes of vulnerability to natural hazards
Pressure and release	Further developed human ecology model to link discrete risks with political economy of resources, and normative disaster management and intervention
Vulnerability to climate change and variability	Explaining present social, physical or ecological system vulnerability to (primarily) future risks, using wide range of methods and research traditions
Sustainable livelihoods and vulnerability to poverty	Explains why populations become or stay poor based on analysis of economic factors and social relations
Vulnerability of social-ecological systems	Explaining the vulnerability of coupled human environment systems

2008]. In recent years, many scholars have done a lot of work in sorting knowledge of vulnerability and assessment research. For example, *Fang et al.* [2009] gave a comprehensive review of the research progress of vulnerability to climate change abroad.

3 Agricultural vulnerability to climate change

3.1 *Definition of agricultural vulnerability to climate change*

Agricultural vulnerability to climate change has not been clearly defined. At first there was only qualitative research of food security vulnerability to climate change [*Downing*, 1991; *Rosenzweig and Parry*, 1994]. The U.S. Department of Agriculture defined vulnerability as the potential for negative consequences that are difficult to alleviate through adaptive measures given the range of possible climate changes that may occur in certain areas of a region, which is the concept of inter-regional comparison [*Reilly*, 1996]. According to the definition of vulnerability to climate change given by the IPCC assessment report, agriculture vulnerability to climate change is the manifestation of the agricultural sensitivity and adaptive capacity to climate changes [*Wang*, 2003], and it changes with the location, time, and socio-economic and environmental situations. Agricultural vulnerability to climate change is the function of characteristics of climate variability, magnitude, and rate of variation within the agricultural system, and the system's sensitivity and adaptive capacity, and it is the degree to which the agricultural system is susceptible to, or unable to cope with adverse effects of climate change including climate variability and extreme events [*Hou and Liu*, 2003]. It is worth noting that in literatures both climate vulnerability and climate change vulnerability have basically the same meaning, which should be differentiated from the vulnerability of agricultural systems themselves.

3.2 *Research progress of agricultural vulnerability to climate change*

Research work in the quantitative assessment of agricultural vulnerability to climate change started early outside China. Such study has gone through three stages: the first stage was studying the vulnerability of crop yield, growth period among other indicators to temperature, precipitation, and other climate factors [*Iglesias et al.*, 2000; *Alexandrov and Hoogenboom*, 2000]; second stage was mainly on the adaptation capability, focused on the exploration of adaptation and response measures [*Burton et al.*, 2002; *Fischer et al.*, 2002]; and the third stage not only dealt with the sensitivity of agriculture to climate change and adaptability, but it also took into account the ability of climate change mitigation [*Zheng et al.*, 2009]. For example, there was regional case study exploring the ways and means of quantitative evaluation of the vulnerability to climate change [*Luers et al.*, 2003]. International Institute for Applied Systems Analysis (IIASA) used Agro-Ecological Zones-Basic Linked System (AEZ-BLS) model for comprehensive evaluation of the world's food vulnerability to climate change.

Since the 1990s, Chinese scholars have continued to improve and optimize research methods to study agricultural vulnerability to climate change. At first, many used indicator system method [*Liu and Lei*, 2002; *Liu*, 2002], because there were many factors and their relationships were complicated, only a few main factors could be used with the indicator system method, and the designed evaluation method were relatively simple. Then wavelet analysis, mathematical statistics, correlation clustering, close value method, analytic hierarchy process (AHP) and fuzzy evaluation principle and other methods were gradually introduced [*Tang*, 2007]. In recent years, application of models has provided a new way for the evaluation of vulnerability to climate change. For instance, the use of regional climate models, socio-economic models, crop models, and GIS technology has played an important role in the comprehensive study of vulnerability to climate change [*Sun*, 2005; *Yang et al.*, 2005; *Xiong et al.*, 2010]. Many scholars [*Luo and Wu*, 2010; *Cai and Smit*, 1996] summarized agricultural vulnerability studies from different perspectives, which included these three main aspects: sensitivity area classification, regional vulnerability, and the vulnerability analysis of major crops. Based on this, Chinese scientists are carrying out the assessment of agricultural vulnerability to climate change through an integrated approach, for example, Adaption to Climate Change in China (ACCC) is a program attempting to comp-

Table 2 Typical studies on the assessment of agricultural vulnerability to climate change in China

Method	Content	Main conclusions and results	Reference
Statistical analysis method	Based on the yield and climate data in rained farming areas of Gansu, the variations of climate and yield were analyzed, and the vulnerability of autumn grain crops in these areas was estimated. The results showed that the climate represented to become warmer and drier in recent 40 years, which was disadvantageous to productivity increase	In areas where the weather factors strongly fluctuated, the production of autumn grain was very vulnerable. The strong vulnerable areas were the eastern part of east Gansu and northern part of Tianshui	[*Wang et al.*, 2006]
Indicator system method	By use of the results of GCM forecast, the possible changes of disaster index are evaluated. The possible change of climate vulnerability of agricultural production in the future in the Loess Plateau is forecasted	The most vulnerable counties will be focused on Huining to Wushan areas which are in the west of Liupanshan, central part of northern Shaanxi, southern part of Ningxia and the eastern part of Gansu	[*Hou and Liu*, 2003]
	The sensitivity index was defined as the climate yield divided by climate potential productivity. Adaptation index was the trend-yield divided by climate potential productivity. Vulnerability index was equal to sensitivity divided by adaptation. Based on these definitions, crop production vulnerability to climate change in Heilongjiang province was analyzed	Spatial distribution of vulnerability index was similar to that of the sensitivity index. As for time variation, the magnitude of the increase of the sensitivity index was the largest, while the magnitude of the increase of vulnerability index was decreasing	[*Duan et al.*, 2008]
	An indicator model for comprehensive evaluation of rice crop vulnerability to climate change was built, and Jiangxi province was chosen as a case area to analyze regional distribution of rice production vulnerability to climate change within the province	The sensitivity of Jiangxi rice was mainly in low to moderately sensitive states, and the adaptation was mainly in low and moderately adaptive states, while the vulnerability of Jiangxi rice was high and it is in moderate to highly vulnerable states	[*Zhu and Zhou*, 2010]
	An mixed zone for agriculture and herd production located in a typical region with vulnerable agro-ecosystem in the north was chosen as a case to construct an indicator system with 17 indices under 4 categories for agro-ecosystem vulnerability assessment	The weight of each index was determined by using analytical hierarchy process, and the method for comprehensively and quantitatively evaluating the vulnerability of agro-ecosystem was established based on the principles of fuzzy estimate	[*Zhao et al.*, 2007]

Table 2 Continue

	The regional agricultural vulnerability to climate change was assessed using the Ningxia Hui Autonomous Region as a case study. By selecting sensitivity and adaptive capacity factors and determining their weights with Artificial Neural Network (ANN) technique, and using climate change scenarios data under A2 and B2 scenarios from the regional climate model system Providing Regional Climates for Impacts Studies (PRECIS) developed by the UK Hadley Center and socio-economic scenario data from the Chinese Academy of Social Sciences, the assessment of agricultural vulnerability to climate change in the future was performed	The study documented the characteristics of temporal and geographical distribution of agricultural vulnerability to climate change in Ningxia	[*Tang*, 2007]
	The spatial unit for this analysis was township. For each of the township values of six indices reflecting the economic activities of local farmers were computed. These indices were: percentage of rural population, percentage of farmland, GDP per acreage, percentage of employment in the first industry, net income per farmer, and percentage of agricultural income. The values of these six indices were then normalized and used for vulnerability assessment	There are large-scale flood risk areas which have a great impact on livelihood of the farmers in the Poyang Lake Region (PLR). 55.56% of 180 townships in flood risk areas have a high degree of vulnerability to flood. These townships stand at the lakefront around the Poyang Lake and the alongshore zones at the "Five Rivers"	[*Ma et al.*, 2007]
Model simulation method	By using climate change scenario produced by PRECIS and the wheat yield data generated by CERES model, the sensitivity and vulnerability of wheat, maize and rice to future climate change in China were studied based on the yield variation and GIS mapping	Preliminary map of the distribution of sensitivity and vulnerability areas of three major grain crops in China were created	[*Sun et al.*, 2005; *Yang et al.*, 2004]
	Based on drought risk theory of natural vulnerability of crops, natural vulnerability curve of typical wheat varieties was simulated by using the drought hazards strength of Chinese wheat and crop growth module in EPIC	Quantitatively assessed the spatial and temporal distribution of drought risk of China's wheat	[*Wang et al.*, 2010]
	To meet integration purpose, the author proposed a framework for vulnerability assessment based on the clarity of definition in view of local ecological risk and vulnerability. The framework included eight steps and the indicator structuring technique which uses the vulnerability scoping diagram (VSD) to organize the data in a circular assessment diagram with vulnerability as the center	Constructed indicators and parameters of vulnerability assessment in sample areas by using VSD model	[*Liu et al.*, 2009]
Comprehensive evaluation method	By using designated comprehensive assessment framework, vulnerability to climate change in the western regions of China was evaluated, which included devising climate scenarios, analyzing sensitivity, determining indicators of vulnerability, surveying and counting adaptation strategies, measuring adaptation capacity, assessing vulnerability, and other steps	Comprehensively evaluated vulnerability to climate change in the western region of China	[*Yin and Wang*, 2004]
	Using a variety of models, indicators and tools, the authors comprehensively evaluated vulnerability to climate change of integrated agro-ecosystem and water resources in the Yangtze River Basin near Shanghai	Most of ecosystem of the Yangtze River Basin was less vulnerable to climate change, but it was more susceptible to extreme events	[*Xu and Ma*, 2009]

rehensively evaluate the agricultural vulnerability to climate change in China.

Table 2 shows main methods that Chinese scholars used in recent years to evaluate agricultural vulnerability to climate change. Statistical analysis method is represented by using a series of observation (statistics) indices combined with functions, and setting counter range for each vulnerability index by comparing to historical statistics. In conducting vulnerability assessments, if the observation value is in the counter range, then the system is considered stable or of low vulnerability even no vulnerability; and vice versa. The disadvantage of this method is that one can only carry out vulnerability analysis for one index each time, which will bring about inconsistencies within the system for complex agricultural system [*Tang*, 2007]. Indicator system method establishes a reasonable index system by comprehensively considering the factors impacting agricultural vulnerability to climate change, and assigning weight according to the importance of each factor, then obtaining agricultural vulnerability to climate change by the weighted sum of factors. This method is the most commonly used evaluation method, but there is a big problem in establishing reasonable evaluation index system and scientifically setting the weight of each index. Comprehensive evaluation method will also consider the combined effect of the biophysical and socio-economic factors to evaluate the agricultural vulnerability to climate change, which is to take into account sensitive factors to climate change in agriculture and also the factors of its adaptation capacity. In this way, it can more comprehensively and objectively analyze the extent of agricultural vulnerability to climate change, and eliminate the shortcomings of the first two methods, which is the direction of the development of assessment methods for agricultural vulnerability to climate change in future [*Tang*, 2007; *Tang et al.*, 2010].

4 The research prospects of agricultural vulnerability to climate change

Although the assessment study of agricultural vulnerability to climate change made some findings, research methods and tools are also under rapid development, so far no widely accepted method has been found. Major problems in the existing studies and the directions of the development are as follows. 1) Currently, the indicator system method was widely used to study vulnerability problems, because of the complex relationship among affecting factors and multiple factors involved and other reasons, how to scientifically construct a reasonable indicator system and determine the index weight (such as, expert analysis, AHP, and artificial neural network method, all have obvious advantages and disadvantages) become the bottleneck of the indicator system method [*Liu and Lei*, 2002; *Tang et al.*, 2010]. More research work in building target, determining weights and mutual relations of indices is needed in future. 2) The adaptation capacity is an important aspect of vulnerability, quantitative research of adaptation capacity is still scarce at present, which should be strengthened in future. 3) The analysis and assessment of vulnerability are two aspects of vulnerability research. Vulnerability of agricultural systems and agricultural vulnerability to climate change should be scientifically identified and distinguished in research, and the problem of uncertainty should be considered in the evaluation process [*Patt et al.*, 2005]. 4) In the assessment of future agricultural vulnerability to climate change, lack of socio-economic scenario data and relatively simple climate scenarios currently applied need to be studied, besides, attention should be paid to availability and reliability of data and information.

With deepening research of climate change, the methods and tools for vulnerability assessment will be innovated and developed. The focus of the research will be moving from the natural ecosystem to a coupled system [*Li et al.*, 2008] (human-environment coupling system, social-ecological system, human-land system, etc.). The scale and level of evaluation will continue to change, and the uncertainties in researches will be constantly identified and reduced.

Acknowledgements

This study is supported by the China Meteorological Administration (No. GYHY200806008) and the China-UK-Swiss ACCC Project.

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