Vulnerability assessment and adaptation of dryland agriculture on the Chinese Loess Plateau and Australian Wheatbelt

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A thesis submitted in fulfilment of the requirements

for the degree of Doctor of Philosophy

School of Life Sciences

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April 2017

Certificate of original authorship

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

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18/04/2017

Acknowledgements

This project was funded by the joint China Scholarship Council (CSC) and the University of Technology, Sydney (UTS) Doctor of Philosophy (PhD) Scholarship. I extend my heartfelt gratitude to many people who helped me during the process of completing my project both in life and work.

I would like to firstly thank my supervisor Prof. Qiang Yu for his open minded supervising style, enthusiasm, encouragement and considered advice. Thanks for your conceptual input and support during all those PhD crises. Also thanks to my co-supervisors Dr. Anna Roberts, Director of Natural Decisions Pty Ltd and former Senior Research Scientist at Department of Primary Industries Victoria (DPI), who is particular assisted early on in the project, and Dr. Longhui Li from UTS, whose critical advice encourage me to become a better researcher.

I would also give my appreciation to my predecessors, collaborators, colleagues and friends. Dr. Chao Chen from CSIRO Agriculture Flagship, Dr. Hongtao Xing from CSIRO Land and Water and Dr. Liang He from National Meteorological Center of China Meteorological Administration shared their knowledge and gave me advices on my crop model studies; Dr. Wenzhao Liu and Wen Lin from Institute of Soil and Water Conservation Chinese Academy of Sciences and Ministry of Water Resources, assisted field experiments and data collection at Changwu station. Dr. Roger Cremades from Climate Service Center Germany (GERICS) gave helpful comments and feedback on my journal article publication. Prof. Alfredo Huete and his team members at UTS helped me practise for my stage assessment presentation and were willingness to help when I had funding issues. Zunyi Xie, Hao Shi, Jianxiu Shen, Qinggaozi Zhu, accompanied me for most of my time and we had enjoyable experience together at UTS. All these bit by bit in life and work and relationships are appreciated and cherished. Last, I want to thank my family for their endless support.

Abstract

Sustainable agricultural production on drylands faces challenges from increasing food demand and climate change. The interrelated issues of production instability, vulnerability to climate change and the need for effective adaptations require a comprehensive and integrated ecological-economic assessment. Accordingly, this thesis examines two key dryland agricultural regions, the Australian Wheatbelt and the Chinese Loess Plateau, to provide new insights and improved approaches for dryland agricultural management.

Decomposition analysis was undertaken to identify the driving forces in growth and instability of Australian wheat production from 1900-2010. Results show that instability of Australian wheat production has not been reduced significantly in the past century. The increasing trend of wheat production was mainly due to sowing area increases whilst the yearly fluctuation of production is mainly caused by variable yields. A focus on yield alone may therefore bias assessments of the vulnerability of agriculture to climate change.

A conceptual framework was developed to assess the agricultural vulnerability of 243 rural counties on the Chinese Loess Plateau. A vulnerability index for each county was calculated from statistical indicators. Within the 49 most vulnerable counties, 42 were characterised by high exposure and sensitivity but low adaptive capacity. The most vulnerable area was found to be located in the central northeast-southwest belt of Loess Plateau.

Upon identifying vulnerable areas, the effectiveness of the regionally significant adaptation, plastic film mulching, on maize growth was assessed in the Loess Plateau. The APSIM model was calibrated and validated using field experiment data, then applied to simulate maize growth during 1961-2010 at Changwu station. Plastic film mulching could significantly increase maize yields by an average of 15.3%, and increase the cumulative probability at mid-range yield levels at Changwu. The advantage was found to be more pronounced in dry years than wet years. Geostatistical analysis was used to extend the modelling across the Loess Plateau to identify areas with climate favourable for adopting plastic film mulching. The central south presented high and stable production while the northwest showed the greatest potential in yield increase and variability reduction.

The multiscale studies concern both developing and developed counties, can be referenced to location-specific information for policy makers and researchers. The principles, frameworks, technologies and tools can be modified and adopted in other dryland regions.

Key words: Dryland, Australian Wheatbelt, Loess Plateau, Climate change, Agricultural production, Vulnerability, Adaptation

Symbols and abbreviations

ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
ABS	Australian Bureau of Statistics
APSIM	Agricultural Production Systems sIMulator
CSIRO	Commonwealth Scientific and Industrial Research Organisation
ESW	Extractable soil water
FAO	Food and Agriculture Organization of the United Nations
IPCC	Intergovernmental Panel on Climate Change
LAI	Leaf area index
WUE	Water use efficiency
RCP	Representative concentration pathways
UNDP	Office to Combat Desertification and Drought
UNSO	United Nations Sudano-Sahelian Office
$	dollar/s

°C	degrees Celsius
ca.	approximately
e.g.	for example
ha	hectare
kg	kilogram
km	kilometre

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Chapter 1: Introduction

1.1 Problem statement

Increasing demand for food in the future will impose considerable pressure on agricultural resources. It is expected that the world's population will reach 9.1 billion by 2050 (UN DESA 2009; Alexandratos and Bruinsma 2012), which requires an approximately 70% increase in food production to achieve food security (FAO 2009). Much of the emergent pressure will fall on dryland regions, despite these having less than 179 annual crop growth days per year by definition (Bot et al. 2000; Koohafkan and Stewart 2008). Drylands are home to more than 38% of the total global population and support 44% of the world's cultivated systems (Bot et al. 2000; Huang et al. 2016). In the context of climate change, dryland areas are projected to continue expansion by 23% and 11%, respectively relative to 1961-1990 baseline under representative concentration pathways (RCPs) RCP8.5 and RCP4.5 (Huang et al. 2016). It is estimated that drylands may sustain 51% of the global population growth from 2000 to 2025 (Huang et al. 2016). As dryland regions are one of the most sensitive areas to climate change and human activities (Huang et al. 2016), the increasing aridity, enhanced warming and rapidly growing human population will exacerbate the risk of land degradation and desertification in the near future in the drylands. The population growth will demand more agricultural production to sustain it. Agriculture on dryland regions has therefore become a focus for management activities aiming to ensure adequate and stable food supplies, increased rural incomes and lower food prices, thereby making food more accessible to the poor. There are, however, studies reporting that crop production in many dryland regions repeatedly falls short of the expected demand and that the yield of major crops has stagnated or even declined (Lake 2012), with prominent examples including wheat in inland east Australia and maize in north China and east Africa (Ray et al. 2012). The stagnation, decline and instability of production is a major threat to dryland regions striving for food self-sufficiency through domestic production and the sources of this instability must be identified.

Stagnating, declining and unstable yields in various dryland agricultural systems are reported to occur as a result of numerous factors, many of which are common to these systems. Foremost amongst these factors is that dryland agriculture is typically dependent on water resources from precipitation, with irrigated areas often subject to increasingly restrictive limitations on water use. Thus, production often experiences large fluctuations between years according to rainfall, with yields sometimes ranging as far as three times higher or lower than that of recorded averages (Koohafkan and Stewart 2008). Furthermore, natural resources in dryland regions are generally in poor health. Dryland soils are often coarse texture, low in fertility, organic matter and water-holding capacity, whilst being highly susceptible to wind and soil erosion (Venkateswarlu and Shanker 2012). Amongst the inhabitants of dryland regions who depend on agricultural production for subsistence, there is often a lack of capital available in quantities sufficient to allow investment in processes necessary to bring about sustainable production of food in the context of unfavourable climate and poor natural resources. All these interrelated internal biophysical and external social-economic factors make dryland agriculture systems more susceptible to changes in climate, which will exacerbate the aforementioned challenges inherent to dryland agricultural production through increasing temperature, variable rainfall and greater frequency and intensity of extreme events such droughts (Stern 2007).

Adaptation is becoming an increasingly important component in the management of dryland regions (Smit and Skinner 2002; Thomas 2008; Asseng and Pannell 2012). With appropriate adaptation strategies, the food security of dryland agriculture can be improved in a cost efficient manner (Lobell et al. 2008; Hannah et al. 2013; Fuss et al. 2015). Adaptations in agriculture should vary with respect to the driving factors to which adjustments are made (e.g. various attributes of climate change, including variability and extreme events) and according to the differing farm types and locations, and the economic, political and institutional circumstances in which the climatic stimuli are experienced and management decisions are made (Smit and Skinner 2002). This presents a challenge for the management of dryland regions, as despite many similarities and common challenges that can increase the efficiency of research and development activities when targeted, there is also great diversity. Dryland regions occupy extensive areas in all continents of the world, spreading from Africa, Asia, to Oceania (Fig. 1.1). These areas account for approximately 40% of the world's land area, and can be further classified into arid (12%), semiarid (18%) and dry subhumid (10%) zones (UNSO/UNDP 1997; White and Nackoy 2003; Koohafkan and Stewart 2008).

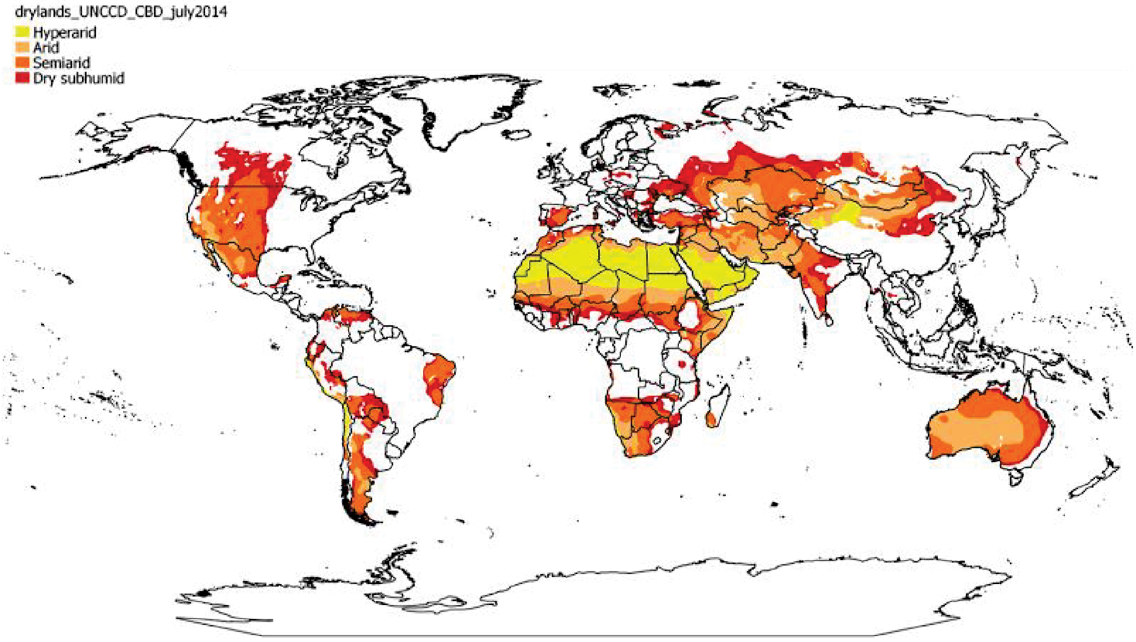


Fig. 1.1 Map of global drylands (Source: Millennium Ecosystem Assessment).

Importantly, dryland systems are present in both developing (most counties in Africa, north-east China) and developed regions (west Australia and East America). Because of the vast and varied geographical contexts, different level of adaptive capacities and the extent of dependence on climate sensitive agriculture and natural resource sectors across these dryland regions, an unequal distribution is expected in the vulnerability of their agricultural systems (Stern 2007; Collier et al. 2008; World Bank 2010; Dasgupta et al. 2014). Vulnerability has been defined as the degree to which geophysical, biological and socio-economic systems are susceptible to, and unable to cope with, adverse impacts of climate change (IPCC 2001). Similarly, agricultural vulnerability is the degree to which the agricultural system is susceptible to, or unable to cope with adverse effects (Hou and Liu 2003; Tao et al. 2011). How best to account for the interrelated factors of agricultural vulnerability in dryland regions and assess their contributions to the stagnating, declining and unstable yields is an imperative concern for understanding and adapting to the issues facing dryland agricultural systems, yet there is a need for novel approaches to quantify and compare vulnerability across systems. Furthermore, mapping spatial differences to identify vulnerable areas of priority intervention is necessary for planning and implementing adaptations for both policy makers and local farmers.

This thesis accordingly represents a cohesive investigation into the management of dryland agricultural systems in the context of the growing need for stability in production from those regions. First, the management of dryland agricultural systems is reviewed, with the Australian Wheatbelt and the Loess Plateau of north western China serving as case studies; the joint University of Technology Sydney and China Scholarship Council scholarship provides a valuable opportunity to transfer technology and knowledge between these two regions which are respectively developed and developing. Second, an analysis of the sources of instability in the production of wheat in the Australian Wheatbelt is conducted, applying statistical methods to yield new insight into future management of this region. Third, the concept of agricultural vulnerability is introduced from the perspective of developing a novel framework for quantifying and comparing agricultural vulnerability in the Loess Plateau. The framework is applied to the Loess Plateau and the results reported, with the implications for the management and adaptation in this region are discussed. Fourth, the Agricultural Production Systems sIMulator (APSIM) is introduced and evaluated for predicting the effect of an emergent adaptation option of interest. Finally, the modelling approach developed in the previous process is scaled out to the entire Loess Plateau, demonstrating how this technology can be used to inform decisions for the management of dryland regions.

1.2 Research questions

This thesis aims at developing an understanding of dryland agricultural systems in the context of increasing food demand and changing climate, then incorporating this understanding into the formulation and application of management support tools. To achieve this aim, five research questions were devised which would sequentially generate the prerequisite knowledge and tools as they were addressed throughout the candidature.

1. What are the specific challenges in aspects of dryland agricultural production and managements for the two dryland regions?
2. What are the driving forces of wheat production growth and instability in Australia?
3. How to quantify spatial variation of agricultural vulnerability across the Loess Plateau to support policy making?
4. How to assess the effectiveness of plastic film mulching as an adaptation?
5. Where and how the climate variation in the Loess Plateau may influence the effect of plastic film mulching and its estimated potential to reduce vulnerability?

A schematic diagram of the relationship between each question within a cohesive body of work is provided in Fig. 1.2. The specific aims and associated research questions are presented below.

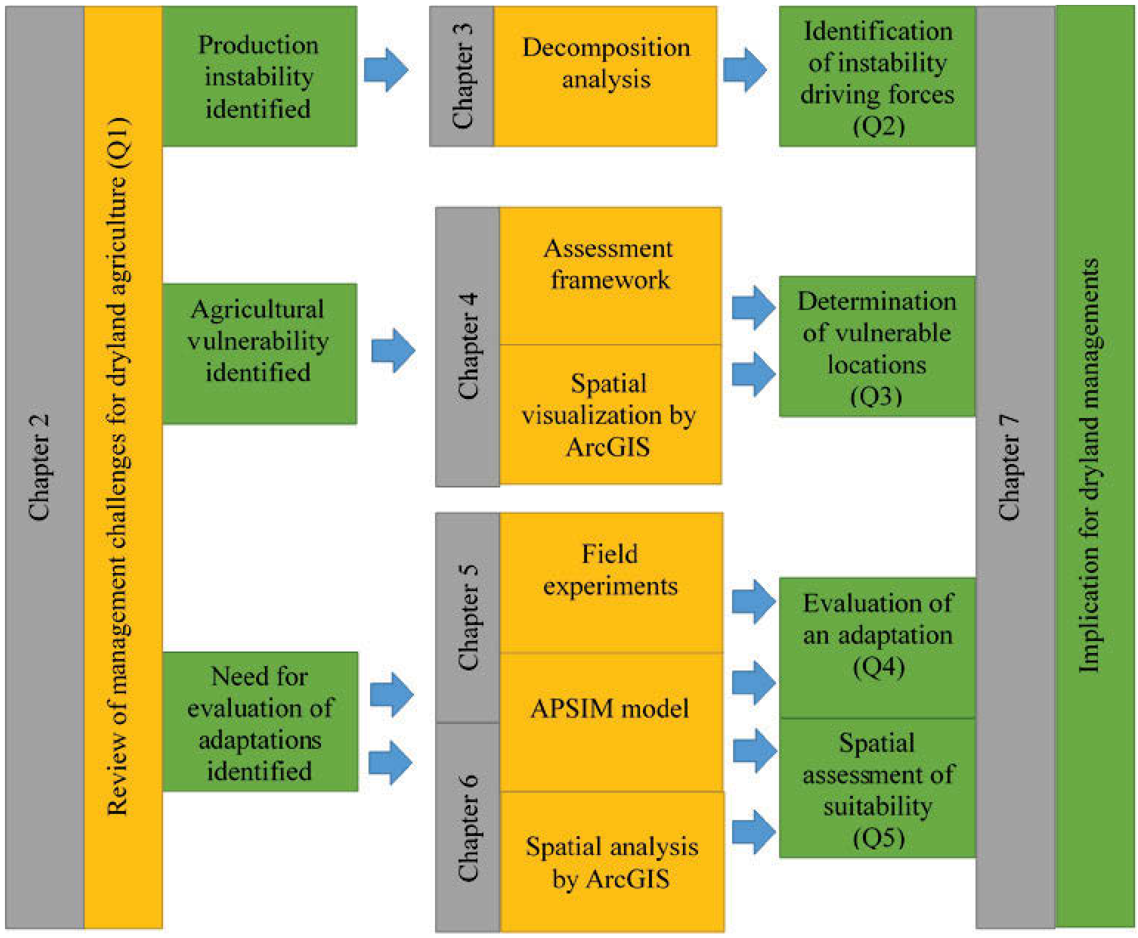


Fig. 1.2 Representation of the thesis structure and research questions showing the chapter numbers (grey boxes), research activities (yellow boxes) and outputs (green boxes).

1: What are the specific challenges for the management of dryland agricultural production?

The geography, history and current management policies of dryland agricultural systems fundamentally determine the threats, opportunities and needs of these systems. Accordingly, the second chapter of the thesis establishes comprehensive context for the investigation. Various secondary sources, primarily peer reviewed journal articles and statistical yearbooks, were reviewed with a specific aim of determining how the current state of key dryland agricultural regions affect their options for management. The

Australian Wheatbelt and the Loess Plateau of north western China are introduced as case studies which are compared and contrasted. The threat of unstable production is explored.

2: What are the driving forces of wheat production growth and instability in Australia?

Unstable agricultural production ultimately derives from a combination of two aspects, changes in area and changes in yield per unit of area. Due to the marginal nature of many dryland regions, the change can be proportionally large. Studies have reported there will be an increased variability of production, decrease of production in certain areas on dryland and changes in the geography of production (Ray et al. 2012). However, most research is limited to study on the instability of yield, the other aspect of agricultural production, unstable cropping area, is generally ignored. Decomposition analysis will be valuable to target where and how to improve the agricultural production and reduce the instability specifically. In Chapter 3, a method for decomposing production data into contributions of area and yield is described and applied to address this research question. In most developing dryland regions, including the Loess Plateau of western China, the availability and reliability of data is questionable and accordingly, the Australian Wheatbelt was chosen as case study for the analysis in order to meet the contextual goals of the candidature including technological transfer.

3: How can spatial variation of agricultural vulnerability be quantified?

Dryland agricultural regions are often heterogeneous in terms of climate, socio-economic conditions and landform. Therefore, understanding the regional differences in circumstances that impact on the vulnerability to climate variability of rural communities has practical significance. The concept of vulnerability however, currently lacks one generally accepted and precise definition. Vulnerability has acquired increased complexity as a multi-dimensional concept that encompasses a variety of elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt (Gallopin 2006; Füssel 2007). It is consensus that vulnerability to climate variability and change is determined by a combination of multiple biophysical and social factors (IPCC 2014). Based on a review of existing research into vulnerability to climate change, a novel framework for quantifying and comparing agricultural vulnerability in the Loess Plateau is developed in Chapter 4 to quantify vulnerability by the combination of indicators for exposure, sensitivity and adaptive capacity. The process of indicator selection and the consideration for uncertainty analysis are outlined in detail.

Urgent adaptations are needed for parts of the Loess Plateau in the face of climate change and the expectation of even greater climatic variation in the future. Assessment and mapping of agricultural vulnerability to climate related stressors could identify regions and is an important process in the formulation and implementation of appropriate adaptation measures and priority setting for agricultural investment (Watson et al. 2013), however this has been seldom attempted on the Loess Plateau. Previous studies at the administrative county level are rare, with incomplete or inconsistent findings due to different study focuses and scales. Capturing complex interactions of anthropogenic activities and the environment at this scale in a holistic manner was attempted by applying the framework developed in Chapter 4 to the Loess Plateau. The process of applying geostatistical and spatial analysis tools using ArcGIS for visualization exercises is described. The results are reported and the implications for the management and adaptation in this region are discussed.

4: How to assess the effectiveness of plastic film mulching as an adaptation to reduce vulnerability?

Appropriate adaptation measures to reduce the vulnerability of agricultural production provide a more effective route to adapt to the effects of rapid climate change. Local food security will be enhanced if more grain can be produced with the same amount of agricultural resources, and if variability in productivity is reduced by better management practices. Local governments at various levels have started to develop adaptation plans and policies and to integrate climate-change considerations into broader development plans. It is farmers, however, who are the managers of the natural resources and are the ultimate decision-makers about the implementation of any conclusions derived from indicators for unsustainable resource management. Adaptations must therefore be palatable and accessible to farms. Plastic film mulching has been widely used as adaptation options to improve the dryland agricultural productivity and reduce instability due to the prevalence of moisture deficit. Many studies based on experiments have been conducted with a lot of informative results and implications. However, as climate is changing over time and different at locations, so too should adaptation be dynamic, thus experiments are limited by short terms and site specificity. To compensate, physical process-based models designed for crop ecosystem simulation, in which the environmental and management factors and their interactions are integrated, are broadly used to project the response of crops to climate scenarios. The Australian crop model, APSIM, is one such model that was developed to improve risk management under variable climate conditions (McCown et al. 1996; Keating et al. 2003). In Chapter 5, APSIM is introduced and evaluated for predicting the effect of an emergent adaptation option of interest, plastic film mulching. The process of parameterising the model to simulate the effects of plastic film mulch on maize yield is described and applied to Changwu research station in the Loess Plateau.

5: Where and how does climate variation in the Loess Plateau influence the effect of plastic film mulching and its estimated potential to reduce vulnerability?

Finally, the modelling approach developed in the previous process is scaled out to the entire Loess Plateau, demonstrating how this technology can be used to inform decisions for the management of dryland regions.

In the penultimate chapter, the production of spring maize under different treatments with and without plastic film mulching across the entire Loess Plateau is explored. The previously described and adapted simulation model from Chapter 5, linked to a Geographic Information System, is used to provide new insight on where and how climatic variations in the Loess Plateau may influence the effect of plastic film mulch on maize productivity. This information is then overlayed with the vulnerability map developed in Chapter 3. The results presented in Chapter 6 will contribute to the identification of areas with both a suitable climate for producing spring maize cultivar 'Xianyu 335' under plastic film mulch and a level of vulnerability where this kind of adaptation is a worthwhile pursuit. Results can be referenced to location-specific information for policy makers and researchers.

1.3 Contributions to knowledge

Mankind cannot overcome food insecurity and poverty without first addressing the issues of sustainable agricultural and rural development. These challenges require a comprehensive and integrated ecological-economic assessment of the impact of climate change on agro-ecosystems in the context of food security and climate change. The present body of work contributes to these requirements by providing new insights and improved approaches related to dryland agricultural management. As the work of an international student from China studying in an Australian university, this thesis takes advantage of access to data and techniques from both countries. The principles, advanced technologies and tools used in dryland agriculture within Australia are a valuable source of learning and can be transferred and adopted to assist in the development of dryland regions in China. A novel decomposition analysis of the sources of instability in Australian wheat production emerged from this work, with the findings presented to the Australian Agricultural and Resource Economics Society in Canberra. The method is universal and can be applied in different regions where the appropriate data are available.

An assessment framework for agricultural vulnerability was adopted and developed which emphasises the specific driving factors for vulnerable dryland agriculture. The characteristics of this framework enabled the creation of a comprehensive and integrated analysis of vulnerability in the entire Loess Plateau of western China at the county level, which has not been achieved previously. Furthermore, the method was not limited to the calculation of vulnerability; the assessment includes statistical analysis of the relationship between vulnerability components in the Loess Plateau. The findings were adapted into a peer-reviewed academic report accepted and published in *Ambio: A Journal of the*

Human Environment (Average 2010-2016 impact factor 2.55). Building on these outcomes, this work has integrated the results into the wider management plan currently in place for the region, which provides novel insight to policy-makers.

The spatial evaluation of plastic film mulching as a water saving technology for use in rain-fed areas of the Loess Plateau provides a ready to use references for decision makers contemplating this technology as a pathway to improve the lives of people who live in dryland areas. It also provides more general evidence of the potential benefits that can be achieved with a shift from conventional agriculture to a more conservation-effective agriculture in the region.

Overall, the multiscale studies concerning both developing and developed counties presented in this thesis can provide useful information for the rest of the world as it prepares for the challenges ahead in the management of dryland agricultural systems.

Chapter 2: Dryland agricultural production, vulnerability and adaptation in two case study regions

2.1 Overview

The geography, history and current management policies of dryland agricultural systems fundamentally determine the threats, opportunities and needs of these systems. In all farming systems, productivity, profitability and efficiency of operation are of great importance. The major concerns of farmers are their productivity and income, however the inconsistency of production may result in inconsistent incomes. A major cause for instability in production and profitability increase is the climate variability, which together with other geophysical and social-economic factors, making the dryland agricultural vulnerable. Minimising the instability and reducing the vulnerability are desirable by governments and famers, which could be achieved by adaptation options such as policy making and effective farming management practices.

This chapter establishes comprehensive context for the investigation. Various secondary sources, primarily peer reviewed journal articles and statistical yearbooks, are reviewed with specific aims of identifying the driving forces of instability in gain production, vulnerability assessment methodology and assessment of effectiveness of adaptation options for dryland agricultural systems. The Australian Wheatbelt and the Loess Plateau of north western China are introduced as case studies which are compared and contrasted.

These two regions share common problems in soil erosion, water shortage, dryland agricultural production, and both are sensitive to climate change. The contextual opportunities to focus on two regions arose from the nature of the candidature, which are outlined in Chapter 1. First, each region is introduced from the perspective of their geography and significance to the study of dryland agricultural management. Second, changes in grain production are compared between the two case studies and global trends, with an emphasis on variability of production over time and space. The causes of this variation in each case study location is hypothesised and reviewed. Finally, research for each region is proposed, leading into the analyses presented in later chapters.

2.2 The Australian Wheatbelt

2.2.1 Overview

Australia is one of the driest countries in the world. Dryland agriculture supports 80% of Australia's sheep, 50% of its meat cattle and 93% of its grain production (Venkateswarlu and Shanker 2012), and is practiced generally in the semi-arid to dry sub-humid regions. Most of this agricultural production, grain production in particular, is confined to a relatively narrow band of land to the east, southeast and south west of the country, between the latitudes 21°S-37°S (Carberry et al. 2010), which is known as the Australian Wheatbelt. The Wheatbelt does not exist as a single administrative entity, and thus its exact boundaries may vary when reported on the basis of climate, land use, soil types or included shires. Regardless of this lack of definition, it invariably occupies a curved zone spanning from central Queensland south through New South Wales (west of the Great Dividing Range), Victoria and then west through southern South Australia (ABS 2012;

Fig. 2.1). In Western Australia, the Wheatbelt continues around the south-west of the state before curving north along the western edge of the continent (ABS 2012). The Wheatbelt covers an area of approximately 700 000 km^2 (ABS 2015).

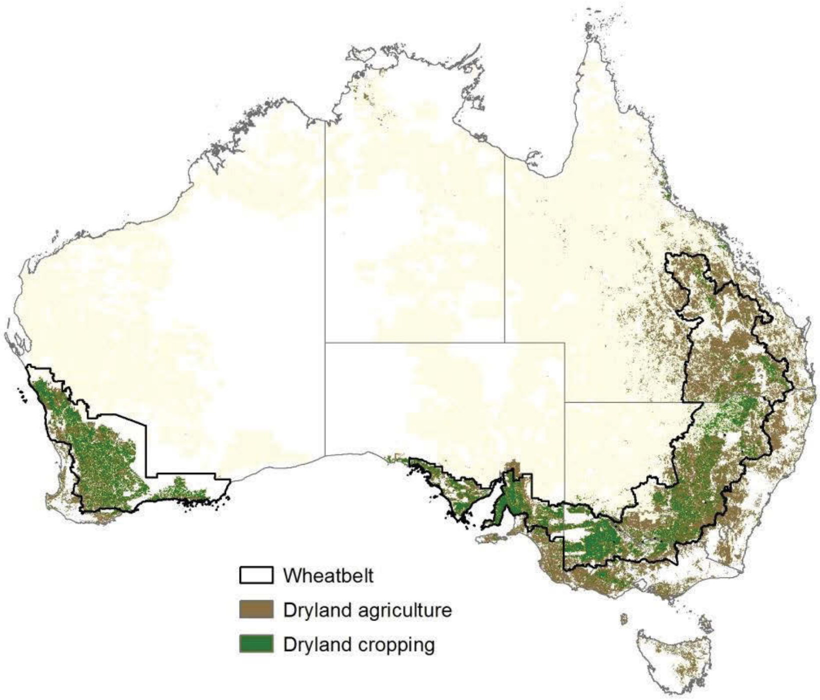


Fig. 2.1 Australian Wheatbelt overlapping with distribution of dryland agriculture (extracted from Land Use of Australia 2010-11). Dryland agriculture includes all dryland cropping, grazing of modified/sown pastures and horticulture where no irrigation is used.

2.2.2 Climate

The climate of Australian Wheatbelt ranges from the subtropical in north to temperate in the south. Summers are hot, with average January maximum temperatures exceeding 30 degrees Celsius (°C) over most of the Wheatbelt. Winters are warmer in the north and cooler in the south. Rainfall on the majority of the Wheatbelt averages 300 to 600 millimetres annually and shows considerable inter-annual variability (Hennessy et al.

2010). Generally, rainfall is higher and more reliable on farms closer to the coast, and less and more variable further inland.

Warming of climate over the past century is beyond doubt (IPCC 2007) with both daily maximum and minimum temperatures are rising. The Bureau of Meteorology and CSIRO (2016) reported that average annual temperature has increased by approximately 1 °C since 1910 and is projected to continue increase. Much of the Wheatbelt has experienced decreasing rainfall with much of this decline occurring in Autumn (March-May). Many regions have been reported to become drier (Hennessy et al. 2010). Droughts related to El-Nino events and caused dramatic decrease in rainfall in the Wheatbelt and wheat production to fall by roughly 61% from 2006 to 2007 (Bryan et al. 2015). Extreme weather phenomena, including droughts, floods, tropical cyclones, severe storms, bushfires and the occasional tornado are likely to occur more frequently and intensively (Hennessy et al. 2010).

2.2.3 Farming systems

Cropping in the Wheatbelt represents the majority of cropping in Australia. In the Wheatbelt, approximately 90% of land is used for agriculture, in a typical proportion of 39% and 50% for cropping and/or grazing respectively (ABS 2015). As the name suggests, cropping in the Wheatbelt is dominated by winter cereals (wheat, *Triticum aestivum* L. and barley, *Hordeum vulgare* L.). Crop production systems are varied and include many mixed farming enterprises with significant livestock and cropping activities. Pastures are mostly managed in rotation with cropping along with crop stubbles grazed by ruminant sheep and cattle to improve diversity and precipitation use efficiency. Other cereals, legumes and oilseed canola are also used in rotation for weed and diseases control and to improve the soil nitrogen (Turner et al. 2011). Production timetables vary from region to region depending on the timing of growing season rainfall (Squires and Tow 1991). Due to the dryland characteristics and the climate restriction, one crop per year is commonly grown in the Wheatbelt, with large proportion of the crop production for export. The national average for the annually cropped area per farm is about 800 hectares (ABS 2015). Improved grain yield under limited water supply is one of major constraints in food grain production in Australian drylands (Carberry et al. 2010; Venkateswarlu and Shanker 2012).

2.3 The Chinese Loess Plateau

2.3.1 Overview

The Loess Plateau covers an area of approximately 640 000 km^2, extending between latitudes 34° N-40° N and longitudes 100° E-115° E, in the geographic centre of the People's Republic of China and the middle region of Yellow River (Fig. 2.2). Agricultural land, including garden plots, forestland and grassland, accounts for approximate 75% of the total land area (An et al. 2014). The majority of the cultivated land is on slopes of varying degrees, which is a significant feature of Loess Plateau.

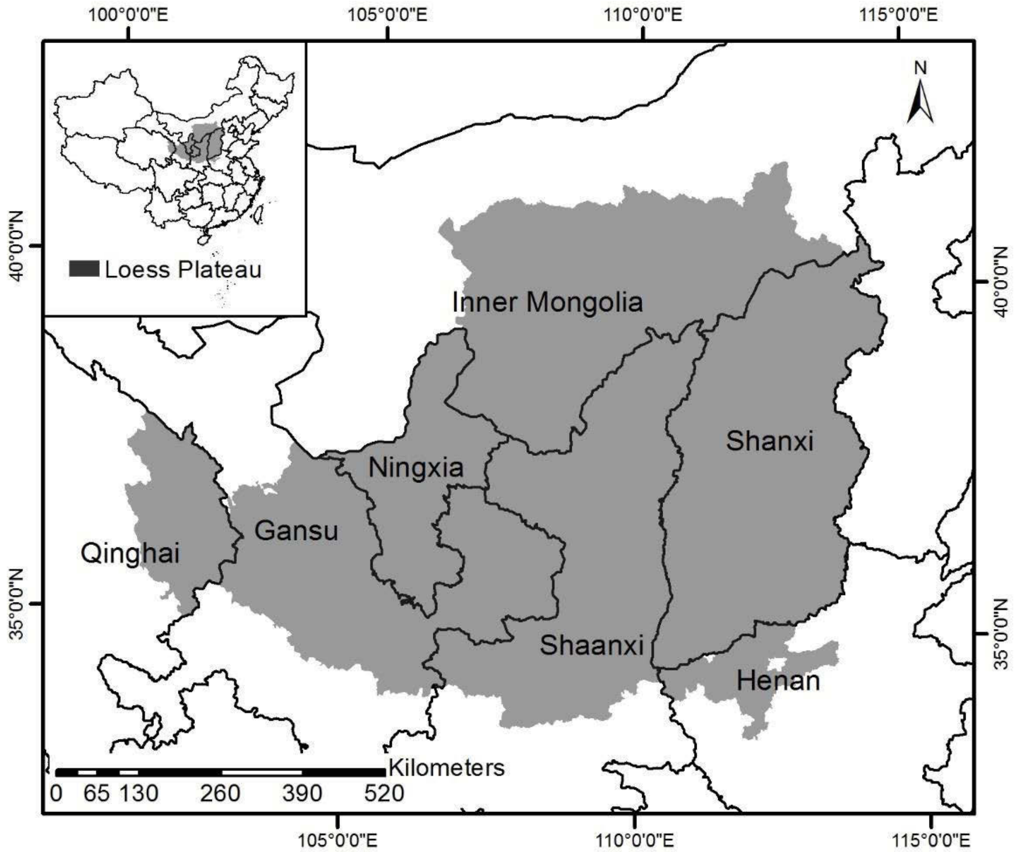


Fig. 2.2 Location of the Loess Plateau in China.

2.3.2 Climate

The climate of Loess Plateau is typically continental monsoonal and also strongly influenced by latitude, longitude, and topography. The most significant aspect of the climatological characteristics is the distinct seasonality of temperature and precipitation distribution. The annual average temperature ranges from 4.3 °C in the northwest to 14.3 °C in the southeast (Guo et al. 2011). Rainfall is summer dominant, with winter typically being cold and dry. Annual precipitation decreases gradually from above 600 mm in the southeast to 100 mm in the northwest, with approximately 78% occurring between May and October. Inter-annual variation is such that rainfall in wet years can be five times higher than in dry ones (He et al. 2014). Notable climate change has been observed on the Loess Plateau in recent decades, with air temperature rising by 0.6 °C and annual precipitation decreasing by 3 mm per decade (Piao et al. 2010; Turner et al. 2011; Wang et al. 2012; He et al. 2014). Like the Australian Wheatbelt, extreme events such as droughts have become more frequent (Piao et al. 2010; Turner et al. 2011; He et al. 2014).

2.3.3 Farming systems

In contrast to the market-driven broadacre that characterises crop production in the Australian Wheatbelt, farming systems of the Loess Plateau are typically a fraction of the size, with average farm size being approximately 1.3 ha (Turner et al. 2011). Despite such small farm sizes, the grain sown area is still typically around half that of the entire Wheatbelt and by extension, Australia. An estimated population upwards of 108 million lives on the Loess Plateau, of which more than 70% are reported to be living and working in agricultural areas (Wang and Li 2010). Subsistence farming of crops by small householders is the most common type of agriculture practiced, although the livestock production and forestry sectors have experienced recent growth as a result of favourable Chinese government policies (Liu et al. 2008; Yin and Yin 2010). Average annual income of farming households in some regions of the Loess Plateau was below 2 US dollars per day (Nolan et al. 2008). Wheat and maize are the dominant crops, accounting for about 35% and 30% of total cultivated area and 30% and 40% of total crop production respectively, with potatoes, buckwheat and other grains also occupying significant shares of cultivated land (An et al. 2014). Single cropping is the dominate cropping system in rainfed agricultural areas, while in area with better climate condition and access to irrigation double cropping is also practised (An et al. 2014).

2.4 Growth and instability of dryland grain production

2.4.1 Grain production

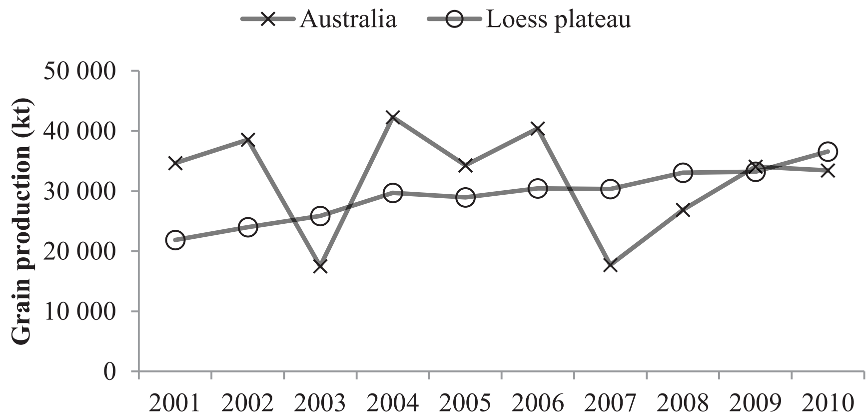
The sustainable growth and stability of grain production is an issue of national and global significance. In 2013-2014, the gross value of Australian wheat production was $8 billion, contributing 15.6% of the total value of Australian farm production (ABARES 2015). Domestic consumption is relatively small compared with total production, making Australia the world's seventh largest wheat producer and the fourth largest exporter (Farrell 2015). Approximately 80% of wheat production is exported, with major markets exist in the Asia-pacific and Middle East regions, where population growth drives increasing demand for Australian wheat (Farrell 2015).

Despite its global significance, Australian grain production has been subject to massive fluctuations in recent years. Statistics from ABARES (2015) show that the total grain production, including wheat, rice and coarse grains, was averaged to be 31 986 kt during 2001-2010 with an average sowing area of 19 028 k ha and a total value at 7257.68 million Australian dollars (Fig. 2.3), however the average level of production masks substantial differences in yearly production statistics. Grain production fluctuated greatly and remained below 2001 levels for the majority of the decade and had not recovered by its end. The lowest production was recorded in 2002-2003 at approximately 17 493 kt, yet the highest production was recorded in the following year, and was 2.4 times of the production in 2002-2003. Grain production held relatively stable until the end of the 2005-2006 year, after which production again plummeted to near 2002-2003 low levels. The low production of wheat during the 2007-2008 season because of droughts was identified as a large contributor to the world's wheat price spikes (Lobell et al. 2011; Ghahramani et al. 2015; Farrell 2015), likely worsening the access to affordable food for many consumers, including the poor in import-dependent countries.

During the same period that Australia was experiencing massive fluctuations in grain production, the grain production of the Loess Plateau experienced a relatively steady increase during 2001-2010, from 21 891 kt to 36 589 kt (Fig. 2.3). This is despite the fact that the sowing area on the Loess Plateau experienced a decrease from 2001 to 2003 as a direct result of the Sloped Land Conversion Program, also known as the "Grain for Green Policy", which was initiated in 1999 to restore ecological balance in the region by encouraging the conversion of low yielding cropland on marginal and steeply sloping land into pastureland and forest. The program and its associated subsidies were suspended temporarily in 2003, resulting in a slight rebound in cropping area representing vulnerable households which had merely exchanged their dependence from marginal cropland to subsidies. After this increase, there was very little change until the late 2000s. As crop production area has shown little long term increase, yet total production has increased steadily, the increase can be attributed to yield increases.

The management requirements to sustain production increase differ between the Loess Plateau and the Wheatbelt. Management on the Loess Plateau strives for self-sufficiency by means of more interventions to grantee local food security, so the growth of production is relatively stable. By contrast, the growth of Australian grain production shows stagnation and even a declining trend, especially noticeable for broadacre wheat in the dryland cropping region, where yields are heavily influenced by climate. Accordingly, it is of great importance to identify the driving forces for the unstable production of Australian wheat in the face of changing climate.

a)



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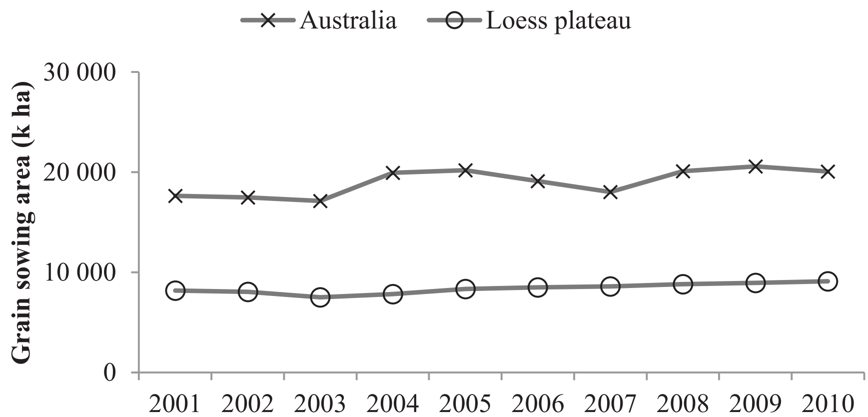

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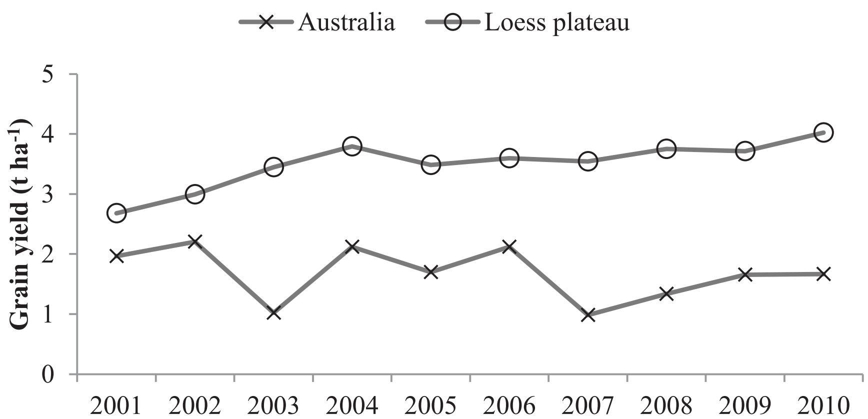


Fig. 2.3 Grain production (a), sowing area (b) and average yield (c) in the Australian Wheatbelt and Chinese Loess Plateau from 2001-2010.

2.4.2 The driving forces of growth and instability in agricultural production

The driving forces of growth and instability of agricultural production are varied and interrelated. Generally, the climate and soil are the prerequisites for agricultural production, which together with the agricultural technology, farm investment and management decisions, determine the production. Fundamentally however, agricultural production consists of three components: yield, cropping area and numbers of harvest per year (Hazell 1984; Zhang 1995; Lizumi et al. 2015; Cohn et al. 2016), and all biophysical and social-economic factors impact the total agricultural production through either of these three components (Verburg et al. 2000; See et al. 2015). For most dryland areas with one crop per year, the significant components of productions are yield and cropping area.

Whilst the most publicised growth of agricultural production worldwide in modern times has been achieved by gains in yield, expansions of crop area is behind considerable production growth (Lizumi et al. 2015; Cohn et al. 2016). Despite this, the studies that examine the changes in the area of cropland and the number of crops in relation to climate variation are rare whilst studies on yield variation are common (Lizumi et al. 2015; Cohn et al. 2016). One study by Reyenga et al. (1999) roughly simulated the expansion and retreat of Wheatbelt area and boundary in South Australia and New South Wales under different climate scenarios, and reported that significant retreat of the boundary occured in New South Wales under the 'dry' scenario with up to 3000 ha becoming unsuitable or marginal for cropping while there was a small retreat in South Australia. More recently, Cohn et al. (2016) used remote sensing and statistical regression methods to analyse administrative data of soy and corn production combined with satellite data of land-use and climate, identifying the change in agricultural output associated with the responses of crop yield, crop frequency and crop area in a key agricultural region of Brazil. It was reported in this study that approximately 70% of the change in agricultural output caused by climate was determined by changes in frequency or changes in area (Cohn et al. 2016). Therefore, in addition to yield, the analysis of the influence of changing sowing area on production should not be ignored.

In the context of climate change, efforts are needed to limit production losses from both crop yield and from changes in cropland area and cropping frequency. A focus on yields alone may therefore bias assessments of the vulnerability of agriculture to climate change. Area responses may contribute to agricultural production and socioeconomic development. With a reported drying trend in the future facing Australia, a complete study on all the components of agricultural production is needed urgently. This could assist to understand how these two pathways (yield and area) may be managed in the future so that agricultural production increases can be achieved without compromising the delicate balance between land use and production. Statistical decomposition analysis has been used in a few studies (Hazel 1984; Zhang 1995), which has the advantages to analyse all the components of change in the variance of total during different periods.

2.5 Agricultural vulnerability assessment

2.5.1 The evolution of vulnerability definition

The definition of vulnerability as a concept for management and research has undergone continuous development and refinement. Similar to "sustainability", vulnerability is a complex concept that lacks one generally accepted and precise definition that would permit it to be readily quantified (Fussel 2007; Gallopin 2006). The scientific use of vulnerability in natural research management has its roots in geography and natural hazards research (Fussel 2007), however its use has gradually expanded to a variety of research contexts including both social and natural sciences regarding poverty and development, public health, biology and climate impacts. Vulnerability is presently a complex, multi-disciplinary concept (Nelson et al. 2010a) and accordingly, the conceptualisation of vulnerability can be very different according to its contexts and research focus.

In the context of climate change, the prevailing definition of vulnerability, as provided by the IPCC, is "the propensity or predisposition to be adversely affected" (IPCC 2014). It is noted in the same reference that vulnerability encompasses a variety of concepts and elements, including the exposure to adverse effects, sensitivity to harm and lack of capacity to cope and adapt. The IPCC also provides definitions for these encompassed elements. Exposure is defined as "the presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected"; sensitivity is defined as "The degree to which a system or species is affected, either adversely or beneficially, by climate variability or change."; and adaptive capacity is defined as "The ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences" (IPCC 2014).

The relationship between the concepts of exposure, sensitivity and adaptive capacity, in addition to their contribution to vulnerability, has been presented in very diverse manner across the body of literature discussing vulnerability science and has changed over time (Gallopin 2006). The inclusion of adaptive capacity in the IPCC's definition represents a more recent trend in vulnerability analysis which is to attempt capturing the role of human beings in managing the impacts of climate change.

2.5.2 Vulnerability assessment methods

The impacts of climate change are expected to be unequally distributed, affecting rural communities in developing countries to a greater extent due to their geographical positions, low adaptive capacities and dependence on climate sensitive agriculture and natural resource sectors (Stern 2007; Collier et al. 2008; World Bank 2010; Dasgupta et al. 2014). The primary challenges for the assessment of vulnerability are to develop robust and credible measures, to incorporate diverse methods that include perceptions of risk and vulnerability, and to incorporate governance research on the mechanisms that mediate vulnerability and promote adaptation and resilience. Therefore, to efficiently apply the concept of vulnerability to climate change in policy-driven assessments, researchers need to be able to measure it quantitatively, which has led to the creation of several frameworks for conceptualising vulnerability. The diversity of these frameworks (Fig. 2.4) has resulted in the range of methods that have evolved to measure vulnerability, and accordingly, the CSIRO Climate Adaptation National Research Flagship notionally summarised the ideas that there are multiple and overlapping ways of measuring vulnerability, regardless of how it is defined (Pearson et al. 2008).

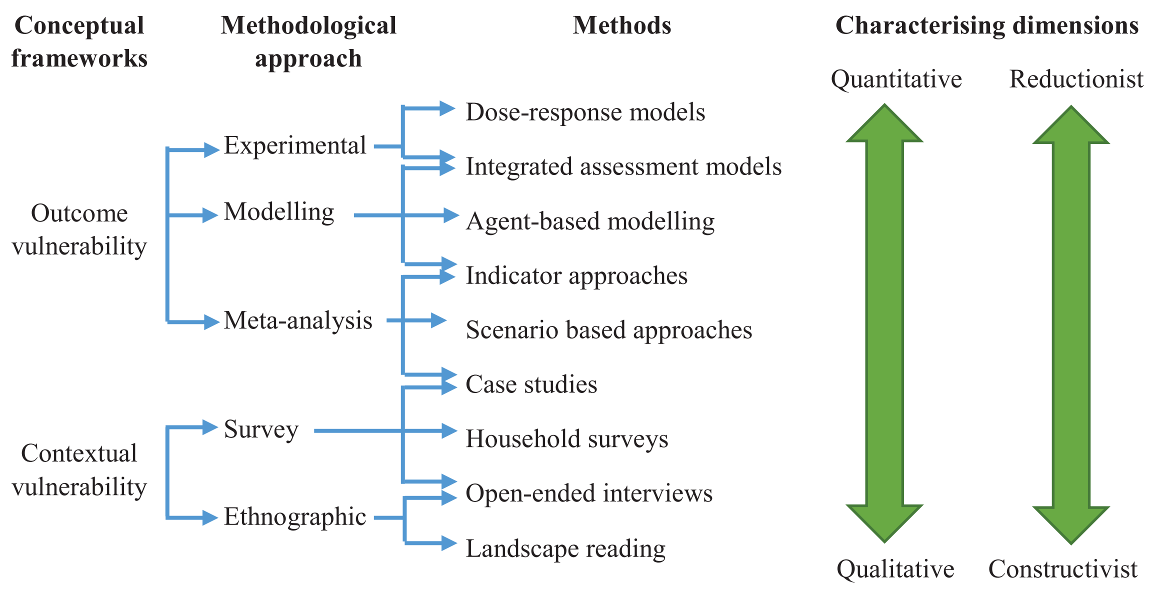


Fig. 2.4 Categorisation of methodologies, methods and characterising dimensions of outcome and context vulnerability (Pearson et al. 2008).

Currently, the dominant approach to measuring the vulnerability of agricultural systems to climate change had been based on agro-ecological models. These models have been successful at modelling the changes in the physical productivity of systems (plant and animal growth, yields and physical production) if exposed to certain hazards. Vulnerability assessment by model simulations have the advantage of using currently available modelling systems to contribute and provide immediate insights into the likely impact of climate change and analysis of vulnerability in the agricultural sector. However, by focusing on biophysical changes in closed, well-defined systems, these frameworks often fail to capture the social-economic outcomes of agriculture's dynamic interactions with society. Meinke et al. (2006) provided tangible evidence that farmers in regions with severe climate variability are not necessarily most vulnerable to current climate risk as they have developed appropriate farming systems to manage this variability. Therefore, the aspect of adaptive capacity of farming systems to climate change should also be incorporated into the vulnerability assessment procedure. There are attempts to integrate economic models with the biophysical models to capture the social-economic impacts on agriculture, for example Kokic et al. (2005) and Heyhoe et al. (2007), but the studies are few (Person et al. 2008). Furthermore, models are reported as having limited capacity to account for mitigation and adaptation options (Person et al. 2008).

As the models are unable to account in all human's adaptation responses and adaptive capacity when facing risk and hazards, the integrated index method provides an alternative. Integrated indexes combine a range of socio-economic, environmental and agricultural production statistics, allowing for encapsulation of these multiple drivers and thereby having improved capability to account in adaptive capacity. For example, rather than using purely climatic and productivity indicators, Liu et al. (2002a; 2002b), Hou et al. (2003) and Wang et al. (2003) made some improvements to assess the vulnerability on the Loess Plateau by taking account of economic and institutional policy factors. Nelson et al. (2010b) constructed an adaptive capacity index by using diverse indicators including human, social, natural, physical and financial capital derived from farm survey data, and combined with hazard/impact modelling to generate a holistic measure of adaptive capacity which was then used to analyse the vulnerability of Australian rural communities to climate change and variability. The indicator approach has demonstrated policy utility in simplifying multiple processes into a single figure. They enable easy comparison across space, and can be used to monitor change over time. However, indices are limited in their application by considerable subjectivity in the selection of variables and their relative weights, by the availability of data at various scales, and by the difficulty of testing or validating the different metrics.

The different methods used to assess vulnerability have advantages and disadvantages in some aspects, and comprehensive use of a variety of these methods and making use of their advantages are the research trend for the vulnerability assessment in the complex agricultural systems. Whether particular methods can be used to support action to reduce vulnerability or build adaptive capacity is significantly influenced by the research purpose, context, and the availability of data (Nelson et al. 2010a).

2.5.3 The research progress of agricultural vulnerability

Research to assess and reduce sensitivity and improve adaptive capacity has always been at the forefront for the Australian agriculture sectors because agriculture is one of the most climate sensitive sectors of the Australian economy (Pearson et al. 2011). Much research has been undertaken and various approaches have been developed with many detailed investigations focusing on broadacre cropping in the Wheatbelt region (Nelson et al. 2005; Nelson R. et al. 2007) to support farmers' decision making (Bryan et al. 2015). The research and development (R&D) has helped Australia become an advanced agricultural country and more resilient when facing climate change.

In contrast to the Australian Wheatbelt, the threats to production in the Loess Plateau are likely to have a greater impact on the livelihoods of a greater number of rural poor due to differences in farming systems; therefore, the human dimension of vulnerability is of increased significance to the management process. As a traditional agricultural region with 80% people depending on it for food and income, the agricultural vulnerability assessment on Loess Plateau are in need. However, the quantification of biophysical and social-economic metrics of exposure, sensitivity and adaptation, which are required for vulnerability assessment, has been seldom attempted on Loss Plateau. Furthermore, studies that assess vulnerability of the Loess Plateau undertaken at the administrative county level are rare. Most notably, Wang and Liu (2003) undertook a vulnerability assessment in 1990 and 1997 based on statistical data from 130 counties, although this was restricted to only three provinces that overlap the Loess Plateau, Shaanxi, Ningxia and Gansu. Counties from Shanxi province, which includes much of the typical hill and ravine terrain that characterizes the Loess Plateau, were not included. Other national scale assessments of vulnerability to climate change have included the Loess Plateau, however the difference of resolution, focus topics and indicator selection have caused the findings to differ (Lin and Wang 1994; Simelton et al. 2009; Yin et al. 2009; Li et al. 2015). The incomplete or inconsistent findings of previous vulnerability assessments indicate the need for a novel framework that uses available county level indicators that are relevant to the specific circumstances in the Loess Plateau and compatible across provinces. An integrated analysis to assist in adaptation options will generate great benefits for the Loess Plateau, in terms of preserving agricultural land capability, maintaining livelihoods and reducing environmental impacts. Future study should focus not only on the vulnerability of the agricultural systems to climate variable and change, but also on relevant adaptation measures to be taken. This strengthened demand for adaptation efforts necessitates access to a range of robust and transparent assessment approaches to enable decision makers to efficiently allocate scarce resources. Assessment and mapping of agricultural vulnerability to climate related stressors is therefore an important process in the formulation and implementation of appropriate adaptation measures and priority setting for agricultural investment (Watson et al. 2013).

2.6 Assessing the effectiveness of adaptation options

2.6.1 The adaptations in two study regions

Adaptation is one of the key components for dealing with climate change and variability. Adaptation is defined by IPCC (2014) as "The process of adjustment to actual or expected climate and its effects". In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects. For grain cropping systems, there are many potential ways to alter management to deal with projected climatic and atmospheric changes.

Due to the importance of agriculture sector, adaptation has been already part of cropping systems management in Australia (Donald 1965; Howden et al. 2010; Pearson et al. 2011). Strategies and adaptation options have been proposed and some have been implemented across all scales from individual to community, industry, regional, national and global and from policy to field level (IPCC 2014). For example, policy-related adaptations implemented include drought support policy, a regional commodity forecasting system for wheat, water distribution systems, public sector support including R&D, training and education programs (Pearson et al. 2008); field-related adaptations include varietal and species changes, crop and soil managements (sowing, tillage, rotation), erosion and salinization management and moisture conservation (Howden et al. 2010).

The potential benefits of management adaptation are substantial. For the wheat industry alone in Australia, relatively simple adaptations to climate change (varietal change and alteration of planning window) was reported to be worth between $100 million to $500 million per year at the farm gate (Howden et al. 2010). Australian farmers, on average, are well-placed to respond to climate change; having access to R&D innovation, agribusiness services, education services, modern infrastructure, a range of marketing and storage systems, and are well-served by financial markets. Therefore, agricultural sectors in Australia are highly adaptive.

By contrast to Australia, developing regions like the Loess Plateau often do not have access to similar quality and quantity of resources to adapt and they appear more vulnerable. Although various types of adaptations including government programs or policy, farm practice changes and technological development are also taking places on Loess Plateau. In the short term, a common adaptation option will be to enhance and promote existing management strategies for dealing with climate variability.

The key for dryland agriculture is to improve the use efficiency of precipitation. Adaptation measures such as changing sowing date according to rainfall, and conversation of water such as achieved by plastic film mulching are used for this purpose. Plastic film mulching is applied to more than 200 000 ha in the northwest of Loess Plateau (Zhang et al. 2014), and can have both positive and negative effects on grain yield and water use efficiency (WUE) (Zhang et al. 2008; Zhang et al. 2014). As there are limited resources to adapt, managers must assess how effective adaptations are in advance. Managers and policy-makers also need to understand the limitation of adaptations so that they do not underestimate potential vulnerability. However, most of adaptation options have yet to be analysed for their benefits under climate change.

2.6.2 The effectiveness of adaptations

The effectiveness of adaptive responses is influenced by (1) the operating context within which responses occur (e.g. the policy and governance setting); (2) the availability of effective adaptation options, and (3) the capacity of individual to access support and implement adaptation options (Marshall et al. 2010). Identification of effective adaptation options could be achieved by (1) applying existing knowledge in more effective and innovative ways including greater collaboration with decision-makers; (2) broadening the array of research approaches used to identify practical solutions and (3) continuing basic research that fills fundamental knowledge gaps, tests the validity of key assumptions and evaluate the effectiveness of adaptation options (Marshall et al. 2010). Methods to assess the effectiveness of adaptation options are needed.

Successful dryland farming management requires the integrated management of soil, water, crops and nutrients. China historically uses many resources to trial adaptations with experiments. Australia has developed advanced tools such as "Agricultural system simulator (APSIM)", which can well assess the effectiveness of adaptation options in Australian (Luo et al. 2009). It would be beneficial to transfer the technology and modify existing tools used in other dryland regions to apply in the effectiveness of adaptation options on the Loess Plateau that share the same dryland agricultural issues.

2.7 Knowledge gap summary

Whilst the total grain production on Loess Plateau is relatively stable, the Australian Wheatbelt presents highly variable grain production. Thus identifying the driving forces of the growth and instability, especially for the economically significant production of wheat, is of significance for sustainable agricultural production of Australia.

Dryland agriculture in both case study regions is sensitive to climate change. Assessment of this vulnerability is necessary in the context of climate change. Whilst Australia has conducted comprehensive assessments and various methods related to vulnerability, the complete study of agricultural vulnerability assessment using consistent methods at administrative levels to support policy making must be undertaken on Loess Plateau.

Adaptation at all scales are necessary and Australian agricultural entities are highly adaptive with many adaptations taking place and effectiveness tools for monitoring and assessing adaptation to support decision marking of policy makers and farmers. For China, which has relatively less public support and resources to adapt, the lessons and technologies of those developed regions like Australia present a worthwhile opportunity for emulation. The modification and adoption of those existing techniques, tools and knowledge will be of value to more efficient development as these two regions share the similar dryland management issues.

Chapter 3: Contribution of area and yield to growth and instability in Australian wheat production

3.1 Introduction

Production increase and supply stability of Australian wheat are of national and global significance. In Chapter 2, it was established that an analysis of the influence of changing sowing area and yield on the growth and stability of Australian wheat production is necessary to understand how these two pathways may be managed in the future so that wheat production increases can be achieved without compromising the delicate balance between land use and production.

In this chapter, decomposition analysis methods were applied to determine the contribution of sowing area and yield to Australian wheat production growth and stability with the aim of identifying patterns in their temporal and spatial differences that can be used to inform management decisions. First, the contribution of sowing area and yield changes to the growth of wheat production between each decade from 1900-2009 were calculated at the national and state levels, delineating the driving types of wheat production growth by decade. Second, the average contribution of sowing area and yield changes to year to year differences of wheat production in each decade were calculated at the national and state levels. Finally, the implications of the results for the future growth and stability of Australian wheat production are discussed by relating them to relevant historical developments and previous research.

3.2 Materials and methods

3.2.1 Data

Australian national and state level wheat production and sowing area data from 1900 to 2010 were obtained from Australian Bureau of Statistics (ABS 2013). Yield was then calculated as production divided by sowing area and accordingly, yield values presented in this paper are regional averages.

As Australian wheat production has an increasing trend with high fluctuation, two time-scale data were analysed to represent the trend and fluctuation, yearly averages and decadal averages of yield, area and production. Yearly data was used for the year to year fluctuation analysis whilst decadal average data was for the purpose to analyse the wheat production trend.

3.2.2 Decomposition analysis

Statistical decomposition analysis is concerned with the problem of the division of a given total into a number of components (Balestra 1975). Production consists of two components, yield per unit area and cropping area, and the relationship of which can be summarized as:

$$P = A \times Y$$

Where P (tonnes) is the annual production of wheat and A (hectares) and Y (tonnes per hectare) are respectively the sowing area and yield of wheat for the cropping season in a given year.

Difference in production between two measurements is caused by changes in the two components, therefore, the production change is the function of the difference of sowing area and yield per unit area (Hazell 1984):

$$\Delta P = f(\Delta A, \Delta Y)$$

$$P_t - P_{t-1} = \Delta Y(t) \times A(t-1) + Y(t-1) \times \Delta A(t) + \Delta Y(t) \times \Delta A(t) \qquad (1)$$

Here, t represents year or decade. When t represents decade, the trend is represented by average decadal productions. The relative change for the target decade compared with the decade before was identified using equation (1). When t represents year, the equation (1) quantifies the year to year fluctuation. As the effect of each component on production fluctuation differs in different years, the average yearly fluctuation and the contribution rates of yield and area to it in each decade were calculated according to the method in Zhang (1995):

$$\mathrm{TP} = \sum |\Delta Y(t) \times A(t-1)| + \sum |Y(t-1) \times \Delta A(t)| + \sum |\Delta Y(t) \times \Delta A(t)|$$

$$\mathrm{IY} = \left(\sum |\Delta Y(t) \times A(t-1)| / \mathrm{TP}\right) \times 100\%$$

$$\mathrm{IA} = \left(\sum |Y(t-1) \times \Delta A(t)| / \mathrm{TP}\right) \times 100\%$$

$$\mathrm{IYA} = \left(\sum |\Delta Y(t) \times \Delta A(t)| / \mathrm{TP}\right) \times 100\%$$

TP: sum of yearly fluctuation of wheat production in decade;

IY: the average relative contribution rate of yield to production fluctuation;

IA: the average relative contribution rate of sowing area to production fluctuation;

IYA: the average relative interaction contribution rate of yield and area in decade t.

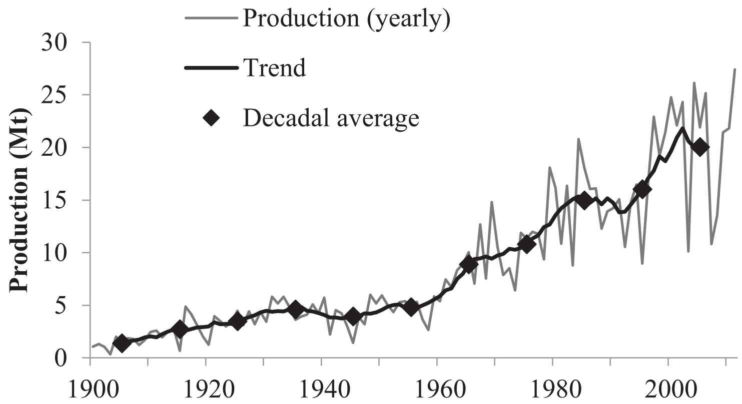
3.3 Results and discussion

3.3.1 Trend and variability of wheat production, sowing area and yield

Australian wheat production has exhibited a general trend of increase over time (Fig. 3.1). The total production had increased until the mid-1930s and then stagnated for two and half decades. From 1960 onward, the production started to increase dramatically until the mid-1980s, followed by one-decade of decrease until 1995. After this, the wheat production again increased dramatically, however it then stagnated and even declined after 2000. The sowing area showed a similar historical trend as the total production during the past 110 years, but with clear declined trend during 1931-1957. Yield increased steadily for most of the period, except for plateaus occurring during 1925-1945 and 1965-1975.

The production started to vary to a greater extent after 1960 along with the much larger total production amount (Fig. 3.1). Wheat yield has exhibited drastic fluctuations from 1900, while inter-annual change in sowing area is proportionally much less.

a)



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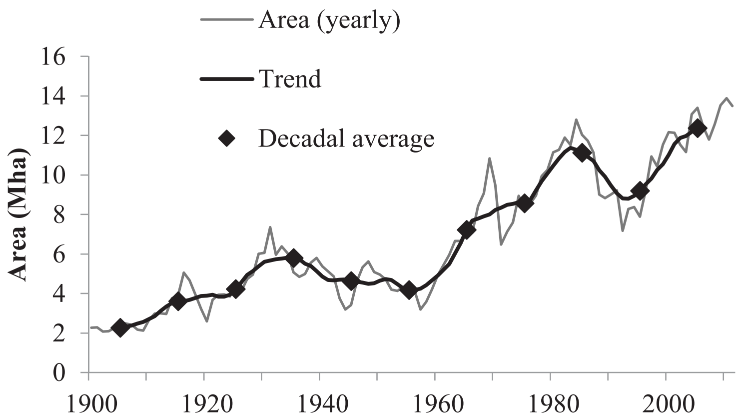

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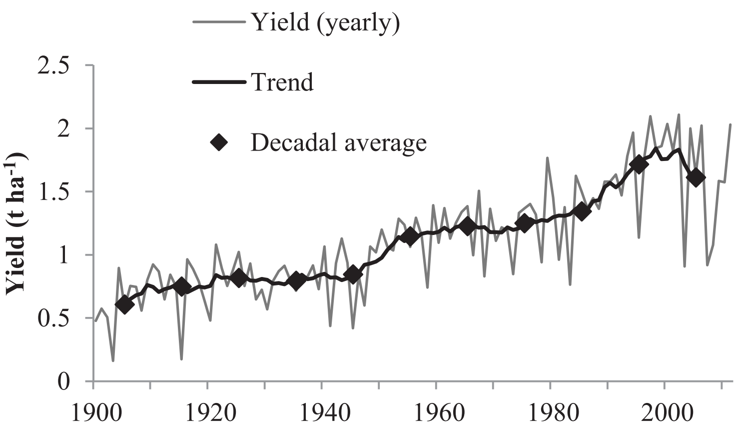


Fig. 3.1 Australian wheat production (a), sowing area (b) and yield (c) from 1900 to 2010.

3.3.2 The contribution of area and yield to the wheat production growth

The contribution of sowing area and yield to growth between decades of wheat production in Australia and its major wheat producing states is shown in Fig. 3.2. For Australia as a whole, changes in sowing area were the more influential source of growth in nine of the eleven decades analysed. The exceptions are 1950s and 1990s, during which sowing area decreased, but the wheat production increased due to increase in yield. In three decades, 1940-1949, 1950-1959 and 1990-1999, the contribution of area was negative, however growth as a result of improvements in yield were able to offset the reduction of sowing area in the case of the latter two decades, leaving the former as the only decade in which national production decreased on average in comparison to the previous. In contrast, yield also contributed negatively to growth in two decades, 1930-1939 and 2000-2010, however sowing area increased by greater proportions in both decades leading to positive growth. In no decades were average contributions of area and yield both negative.

The contribution of each pathway to this growth differs between decades and states. New South Wales and Western Australia were found to be the states with the highest production in most years, and both states closely match the nation as a whole in terms of area contribution being the main source of both positive and negative growth. Like the national averages, wheat production in Western Australia has increased in all decades except 1940-1949 whereas average wheat production in New South Wales has decreased in three decades, 1940-1949, 1950-1959 and 1990-1999. As with the national averages, these decades all experienced major negative contributions by sowing area, however yield increases in New South Wales were on average inadequate compensation and production therefore decreased. It is also evident in these states that the contribution of yield, either positive or negative has been increasing unsteadily since the 1950s.

It was found that yield contribution in South Australia and Victoria was proportionally much greater than that of other states in the first 5 decades studied, however area was typically the driving force of production growth in the other states. In the early decades, the change in mean yields dominated the contribution ratio in South Australia and Victoria. For example, the average contribution rate of yield to total production were 80.4% and 46.9% in South Australia in 1900s and 1910s, while that were 47.7% and 72.6% in Victoria in 1910s and 1920s. Because South Australian and Victorian wheat industries developed earlier in Australia’s history (Henzell 2007), the cropping land cultivated earlier and the average sowing area in the early decades were relative stable, which emphasis the relative importance of yield increase. The wheat production decrease in 1940s and/or 1990s of South Australia and Victoria is also caused by sowing area decrease.

In Queensland, a subtropical region with environmental disadvantages for wheat growth, the dominant contribution factor for production change is the increase in mean areas until the 1980s, after which point the expansion of sowing area slowed. Technology-driven yield increase drove change in 2000s for wheat production growth, indicating that yield improvement is of increasing importance for future development when the area expansion potential is limited.

In summary, growth in sowing area drove the wheat production trend of increase in Australia, however the contribution rate decreased in recent decades, which highlights the increasing importance of raising yield to future growth.

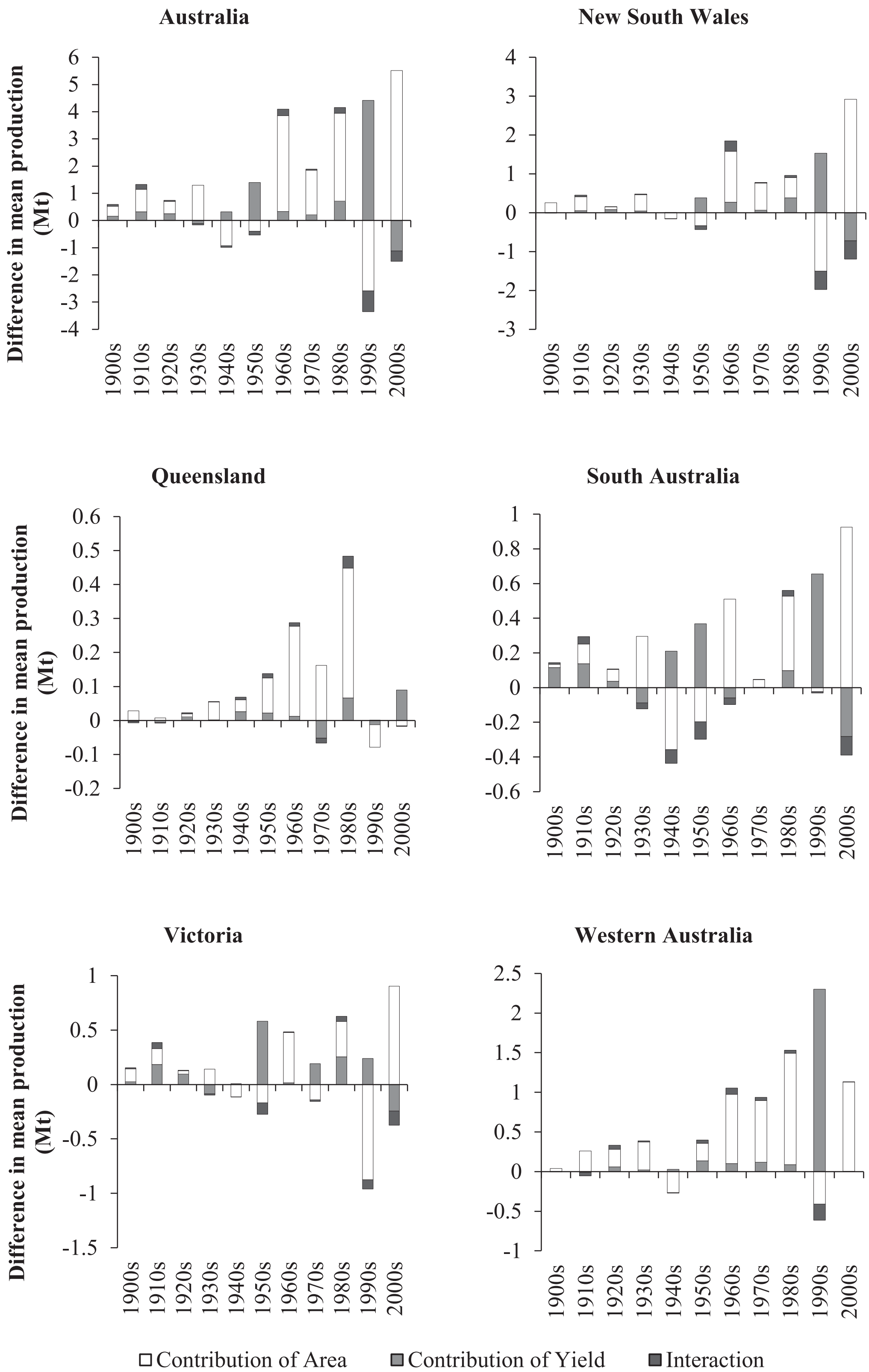


Fig. 3.2 Changes in average decadal production of Australian wheat.

3.3.3 The contribution of area and yield to the yearly fluctuation in wheat production

The average yearly fluctuation of wheat production in Australia and its major wheat producing states is shown in Fig. 3.3. Yearly variation of Australian wheat production has been increasing in general. Mean annual production variation was less than 1 Mt in 1900s, however it raised to above 8 Mt in 2000s. New South Wales has the highest year-to-year wheat production fluctuation, with an average annual 3.22 million tonnes difference between years during 2000s, followed by Western Australia, which experienced a dramatic increase to average annual production change of 3.08 million tonnes in 2000s. The total wheat production fluctuated the least in Queensland relative to the other wheat production states, with an average annual change of 0.48 million tonnes in 2000s, as shown in Fig. 3.3. While the production fluctuation caused by unstable yield increases in recent decades in most states, it shows a decreasing trend after the peak in 1980s in Queensland. This indicates that yield fluctuation in Queensland is decreasing (Fig. 3.3). The production fluctuation was caused by unstable area increases in Western Australia and Queensland where area expansion has occurred in recent decades. The contribution of area to production fluctuation shows a decreasing trend in recent decades in Victoria and South Australia, and no clear trend in New South Wales. This indicates that sowing area has become more stable in recent decades in Victoria and South Australia, yet has not stabilised during recent decades in Western Australia and Queensland.

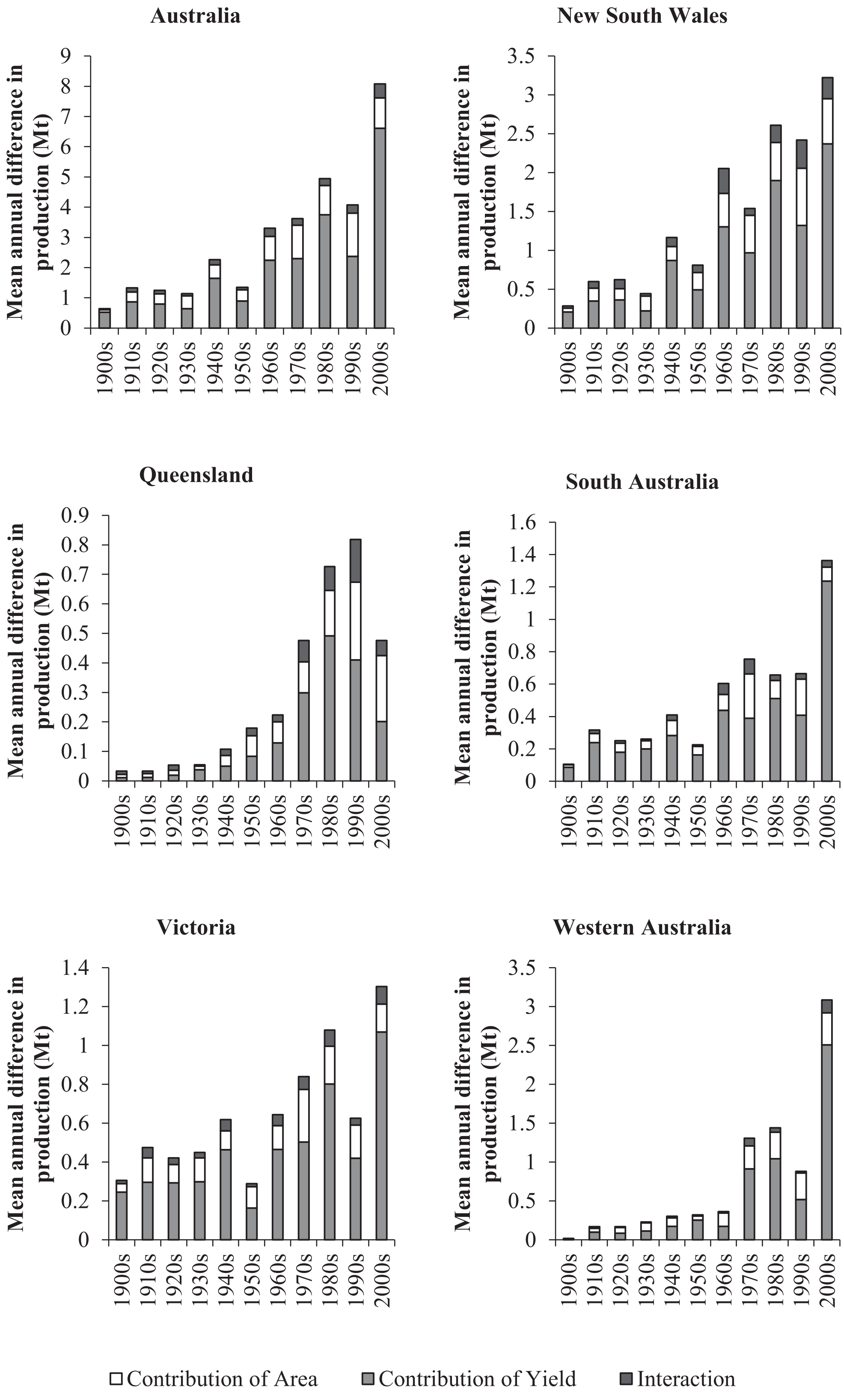


Fig. 3.3 Changes in average yearly production of Australian wheat.

The contribution rates of sowing area and yield to the wheat production in Australia and its major wheat producing states are shown in Fig. 3.4. Respectively 72.7% and 49.8% of wheat production fluctuation in South Australia and Queensland was caused by unstable yield (Fig. 3.4). By contrast, more than 70% of wheat production in Western Australia and Queensland was caused by sowing area, while the ratio was relatively less in Victoria and South Australia. These results indicate that in South Australia and Victoria, states where wheat production developed earlier and sowing area was relatively stable, the yield variation was the major cause of the wheat production fluctuation. To increase year-to-year stability in those states, reducing yield fluctuation is a logical approach. For Western Australia and Queensland, although yield was the major cause for the fluctuation, area also contributed one third of the wheat production fluctuation, which should not be ignored. Thus both the variability of wheat yield and area should be reduced to control the wheat production fluctuation.

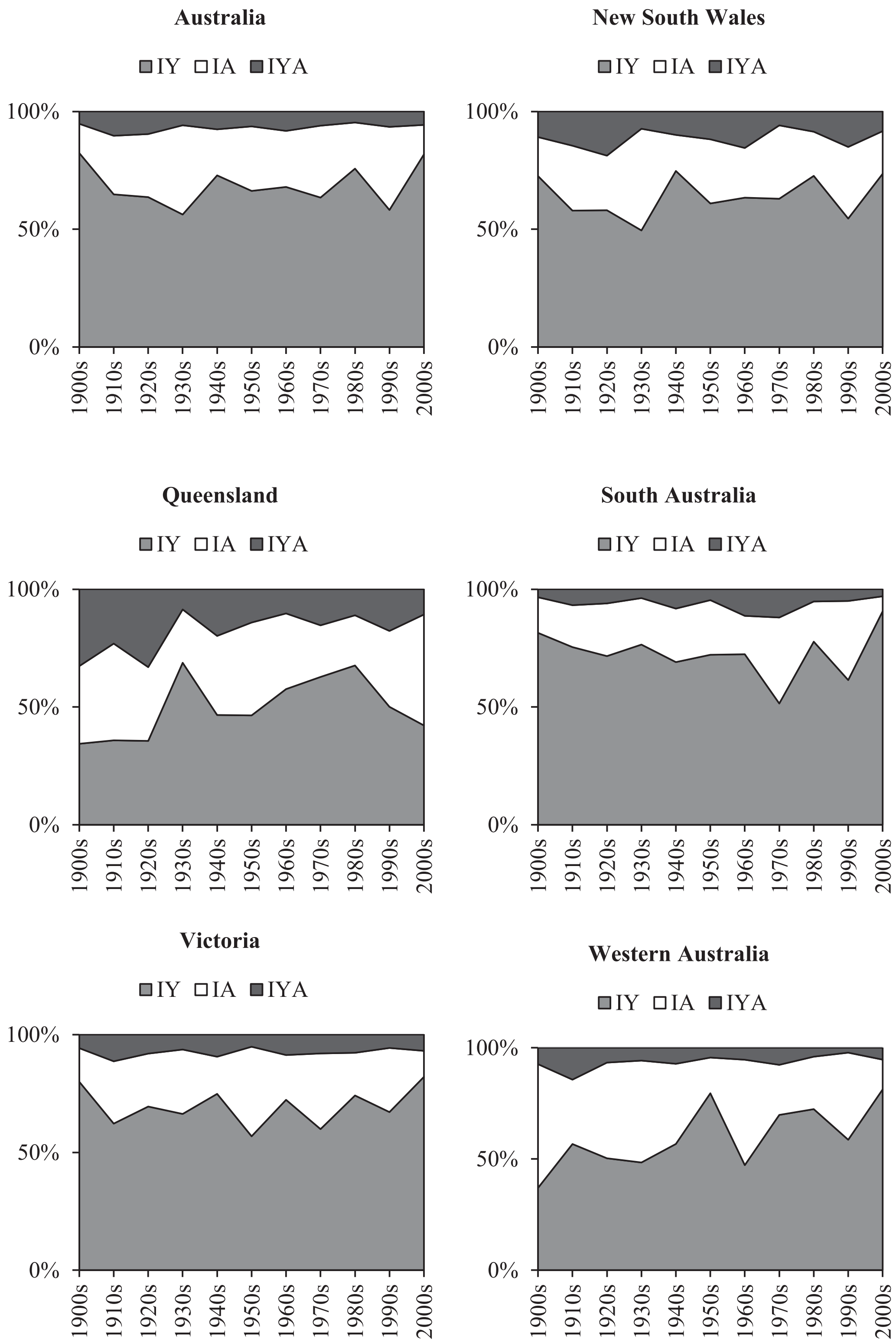


Fig. 3.4 Effect of yield and area on mean annual fluctuation of Australian wheat production by decade. IY, the average relative contribution rate of yield to production fluctuation; IA, the average

relative contribution rate of sowing area to production fluctuation; IYA, the average relative interaction contribution rate of yield and area to production fluctuation.

3.3.4 Policy implication

Stabilisation and improvement of wheat yield and the avoidance of yield failure are of significant importance. Yield has been shown to have an increasing influence on the trend of wheat production whilst contributing the most to production fluctuation. Although yield has been generally increasing since 1900 and with the average up to 2.1 t ha^{-1} according to statistical data of Australia, the yield fluctuated the most during 2000s. However, there is reported stagnation or even decrease of wheat yield (Ray et al. 2012), which was also evidenced by statistical data revealing that wheat yield shows a decrease trend after 2000, thereby challenging the Australian wheat industry. This is of particular significance when facing increasing demand from partner countries who have signed the free trade agreements with Australia. It is difficult to close the yield gap in a short term without major technological breakthrough. Thus, to stabilise Australia's wheat production, one action is to avoid the yield failure caused by natural disasters such as drought and frost. In addition, increasing the wheat yield in low yielding regions could be achieved by the improvement of techniques and farming management strategies.

Sowing area has been a major contributor to the increase trend of wheat production in Australian agricultural history. However, the effect of sowing area to wheat production increase has been seen decreasing, especially in the earlier developed wheat production states such as Victoria and South Australia. Therefore, to maintain Australia as one of the major wheat exporter in the world wheat markets, it is advised to stabilise the size of wheat sowing area as the basic activity to maintain or increase wheat production, especially when wheat yield is relatively low in Australia. The sowing area of dryland farming is also affected by rainfall, natural resources, mixed farming system, policy and social factors (Iizumi et al. 2015). With the exception of Queensland and Western Australia, which presented rapidly increasing rates in sowing area, the wheat sowing area had become relatively stable in recent decades. The potential for sowing area increase is limited. The main limiting factor differs between states and areas. As the Wheatbelt mostly lies in the rainfall range from 300 mm to 600 mm, variable rainfall is the primary challenge in the southeast (Henzell 2007), whereas poor soils are the main problem facing Western Australia where the rainfall is reliable. Infrastructure for transport and storage further limits the expansion of wheat production.

For most years, sowing area or yield per unit increase means the increase in Australian wheat production, but not always. When area expands to marginal dry area or crop failure occurs due to weather, or yield per unit increase during the period of sowing area decrease, this results in the decrease of the total wheat production. For example, the wheat production in 1990s of New South Wales, the sowing area decreased in the east Wheatbelt, whilst the yield increased in most area with a positive contribution to wheat production, which was demonstrated by the negative value of interaction between changes in mean yields and mean areas in Fig. 3.2. Therefore, to stabilize or to increase the wheat production in Australia, the changes in both components and their interaction should be managed.

3.4 Conclusion

Decomposition analysis methods were applied to determine driving forces of the trend and instability of Australian wheat production. It is concluded that the instability of Australia's wheat production has not been reduced significantly in the past century. The increasing trend of Australian wheat production was mainly due to sowing area increase in the past century. The yearly fluctuation of production was mainly caused by unstable yield. Therefore, to stabilise or to increase the wheat production in Australia, the changes in both components and their interaction should be managed. Managers should be aware that the potential to increase production by increasing sowing areas is almost exhausted. It is advised to stabilise wheat sowing area as the basic activity to maintain or increase wheat production, especially when wheat yield is relatively low in Australia. The continuing impact of climate change on cropping area needs further investigation.

Chapter 4: Agricultural vulnerability over the Loess Plateau in response to climate change

4.1 Introduction

In Chapter 2, the Loess Plateau of western China was identified as a region where climate sensitive dryland agriculture is the primary economic activity on which millions of livelihoods depend, despite being threatened by a complex interaction of anthropogenic and environmental factors. In addition to climate challenges, agricultural production in the Loess Plateau is also threatened by severe environmental degradation, particularly soil erosion, leading to a decline in agricultural productivity and subsequent poverty. Climate change, including increased climate variability, has been identified as a major driving force of this degradation as it exacerbates existing stressors such as naturally unstable soils and low annual rainfall (Li et al. 2003; Xu et al. 2006; Yin and Yin 2010), and it compels local producers to engage in unsustainable land management practices (Li et al. 2003; Lu et al. 2004; Nolan et al. 2008). To compensate for low productivity and meet food demand during periods of poor rainfall, natural land has been reclaimed and cultivated for farming, depriving the fragile soils of vegetation cover and accelerating erosion and water loss. The loss of soil quality leads to even lower productivity and greater susceptibility to damaging weather, further restricting regional agricultural development. In this context, farmers are driven to clear and cultivate even more marginal land to maintain food production, thus perpetuating a spiral of unsustainability on the Loess Plateau.

Adaptation measures are needed for the Loess Plateau in the face of climate change and the expectation of even greater climatic variation in the future (Lu et al. 2004; Nolan et al. 2008; He et al. 2014). Accordingly, a comprehensive management plan has been developed by the National Development and Reform Commission et al. (2010) that prescribes ecological construction interventions based on geomorphic zoning. It has been reported, however, that clarity and rationality of goals during previous ecological restoration and sustainability oriented interventions in the Loess Plateau has been a major area for improvement (Xu 2011). Assessment and mapping of agricultural vulnerability to climate related stressors is therefore an important process in the formulation and implementation of appropriate adaptation measures and priority setting for the management of the region (Watson et al. 2013).

The concept of vulnerability was explored in Chapter 2 and a theoretical basis for its quantitative analysis is provided in that chapter. Vulnerability assessment usually requires the quantification of biophysical and social-economic metrics of exposure, sensitivity and adaptation, which has been seldom attempted on Loss Plateau. Incomplete or inconsistent findings of previous vulnerability assessments in the Loess Plateau reported in Chapter 2 indicate the need for a novel framework which uses available county level indicators that are relevant to the specific circumstances in the Loess Plateau and compatible across provinces.

In this chapter, a report on an investigation into quantifying agricultural vulnerability is presented. First, a conceptual framework for quantifying agricultural vulnerability to climate change in the entire Loess Plateau, developed according to the principles described in Chapter 2, is applied to assess the agricultural vulnerability of 243 rural counties on the Chinese Loess Plateau. Indicators representing the climate/agriculture interface were selected to describe exposure and sensitivity, whilst stocks of certain capitals were used to describe adaptive capacity. A quantitative assessment which analyses the relationships between vulnerability components, sensitivity, exposure and adaptive capacity is then performed. Finally, spatial distribution is mapped.

The information presented in this chapter was adapted into a peer-reviewed academic report accepted and published in *Ambio: A Journal of the Human Environment* (Average 2010-2016 impact factor 2.55). In addition to the method, results, discussion and conclusion presented in this Chapter, the published version (attached as Appendix I), also includes a more comprehensive introduction and review, largely derived from the information presented in Chapter 2. Figure numbers differ from those presented in this thesis and American English is used as per the journal's guidelines for authors. As lead author, the candidate was responsible for the design, establishment and execution of the investigation, subsequent statistical analysis, the writing of the paper and attending to all revisions. Co-authors variously contributed input in the conceptualisation of the whole cohesive body of work in which this manuscript resides, statistical advice, proofreading and other supervisory duties.

4.2 Method

4.2.1 Study area

The study area is located between longitudes 100°54’E-114°33’E and latitudes 33°43’N-41°16’N, occupying the geographic centre of the People’s Republic of China. It spans an area of approximately 648 700 km^2, which includes jurisdictions from seven provincial level administrations, which are further divided into prefectures and then counties. The county was selected as the vulnerability assessment unit as it is the smallest administrative division still included in aggregate national statistics. Fifty-six county-level municipalities with little or no agricultural production were excluded, leaving 243 rural counties to be analysed in this study.

4.2.2 Vulnerability framework

Capturing complex interactions of anthropogenic activities and the environment in a holistic manner requires the use of frameworks (Angelstam et al. 2013). In this study, features from existing frameworks were adapted according to our study objectives. Vulnerability was defined as the propensity or predisposition to be adversely affected in accordance with the IPCC (2014) AR5 definition. It encompasses a variety of concepts and elements, including the exposure to adverse effects, sensitivity to harm and lack of capacity to cope and adapt. Exposure together with sensitivity represents the propensity and predisposition of the studied system to be adversely affected by climate change, whereas adaptive capacity reduces these effects (Gallopín 2006; Nelson et al. 2010b). Therefore, vulnerability can be expressed as the positive function of exposure and sensitivity, but negative function of adaptive capacity (Li et al. 2015):

$$Vulnerability = f(Exposure, Sensitivity, Adaptive\ capacity)$$
$$= (Exposure \times Sensitivity)/Adaptive\ capacity$$

An integrated vulnerability index was created by combining indicators for exposure, sensitivity and adaptive capacity (Fig. 4.1).

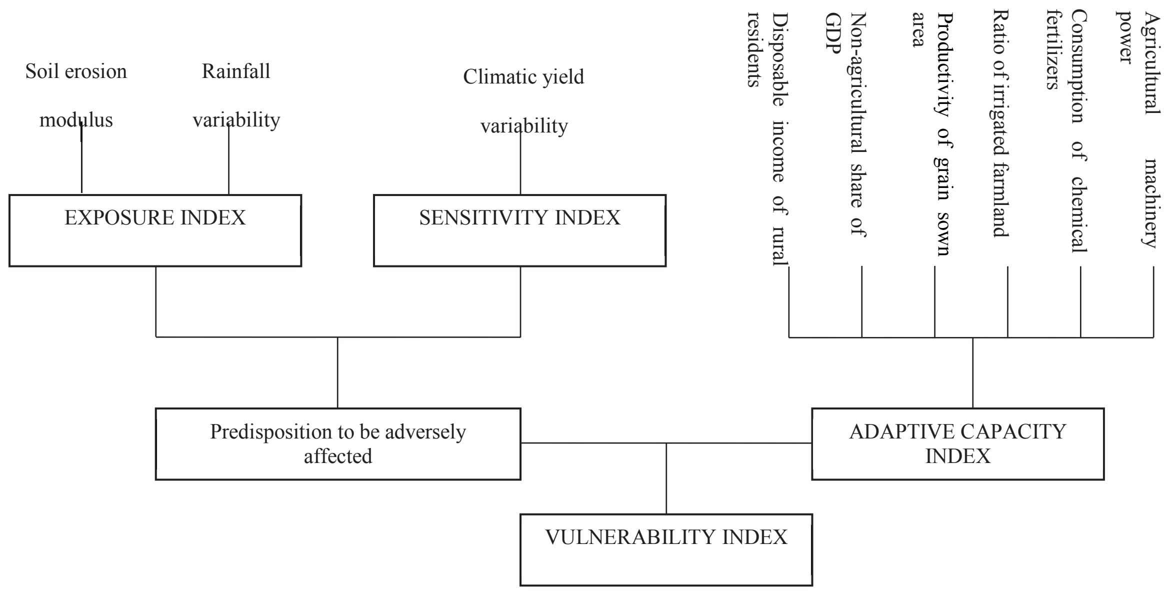


Fig. 4.1 Conceptual framework for assessing agricultural vulnerability to climate change as a function of statistical indicators.

4.2.3 Indicators of vulnerability to climate change

The indicators used to create vulnerability index are shown in Table 4.1. The selection of indicators, their hypothesised relationship to vulnerability and the calculation of each index are described below.

Table 4.1 Vulnerability indicators, variables and data sources.

Component of vulnerability	Component indicators	Description of indicators	Data source
Exposure	Rainfall variability	The coefficient of variability of annual rainfall during 2001-2010	Chinese Meteorological Bureau
	Soil erosion modulus	Extracted from land resources data	Earth system science data sharing platform of Chinese Academy of Science
Sensitivity	Grain yield variability	The coefficient of variability of annual grain production 2001-2010	China Statistics Bureau
Adaptive Capacity	Disposable income of rural residents	Per capita net income of rural residents (yuan person^{-1}) 2010	China Statistics Bureau
	Non-agricultural share of GDP	The ratio of value-added of secondary and tertiary industry to Gross Regional Product (%) 2010	China Statistics Bureau
	Productivity of grain sown area	Total grain yield of each county divided by its grain sown area (kg ha^{-1}) 2010	China Statistics Bureau
	Ratio of irrigation area	The ratio of effective irrigation area to cultivated land area (%) 2010	China Statistics Bureau
	Consumption of chemical fertilisers	Consumption of chemical fertilisers divided by cultivated land area (ton ha^{-1}) 2010	China Statistics Bureau
	Agricultural machinery power	Total power of agricultural machinery divided by cultivated land area (kwh ha^{-1}) 2010	China Statistics Bureau

Exposure is defined by the IPCC as "The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected" (IPCC 2014). To quantify this in the Loess Plateau, the inverse was taken; (the presence of driving forces behind adverse effects). Rainfall variability and soil erosion have been repeatedly identified as the driving forces of adverse effects (Li et al. 2003). Accordingly, exposure index (V_e) was represented by the sum/average of the standardised value of the following two indicators.

1) Rainfall variability: represented by the coefficient of variation of annual rainfall from 2001 to 2010 for each county. Rainfall for each county was obtained by interpolation of rainfall data from 44 meteorological stations distributed throughout the Loess Plateau, using ArcGIS 10.1.
2) Soil erosion modulus: extracted from land resources data obtained from the earth system science data sharing platform of Chinese Academy of Science. Soil erosion modulus for each county was obtained by zonal statistics using ArcGIS 10.1.

Sensitivity measures the responsiveness of a system to climate change, therefore its indicators should have a demonstrated relationship with agents of exposure and significance to the wellbeing of the vulnerable area. Grain yield variability was identified as the key indicator of agricultural sensitivity to climate change in the Loess Plateau for several reasons. First, rainfall is known to influence the productivity of grain sown land, both directly, through access to water, and indirectly, by influencing farmer practice (An et al. 2014). Second, the catastrophic erosion experienced in the Loess Plateau both causes and is exacerbated by low productivity (Li et al. 2003). Third, households practicing subsistence agriculture often have little interaction with markets and accordingly, income levels are not necessarily coupled with climate variation, nor are they entirely reflective of livelihoods. Fourth, the production of grain is an issue of political significance to China. Sensitivity index (V_s) was represented by the coefficient of variation of climatic yield. As time series of grain yields (2001-2010) consist of a technology-driven trend and variations caused by climate fluctuations (Yu et al. 2001; Zhong and Xing 2004), a detrending model (Zhong and Xing 2004) was employed to eliminate the technologically driven trend component (Y_0) to obtain the variation yield affected by climatic factors (Y_w). Therefore, $Y_w = Y - Y_0$, here Y is the actual yield. The coefficient of variation of Y_w is for the description of the effects of climate factors on grain production. The indicator, hereafter referred to as climatic yield variability, was normalised and taken as V_s.

Adaptive capacity refers to the preconditions within a system that are necessary to enable it to execute a deliberate response in anticipation of or in reaction to climate change (Nelson D. et al. 2007). To represent these preconditions, social characteristics, physical and economic elements of Loess Plateau counties are necessary to be considered. Six indicators were chosen with the criteria of relevancy, adequacy, administrative practicability and data availability to represent the adaptive capacity for each county. The significance of each indicator is as follows:

1) Disposable income of rural residents: provides an approximate indication of the financial capital available for adaptation to detrimental climate change. The significant contribution of financial capital to adaptive capacity arises from the liquidity and fungibility of finances (Nelson R. et al. 2007), particularly valuable

in the face of climatic uncertainty. Furthermore, income is an indicator of the local economic power that can be called upon to resolve emerging threats (Yin et al. 2009).

2) Non-agricultural share of GDP: represents the potential diversity of non-farm employment opportunities and ability to switch between alternative sources of income as a form of adaptation (Nelson R. et al. 2007).
3) Productivity of grain sown area: represents natural capital. Productive land has greater fungibility, being able to accommodate a wider range of farming options than marginal land or wasteland.
4) Ratio of irrigated farmland: reflects the extent to which farms can access water from alternative sources that are less reliant on rainfall in the event of poor rainfall conditions.
5) Consumption of chemical fertilisers: reflects the impacts of technological conditions on production (Yin et al. 2009).
6) Agricultural machinery power: indicates the physical assets available to agricultural producers that may be used for adaptations to climate change.

Adaptive capacity (V_a) was calculated as:

$$V_a = \sum_i Y_i \times W_i$$

Where Y_i represents the adaptation ability degree of the i-th indicator and W_i denotes the weight of the i-th indicator. The equal weights method, which is based on the premise that no objective mechanism exists to determine the relative importance of different indicators, was adopted in this paper.

Indicators were first normalised as dimensionless values ranging from 0 to 1 using $p_i=[p_i-min(p)]/[max(p)-min(p)]$. Then, V_e, V_s and V_a were each calculated. A vulnerability index was calculated as:

$$V_v=(V_e \times V_s)/V_a$$

4.2.4 Classification and mapping

Calculated indexes of exposure, sensitivity, potential harm, adaptive capacity and vulnerability for 243 counties were ranked from lowest to highest and then divided into five classes by quintile (lowest, low, mid, high and highest), each containing 48 or 49 counties. The relationship between vulnerability and its components were analysed and the values of indexes were shown on maps to identify the spatial distribution of vulnerability by ArcGIS 10.1.

4.2.5 Sensitivity analysis

The robustness of the result was analysed by calculating the average shift in county vulnerability ranks in response to changes in indicator choice and weighting method. The effect of indicator choice was analysed as the average change in ranking when individual indicators are excluded from the analysis. Where indicators were combined to form a single vulnerability component score, the potential effect of indicator weight was analysed as the average change in ranking when the weight of each indicator is increased or decreased in proportion to the others.

4.3 Results and discussion

4.3.1 Relationship between vulnerability components and indicators

The correlation between calculated exposure, sensitivity and adaptive capacity indexes for all 243 counties was found to be weak (Table 4.2), indicating that the three components were independent of each other. This suggests complexity in the circumstances of individual counties and the agricultural producers within them.

In general, most indicators contributing to the vulnerability components were concentrated in a narrow range after standardisation (Fig. 4.2), indicating that a small proportion of counties perform extremely high or low rather than an even distribution across the range of possible scores. Furthermore, as a complex system, some indicators were found to interact with each other.

Table 4.2 Pearson's Product Moment Correlation Coefficients of calculated vulnerability components from 243 counties on the Loess Plateau.

Components	Exposure	Sensitivity	Adaptive Capacity
Exposure	1	0.04	0.02
Sensitivity	0.04	1	0.15
Adaptive Capacity	0.02	0.15	1

Amongst exposure indicators, it is expected that rainfall, which is typically higher in areas with lower rainfall variability, would accelerate and therefore correlate with soil erosion.

However the effect is only present in the top four exposure classes (highest R^2 = 0.80, high R^2 = 0.96, medium R^2 = 0.95, low R^2 = 0.89, lowest R^2 = 0.02). It is likely that these counties in the lowest exposure class possess advantages such as increased vegetation cover or adaptations that prevent rainfall from causing soil runoff. Climatic yield variability was very low in the majority of the counties (Fig. 4.2), resulting in a pronounced skew in the sensitivity index. Notably, 80% of counties were found to have a sensitivity index less than 0.26. This suggests that for most counties, climatic yield is relatively stable, with only a few counties having highly unstable grain production. The extremely narrow interquartile range highlights the disparity in the effects of climate on different counties and the need to focus on the most vulnerable areas.

Amongst adaptive capacity indicators, the non-agricultural share of GDP in most counties was proportionally high (Fig. 4.2), indicating that the interaction of agricultural sectors with the economy is limited despite its significance to livelihoods. By contrast, the values of fertiliser, machinery power and irrigation were grouped tightly towards the bottom of their respective ranges, showing that the use of these technologies present in the plateau but is relatively low.

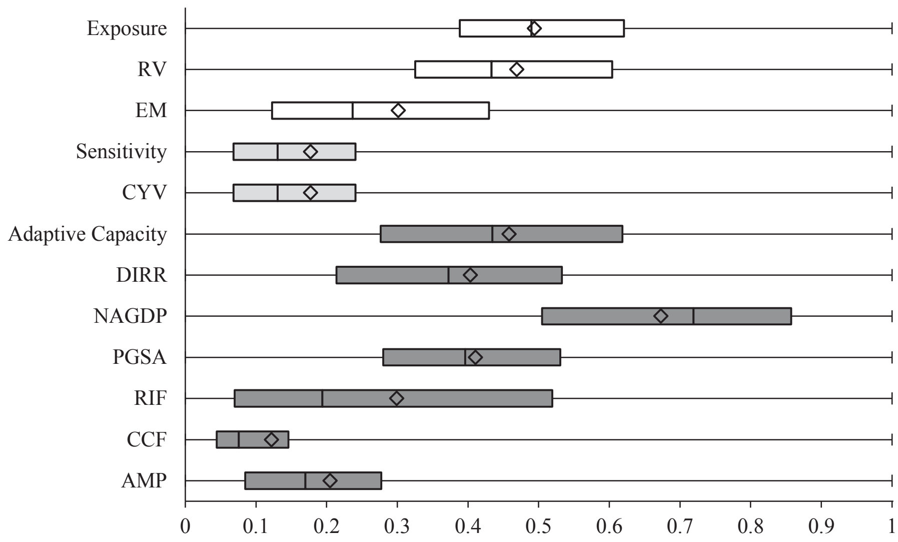


Fig. 4.2 The distribution of 3 calculated components (exposure, sensitivity, adaptive capacity) and 9 normalized indicators of vulnerability to climate change from 243 rural counties in the Loess Plateau. Vertical bars and left and right edges of boxes indicate minimum, maximum, 25 and 75 percentiles of the total data, thick black line and diamond are the median and average, respectively. RV = rainfall variability; EM = soil erosion modulus; CYV = climatic yield variability; DIRR = disposable income of rural residents; NAGDP = non-agriculture share of GDP; PGSA = productivity of grain sown area; RIF = ratio of irrigated farmland; CCF = consumption of chemical fertilizers; AMP = agricultural machinery power.

4.3.2 Vulnerability to climate change in the Loess Plateau

Upon classification, it was found that the highest vulnerability class accounted for 81% of the integrated vulnerability index range despite including only 20% of the counties. Forty-two of the 49 most vulnerable counties had exposure and sensitivity in the high or highest classes, with low or lowest adaptive capacity.

The exceptions amongst the highest vulnerability class were one county (Fugu) that had a high adaptive capacity index and six counties (Tianzhen, Fengzhen, Zuoyun, Ningwu, Shenchi, Haiyuan) with low or lowest exposure. Fugu county ranked high in adaptive capacity as it has amongst the highest per capita net income of rural residents and non-agricultural share of GDP. However the county’s serious soil erosion, barren land and fragmented terrain contributed to higher sensitivity and exposure indexes which carried greater weight in this analysis due to their lower median scores for all counties. For the remaining six counties with comparatively low exposure, all have highest sensitivity and lower adaptive capacity (4 lowest and 2 low), indicating that current structure of agriculture in these six counties may be both poorly suited to the environment and lacking the capital to change. Given the low variability in the integrated vulnerability index of all classes but the highest, those 49 counties (Table 4.3) that represent the majority of the vulnerability range should be prioritised for adaptations.

4.3.3 Spatial distribution of vulnerability on Loess Plateau

Counties with relatively high exposure indexes were typically located at middle northeast-southwest belt of Loess Plateau, primarily in northwest Shanxi, mid-north Shaanxi and east Gansu (Fig. 4.3a). The high exposure can be attributed primarily to serious soil erosion. Some counties located on the northwest and southeast edge of Loess Plateau with lower soil erosion were also classed as high exposure because of high rainfall variability.

Table 4.3 Identified 49 most vulnerable counties on Loess Plateau.

Province	Vulnerability type	County Name
Shaanxi	Highest ES/Lowest AC	Qingjian, Jiaxian
	Highest ES/Low AC	Yanchang, Zizhou, Suide
	Highest ES/Mid AC	Wuqi, Dingbian, Mizhi, Wubu
	Highest ES/High AC	Fugu
Shanxi	Highest ES/Lowest AC	Loufan, Tianzhen, Youyu, Jingle, Ningwu, Shenchi, Kelan, Xingxian, Pianguan, Linxian, Baode, Shilou, Lanxian, Jixian, Daning, Yonghe, Fenxi
	Highest ES/Low AC	Zuoyun, Wuzhai, Hequ, Liulin, Fangshan, Fushan, Yuanqu
	High ES/Lowest AC	Xixian
	High ES/Low AC	Pinglu
Gansu	Highest ES/Lowest AC	Huanxian
	Highest ES/Low AC	Qingcheng
	High ES/Lowest AC	Tongwei, Zhenyuan
Inner Mongolia	Highest ES/Lowest AC	Zhuozi
	Highest ES/Low AC	Fengzhen, Qingshuihe, Guyang,W uchuan
	Highest ES/Mid AC	Liangcheng
Ningxia	Highest ES/Lowest AC	Tongxin, Haiyuan
	Highest ES/Low AC	Yanchi

ES = Exposure×Sensitivity = Potential Harm; AC = Adaptive Capacity

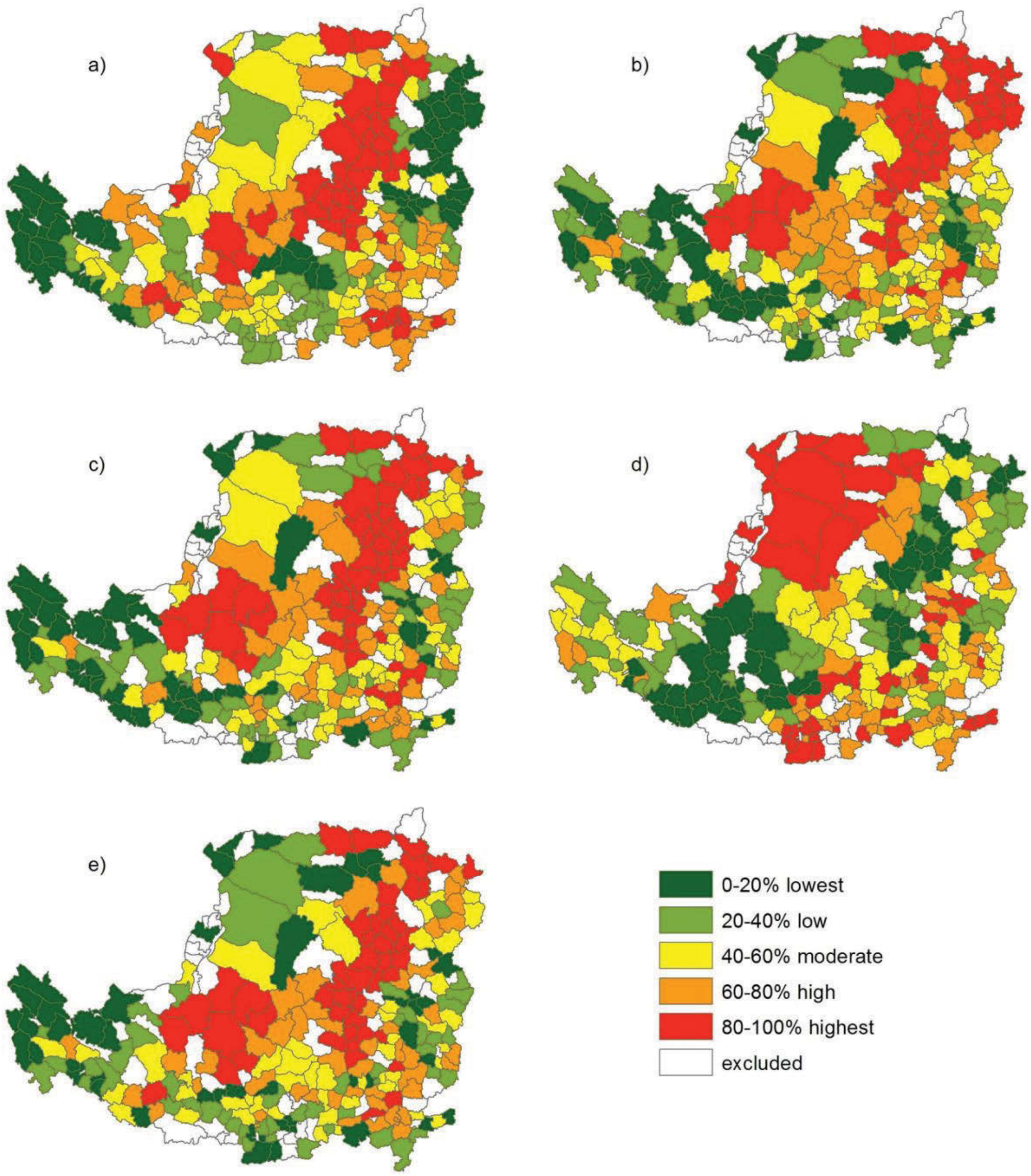


Fig. 4.3 Spatial distribution of vulnerability to climate variability and its components in the Loess Plateau: (a) exposure; (b) sensitivity; (c) potential harm; (d) adaptive capacity; (e) vulnerability.

High sensitivity indexes were found to be partly overlapped with exposure; the most sensitive counties mostly lie on the southeast of Inner Mongolia on the edge of Shanxi, northwest Shanxi and mid-north Shaanxi, south Ningxia and east Gansu, where the exposure values are also relatively high (Fig. 4.3b). Accordingly, counties with the greatest potential for harm consistently lie in the middle northeast to southwest belt where these two indexes overlap, with three areas identified: the southeast of Inner Mongolia on the edge of Shanxi, northwest Shanxi and middle part of north Shaanxi, south Ningxia and east Gansu (Fig. 4.3c).

The spatial distribution of adaptive capacity was found to be roughly the inverse of exposure, sensitivity and potential harm. The highest adaptive capacity was concentrated on the northwestern and southeastern edges of the plateau (Fig. 4.3d). The northwestern part has high disposable income of rural residents, productivity of grain sown area and ratio of irrigated farmland, whereas the southeastern regions are characterised by high consumption of chemical fertilisers and agricultural machinery power in addition to high productivity of grain sown area. By contrast, the middle northeast to southwest belt, featuring the greatest concentration of counties with high predisposition to be adversely affected, was found to also be made up of counties with the lowest adaptive capacity, aggravating that area's integrated vulnerability score.

In general, counties with high exposure and sensitivity, in addition to low adaptive capacity tended to be close to one another. Therefore, the most vulnerable counties occupy a clearly defined zone, visible in Fig. 4.3e. A vulnerability belt was identified, running from northeast to southwest across the southeast of Inner Mongolia, the northwest of Shanxi and middle part of north Shaanxi, the south part of Ningxia and east Gansu.

The result is consistent with the previous partial assessment of the Plateau conducted by Wang and Liu (2003), in that the counties present in both analyses have similar vulnerability relative to each other. It was found however that the highest proportion of vulnerable counties was concentrated in Shanxi province (Table 4.3), which was not assessed by Wang and Liu (2003). Furthermore, the results appear to validate what is implied by other studies conducted at a lower resolution; where Lin and Wang (1994) reported that Shaanxi, Inner-Mongolia, Gansu, Shanxi, Qinghai and Ningxia all had agriculture which was at an elevated risk of climate change, this study has specifically shown how this vulnerability is concentrated in a middle northeast and southwest vulnerability belt.

4.3.4 Sensitivity of results to indicator choice and weighting

The impact of individual indicator choice on county ranking according to the integrated vulnerability index is shown in Fig. 4.4a. Climatic yield variability, as the sole indicator of the sensitivity index, has the greatest impact on vulnerability rankings. By contrast, the average shift in ranking is no greater than 7 when any indicator of adaptive capacity is excluded. This is only a small rank change out of total 243.

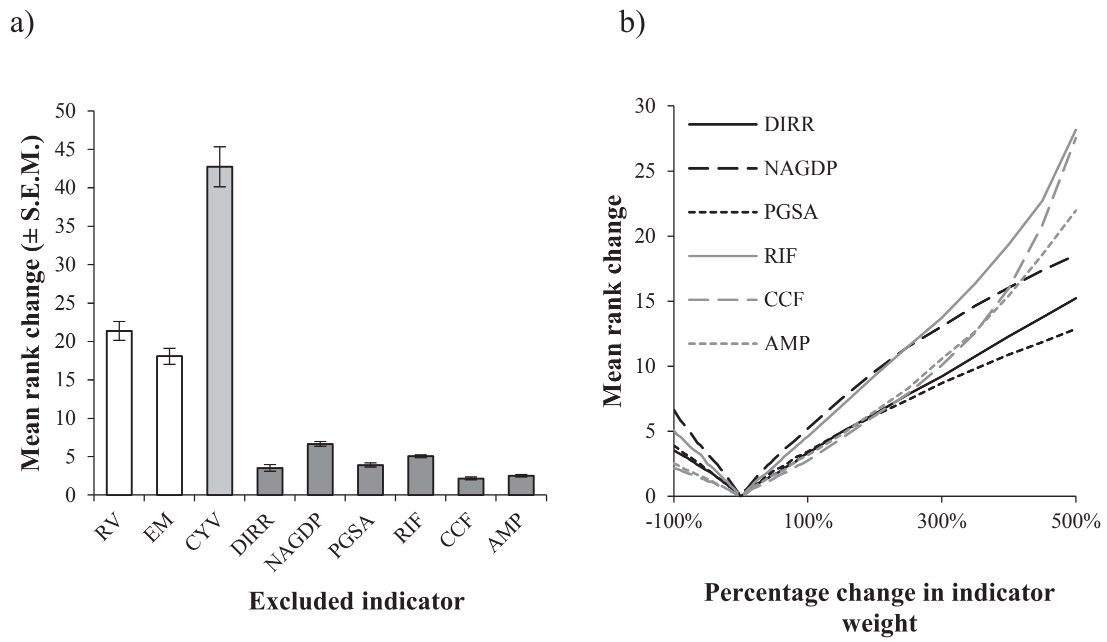


Fig. 4.4 Mean absolute change in ranking of 243 counties of the Loess Plateau according to integrated vulnerability index when individual indicators are removed from the calculation of the index (a) and during one-way sensitivity analysis on the weights of six indicators of adaptive capacity (b). RV = rainfall variability; EM = soil erosion modulus; CYV = climatic yield variability; DIRR = disposable income of rural residents; NAGDP = non-agriculture share of GDP; PGSA = productivity of grain sown area; RIF = ratio of irrigated farmland; CCF = consumption of chemical fertilizers; AMP = agricultural machinery power.

The effect of potential weighting schemes on county ranking is explored in Fig. 4.4b, which indicates that an extensive shift in ranks only occurs beyond what is typical for mathematically and option derived weighting schemes. Thus it was concluded that adopting equal weights for adaptive capacity indicators can yield robust results whilst avoiding the pitfalls associated with complex weighting schemes (Saisana et al. 2005).

An interesting revelation of the sensitivity analysis is that 68% of counties do not change vulnerability class when adaptive capacity is removed entirely from the assessment. This indicates that adaptive capacity in the majority of the Loess Plateau is inadequate relative to the current threat posed.

4.3.5 Policy implications

According to zoning activities undertaken by the National Development and Reform Commission et al. (2010) to guide management decisions on the Loess Plateau, 34 of the 49 counties that were identified as being in the highest vulnerability class are also located within the loess hilly and gully region (Fig. 4.5). This therefore suggests the loess hilly and gully region should be prioritised for interventions. The current comprehensive management plan prescribed for this region includes extensive ecological construction aiming to minimise erosion and conserve water (National Development and Reform Commission et al. 2010). Judicious use of similar policies has demonstrated value in reducing exposure and sensitivity to climate risks, however it has been reported that more beneficial sustainability outcomes could be achieved if projects were designed to target specific local problems instead of focusing on achieving area based quotas for ecological restoration (Xu 2011). In this regard, the results can be used by policy-makers to identify priority counties for adaptation and make decisions according to their specific needs.

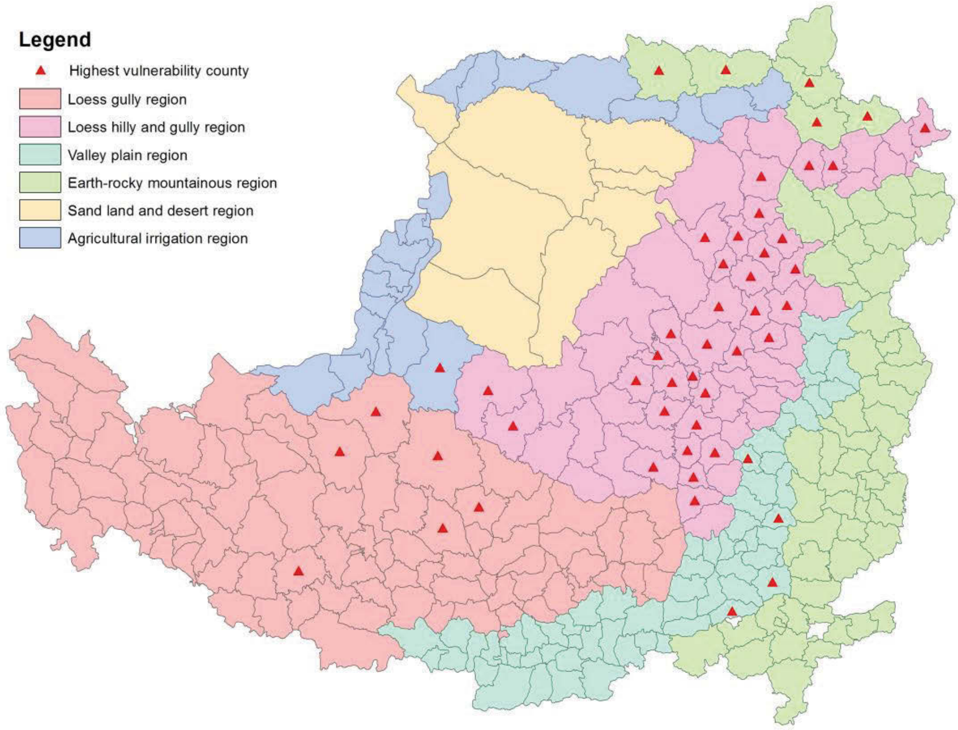


Fig. 4.5 Comprehensive management of Loess Plateau area zoning map (National Development and Reform Commission et al. 2010) with highest vulnerability class counties identified in this study marked.

The need for a greater emphasis on measures which improve the adaptive capacity in vulnerable areas is also evident, as there were few counties analysed that were found to have both high potential for harm and high adaptive capacity to compensate. To build sustainable agricultural systems that are capable of resisting and adapting to uncertain climate effects as they emerge, the Chinese government should continue its policy of improving rural livelihoods with a focus on the most vulnerable counties identified in this analysis. Specific attention should be paid to promoting investment in productivity enhancing and drought resisting adaptations that will yield a sustainable increase in incomes lasting beyond the intervention period. These measures will provide farmers with alternatives when faced with unfavourable climatic conditions.

4.4 Conclusion

This study describes and applies a conceptual framework to analyse the vulnerability of 243 counties to climate change on the Loess Plateau. The results indicate that vulnerability to climate change on the Loess Plateau is concentrated to 49 counties and that these counties lie in clearly defined zones. The middle northeast to southwest belt, located at the southeast of Inner Mongolia on the edge of Shanxi, northwest Shanxi and middle part of north Shaanxi, south part of Ningxia and east Gansu included the most vulnerable counties, which were characterised by high exposure and high sensitivity and low adaptive capacity. It is concluded that adaptation measures for both ecological restoration and economic development are needed for those counties to cope with future climate change. Further studies should be undertaken to investigate potential adaptation options on those areas identified as most vulnerable as this is an important issue for future research contributing to sustainable development in the face of changing climate.

Chapter 5: Analysis of the effectiveness of plastic film mulching as an adaptation

5.1 Introduction

Farmers are typically both decision makers and implementers of adaptation options to climate change and variability. The modification of agronomic practices are common adaptations to reduce agricultural vulnerability. Improved agronomic techniques and farming practices are continuously designed, tested and either adopted or rejected by farmers. It was established in Chapter 2 that adaptation in a manner that improves the use efficiency of precipitation is an essential process to increase the agriculture productivity on drylands, which can also assist to reduce agricultural sensitivity to unfavourable climatic conditions. When use efficiency is increased, less water can achieve the same unit of yield because rainfall fluctuations bring about less water stress. As a result, yield sensitivity to climate variability and change is reduced. In Chapter 4, it was found that agricultural sensitivity to climate change, as expressed by the coefficient of variation in climatic yield of grain over time, was by a wide margin the most influential factor determining vulnerability.

The Loess Plateau is one of the most important dryland farming regions in China. Rain-fed agriculture is the major cropping system and maize accounts for 30% of the total cultivated area and 40% of the total crop production (An et al. 2014). It was reported that the actual average maize yield on the Loess Plateau is 4812 kg ha^{-1} (Li et al. 2002), making maize the highest yielding grain crop in the region. This relatively high production is because of the high efficiency of maize C4 photosynthesis and the favourable alignment of the growing season. The annual rainfall is mainly distributed in the growing season to sustain the production on the Loess Plateau. As such, maize contributes greatly to the food security in the northwest, where the pressure of population growth and food demand is high. However, crop productivity on the Loess Plateau is still limited by its dryland characteristics, in particular scarce and unpredictable precipitation and low water availability from rivers and ground water. These issues have been magnified by climate change. Inefficient use of limited water resources coupled with drought and heat stress during the cropping season threatens agricultural sustainability in dryland environments. To address the problems, technologies have been developed to increase the water use efficiency in dryland farming systems.

The application of plastic film mulch to fields sown with certain grain crops is an adaptation for dryland agriculture that can reduce water losses from evaporation in soils by physically obstructing the transfer of water to the atmosphere (Zhou et al. 2009; Wang et al. 2011). Numerous studies based on agronomic field experiments have been undertaken previously to design the best mulching practices for farmers (Zhou et al. 2009; Bu et al. 2013; Liu et al. 2014; Qin et al. 2015; Eldoma et al. 2016). Their major results indicate positive effect of applying plastic film mulch, with benefits to grain yield and WUE. It was reported that, on average, alternative practices with 100% plastic film mulch covering can increase crop yield by 76% compared with conventional practices (Zhang et al. 2014). This result is supported by the analysis of 36 studies carried out in smallholder farms and experimental stations under rain-fed conditions on the Loess Plateau (Zhang et al. 2014). However, the yield and WUE responses to management practices relative to conventional skills had a wide range of variation. Adverse effects on maize yield resulted from plastic film mulching in dryland are also reported in some studies (Zhang et al. 2008). As the effect of mulching is affected by many factors including soil properties, mulch types and field practices, it is difficult to accurately quantify. Empirical assessment of the suitability of plastic film mulch as an adaptation on a farm-specific basis is impractical, being time-consuming, laborious, costly, and having little applicability to different climate and year patterns. For these situations, agricultural system models are valuable tools, as they can simulate crop production and water use under different climate, soil and agricultural management practices over time.

In this chapter, the Agricultural Production Systems sIMulator (APSIM) was used to evaluate the effectiveness of applying plastic film mulching to maize crop as an adaptation option on the Loess Plateau under uncertain climate conditions. The case study of the maize production was conducted at Changwu. The comparison of plastic film mulching with the conventional method could provide information to determine whether the mulching application is efficient or not at different climate year patterns.

5.2 Materials and methods

5.2.1 Study site, soil and climate data

The Changwu agro-ecological experiment station was selected as the case study site, which is located in the south-central region of the Loess Plateau (107°41′E，35°14'N, ca. 1200 m above sea level; Fig. 5.1). Changwu features a warm temperate semi-humid continental monsoon climate (Zhang et al. 2013) that is wetter than the average for the Loess Plateau. Mean annual precipitation is 578.5 mm, with 73% (426 mm) falling between May and September; mean annual temperature is 9.1 °C.

(a)

(b)

Fig. 5.1 Changwu agro-ecological experiment station, (a) location within the Loess Plateau, and (b) view of the experiment site.

The soil texture at Changwu is predominately silty clay loam (Wang et al. 2011; He et al. 2014). The soil data measured at Changwu are shown in Table 5.1, which were used to parameterise APSIM, including soil physical characteristics (texture, bulk density), organic carbon concentration and soil hydraulic characteristics (saturation, field capacity, lower limit) in different layers, which were also reported in Zhang and Liu (2005) and He et al. (2014). These data were obtained from field experiments and the soil database of China (http://www.soil.csdb.cn).

Long-term daily meteorological data (1961–2010), including maximum and minimum temperatures, rainfall and solar radiation, were used for simulation studies. These data were shared and collected from the China Meteorological Administration (http://cdc.cma.gov.cn/). Solar radiation was calculated from sunshine hours with a_s=0.25 and b_s=0.50 by using the Ångström–Prescott equation (Prescott 1940). Mean daily temperature and solar radiation, and total precipitation from April to September were calculated to represent climatic conditions during growing seasons of maize. Due to the large inter-annual variability in precipitation, spring maize growing seasons were divided into dry and wet years. Years with precipitation less than the long-term average were classified as dry years and the others as wet years.

Table 5.1 Soil properties at experiment site at Changwu agro-ecological experiment station.

Soil depth (cm)	0-20	20-40	40-60	60-80	80-100	100-180
Texture	Silty clay loam	Silty clay loam	Silty clay loam	Silty clay loam	Silty clay loam	Silty clay loam
BD (g cm^{-3})	1.41	1.41	1.38	1.31	1.26	1.40
SAT (mm mm^{-1})	0.425	0.404	0.392	0.452	0.455	0.432
DUL (mm mm^{-1})	0.305	0.305	0.313	0.311	0.309	0.309
LL (mm mm^{-1})	0.094	0.094	0.115	0.110	0.106	0.106

BD: bulky density; SAT: saturation; DUL: field capacity; LL: lower limit.

5.2.2 Field experiments

Field experiments of spring maize growth with and without plastic film mulching were conducted at Changwu station in three years. Maize cultivar Xianyu 335 was sown on April 20, April 18, and April 24 in 2007, 2008 and 2010 respectively. In 2007 and 2008, two management treatments conventional farming and film mulching (0.7 m wide and 0.005 mm thick) were applied under rain-fed condition (Liu et al. 2010). Fertilisers were applied at rates of 110 kg N ha^{-1} in the form of urea and 50 kg P ha^{-1} in the form of calcium superphosphate (P_2O_5), before maize was sown at a depth of 5 cm with a density of 85 000 plants ha^{-1} (Liu et al. 2010). Prior to backfilling, 300 ml water was poured into each seed hole to encourage seeding germination and additional nitrogen was applied at the jointing and tasselling stages at rates of 80 kg N ha^{-1} and 90 kg N ha^{-1} respectively (Liu et al. 2010). In 2010, only conventional farming with a 5 cm sowing depth and a density of 65 000 plants ha^{-1} was conducted, with fertiliser applied at rates of 139 kg N ha^{-1} and 39 kg P ha^{-1} in the form of urea and calcium superphosphate (P_2O_5) before sowing. Timing of phenological stages, leaf area index (LAI), biomass, grain yield and soil water content were measured throughout the experiments. The data of year 2010 was obtained from Chinese Ecosystem Research Network Data Sharing (http://www.cerndata.ac.cn/). Maize was harvested when ripe.

5.2.3 APSIM model and its parameterisation

APSIM version 7.6 was employed to simulate the effects of different management practices on maize growth and production. Built-in modules including maize crop (MAIZE), soil water (SOILWAT2), soil nitrogen (SOILN2), crop residue (RESIDUE) and management specification (MANAGER) were used for the simulation of crop growth and development, soil water, soil nitrogen and crop managements. This allows flexible simulations of management options such as rotation type, fertilization and irrigation, grain yield and water balance of spring maize in a rainfed cropping system. Detailed descriptions of each module can be found at the APSIM website: http://www.apsim.info.

The APSIM model runs at a daily time-step using daily meteorological and soil data. Crop and soil data from spring maize cropping experiments were used to calibrate and validate the APSIM model. Measured LAI, biomass, yield and soil water content from the 2010 field experiment was employed to calibrate the model and determine the crop parameters. The calibrated model was then validated using field data from spring maize experiments in 2007 and 2008. After validation, the APSIM model was inputted with long term weather data and run to assess the effectiveness of applying plastic film mulching as an adaptation under different climate year patterns.

5.2.4 Model settings and simulation experiment design

Spring maize at Changwu is generally sown in mid- and late-April and harvested in mid-September, thus a dynamic sowing window was set from 10 to 30 April. It was assumed that same cultivar Xianyu 335 was sown in the past 50 years to observe sole climate impact under current productivity scenarios. The sowing density was set at 60 000 plants ha^{-1} and sowing depth at 5 cm according to local farming practices. Soil water was set as the value according to the commencement of the field experiment. Fertilizers N and P were applied at sowing, at the rates of 139 kg N ha^{-1} and 39 kg P ha^{-1}. Soil nitrogen, phosphorus, water and residues were reset to initial condition at each sowing. Harvesting occurs at physiological maturity.

In addition to the general model setting, simulation experiments for the effect of plastic film mulching were designed based on its effects of reducing soil evaporation and increasing soil temperature. Three scenarios were simulated.

Scenario 1 (S1): Conventional farming without plastic film mulching. Summer Cona = 3, Summer U = 6 and Winter Cona = 3, Winter U = 6 were set in the APSIM soil module; air temperature in climate file of APSIM (met) was set according to local metrological records.

Scenario 2 (S2): Plastic film mulching effect on soil evaporation. The effect of plastic film mulching on dryland maize production was entirely represented by inhibiting evaporation from soil, thereby increase soil moisture. Soil evaporation was reduced by 50% by setting Summer Cona = 1, Summer U = 1.5 and Winter Cona = 1, Winter U = 1.5 in the APSIM soil module; air temperature was set as per S1.

Scenario 3 (S3): Plastic film mulching effect on both soil evaporation and temperature. In addition to the effect of plastic film munching on soil evaporation as per S2 (Summer Cona = 1, Summer U = 1.5 and Winter Cona = 1, Winter U = 1.5), this scenario also considered the effect of plastic film mulching on soil temperature. APSIM does not account for soil temperature in any existing module, and the only input related to temperature within control is in the climate file. Accordingly, an approach based on the theory of 'cumulative soil temperature compensates for the cumulative air temperature' (Chen and Nan 1983) was adopted. This theory is based on the report that 'in a certain air temperature range, the compensation effect is mainly determined by the ratio of soil temperature to air temperature, and the increment of soil temperature; in general, the bigger those values, the better the compensation effects' (Chen and Nan 1983). A temperature increment ΔT was added to daily minimum and maximum temperature in the weather data file (met) to simulate the effects on crop growth. The calculation of temperature increment ΔT was according to the methods in Zhang et al. (2008) and van Oort et al. (2016). Temperature correction was applied during mid-April to mid-June (60 days from day 105 to day 164) with an average ΔT = 0.77 °C. Temperature correction was not applied at other times because the plastic film mulching mainly raises soil temperature when the soil is unshaded in the sowing to silking stages of maize (Li et al. 2010; Bu et al. 2013; Li et al. 2013).

5.2.5 Data analysis

The coefficient of determination (R^2) of the regression lines between simulated and observed values of LAI, total biomass and soil water were determined to assess goodness of fit.

The model outputs from the three scenarios as described above were used to generate yield and WUE cumulative probability lines for comparison. Simulated maize yields and components of the water balance model (evapotranspiration, drainage and runoff) were used to calculated WUE as grain yield/(evapotranspiration + drainage + runoff) (Acuña et al. 2015). The difference between yield and WUE values outputted by each scenario were tested for statistical significance using paired Student's T-Tests. Temporal variability for spring maize yield were further analysed by comparing each scenario in wet and dry years.

5.3 Results

5.3.1 Model calibration and validation

The calibrated cultivar specific parameters for Xianyu 335, being maximum grain number per head, grain filling rate, thermal time required from emergence to end of juvenile, photoperiod slope, thermal time required from flowering to maturity, thermal time required from flowering to start grain-filling, are shown in Table 5.2.

Table 5.2 Derived values of parameters for APSIM-Maize at Changwu (Variety: Xianyu 335).

Parameters	Values
head_grain_no_max (maximum grain number per head, kernels head^{-1})	750
grain_gth_rate (grain filling rate, mg grain^{-1} day^{-1})	10
tt_emerg_to_endjuv (thermal time required from emergence to end of juvenile, °C d)	230
photoperiod_slope (°C hour^{-1})	14
tt_flower_to_maturity (thermal time required from flowering to maturity, °C d)	700
tt_flower_to_start_grain (thermal time required from flowering to start grain-filling, °C d)	80

The simulations of APSIM generally matched well with the measured parameters (Fig. 5.2a, 5.3a, 5.4a). Simulated LAI for 2007 and 2008 closely conformed to the seasonal pattern of growth that was observed (Fig. 5.2a), with an R^2 value of 0.78 (Fig. 5.2b), when calibrated with data from 2010. Biomass and yield simulation also closely followed the observation (Fig. 5.3a), however there was a slight tendency to underestimate yield. The model was however able to explain more than 96% of the variation in observed biomass values (Fig. 5.3b). The calibrated soil water corresponded well with measured values (Fig. 5.4a), being able to explain more than 95% of the variation. All the slopes of the regression lines were close to 1.0. Considering possible errors in the measurement data, the performance of the model was considered to be satisfactory for the simulation of crop growth for the maize cropping system.

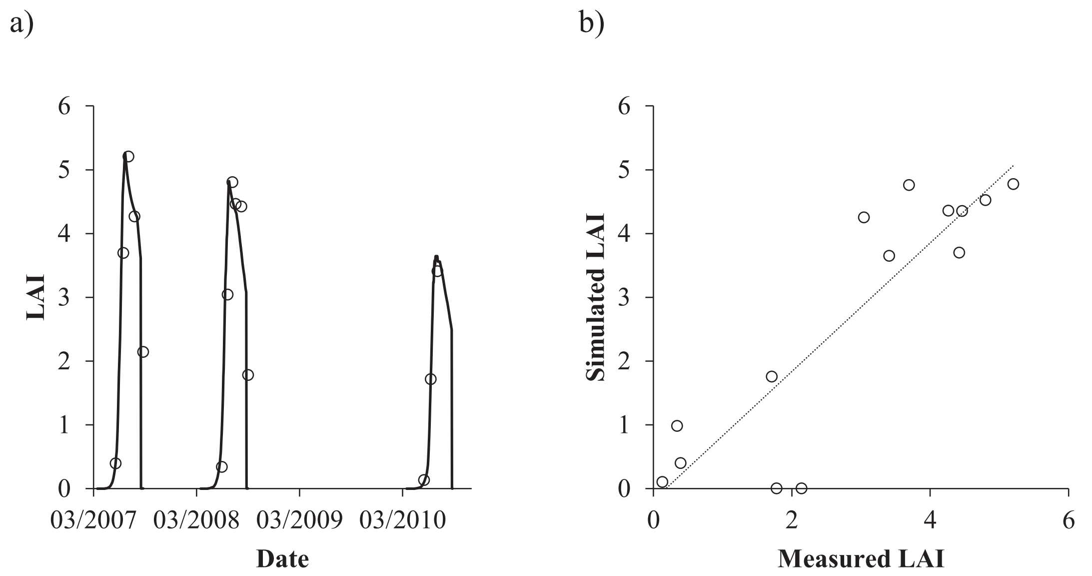
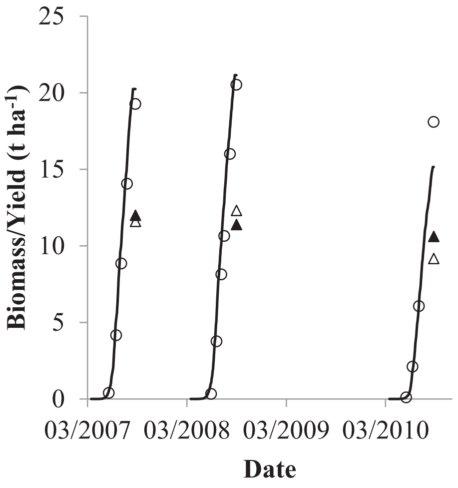


Fig. 5.2 Calibration and validation results of APSIM-Maize using Leaf Area Index (LAI) data from three maize growing experiments at Changwu. (a) Data from the 2010 experiment was used to calibrate the model which was then used to simulate the 2007 and 2008 experiments (circles = observed LAI; lines = predicted LAI). (b) Regression of observed and simulated LAI values (y = 1.0082x - 0.1803, R^2 = 0.78, p < 0.01).

a)



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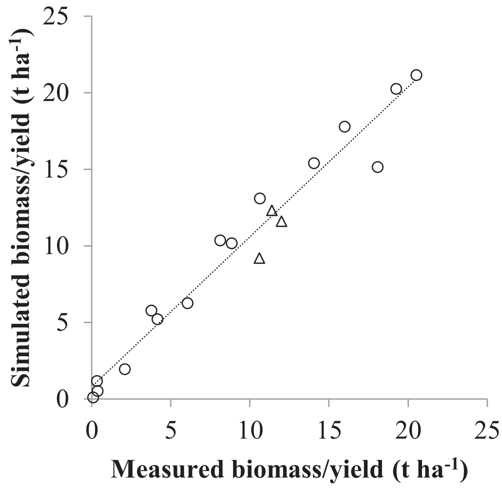


Fig. 5.3 Calibration and validation results of APSIM-Maize using biomass and yield data from three maize growing experiments at Changwu. (a) Data from the 2010 experiment was used to calibrate the model which was then used to simulate the 2007 and 2008 experiments (hollow circles = observed biomass; lines = predicted biomass; filled triangles = observed yield; hollow triangles = predicted yield). (b) Regression of observed and simulated biomass and yield values (hollow circles = biomass; hollow triangles = yield; $y = 0.9789x + 0.8024$, $R^2 = 0.97$, $p < 0.01$).

a) b)

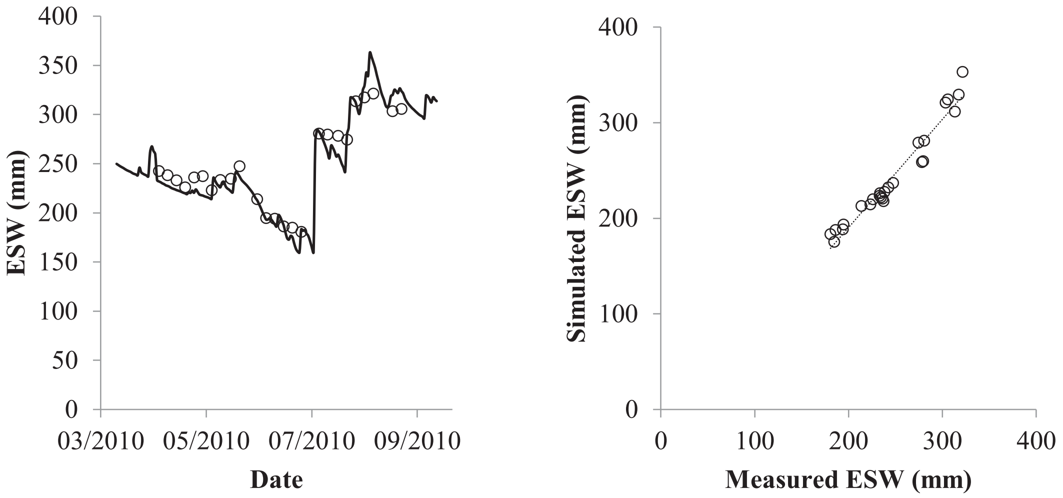


Fig. 5.4 (a) Calibration results of APSIM-Maize Extractable Soil Water (ESW) data from maize growing experiments at Changwu in 2010 (circles = observed ESW; line = simulated ESW); (b) Regression of observed and simulated ESW values (y = 1.1313x -35.842, R^2 = 0.95, $p < 0.01$).

5.3.2 Temporal variability of climate from 1961-2010

The variations of climate variables during maize growing season from 1961-2010 are shown in Fig. 5.5. The daily mean temperature averaged 17.7 °C and ranged from -4.6 to 29.4 °C with a standard deviation of 4.87 °C over growing seasons. Solar radiation averaged 18.4 MJ m^{-2} d^{-1} and ranged from 7.0 to 30.5 MJ m^{-2} d^{-1}, with a standard deviation of 6.86 MJ m^{-2} d^{-1}. The total precipitation during maize growing season averaged 466.3 mm with a range from 227.1 to 762.5 mm. 56% of maize growing seasons are classified as dry while 44% as wet (Fig. 5.6).

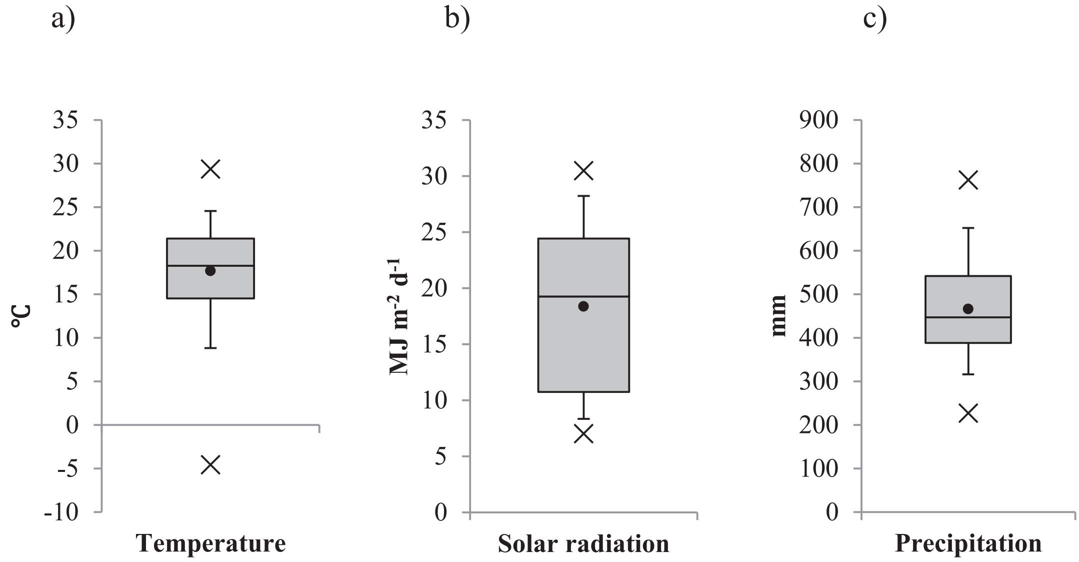


Fig. 5.5 (a) Mean daily air temperature, (b) solar radiation and (c) total rainfall during maize growing seasons from 1961-2010. The boxplots show the 5th, 25th, 50th, 75th and 95th percentiles. Circles indicate the mean and crosses indicate the minimum and maximum.

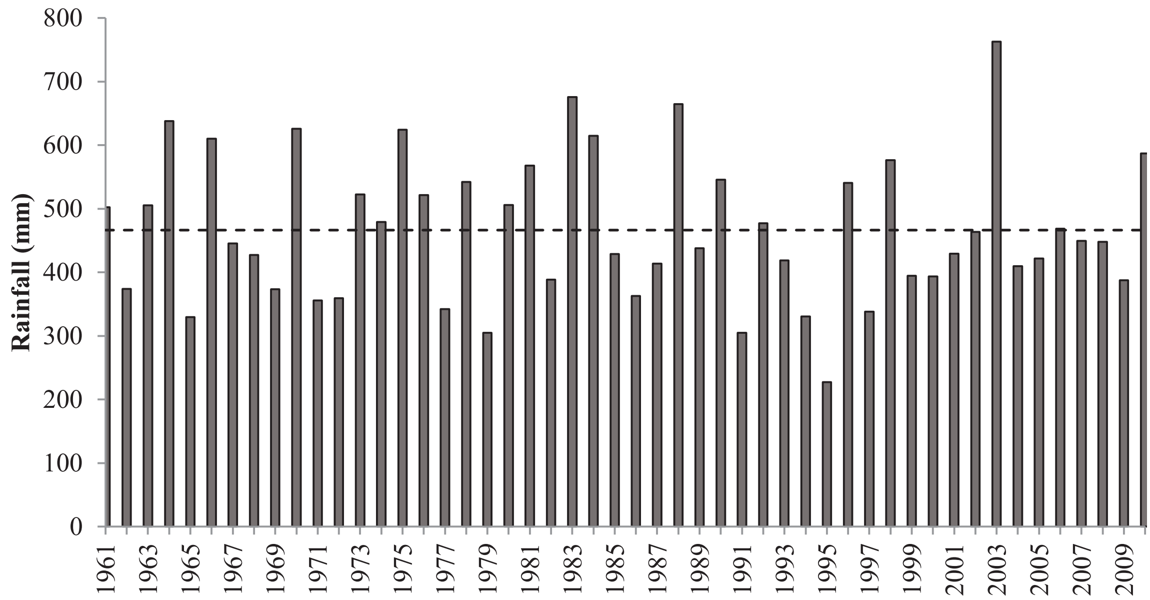


Fig. 5.6 Total annual within season rainfall from 1961-2010 recorded at Changwu (vertical bars) and long term average (horizontal line).

5.3.3 Yield response to the application of plastic film mulch

Simulation results of maize yield in response to different plastic film mulching effect scenarios are shown in Fig. 5.7. Average maize yields were predicted to be 7.66 t ha^{-1}, 9.12 t ha^{-1} and 9.27 t ha^{-1} under S1, S2 and S3 respectively. Maize yields increased significantly under S2 and S3 compared with those without mulching effect in S1 ($p < 0.005$). The average yield difference between the two plastic film mulching scenarios S2 and S3 was not significant ($p > 0.05$). Cumulative probability of exceedance of yield shows maize cultivar Xianyu 335 generally performed well at Changwu with the simulation assumptions (Fig. 5.8). In more than 80% of years, the maize yield is above 6 t ha^{-1} in all three scenarios. Maize yields exceeding 7.5 t ha^{-1} can be attained in 56% of years under simulated conventional farming. With the effect of mulching, the probability of exceedance at 7.5 t ha^{-1} yield level is increased to 88% and 90% under S2 and S3 respectively. The effect of plastic film mulching could substantially increase the probability of the medium yield level (7.5-10 t ha^{-1}) while it has little effect on lower or higher yields, which can be seen in Fig. 5.8.

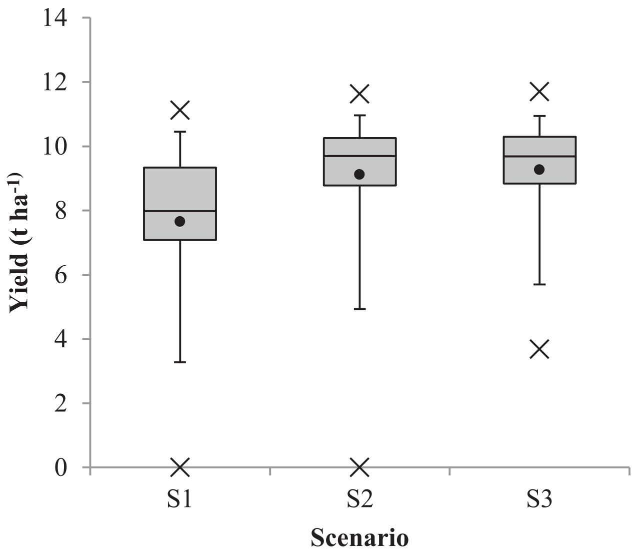


Fig. 5.7 Simulated maize yields during 1961-2010 at Changwu under three scenarios; S1 conventional farming without plastic film mulching; S2 farming with plastic film mulching's effect on reduced soil evaporation by 50%; S3 farming with plastic film mulching's effect on both soil evaporation reduction by 50% and temperature increase with an average increase of 0.77 °C.

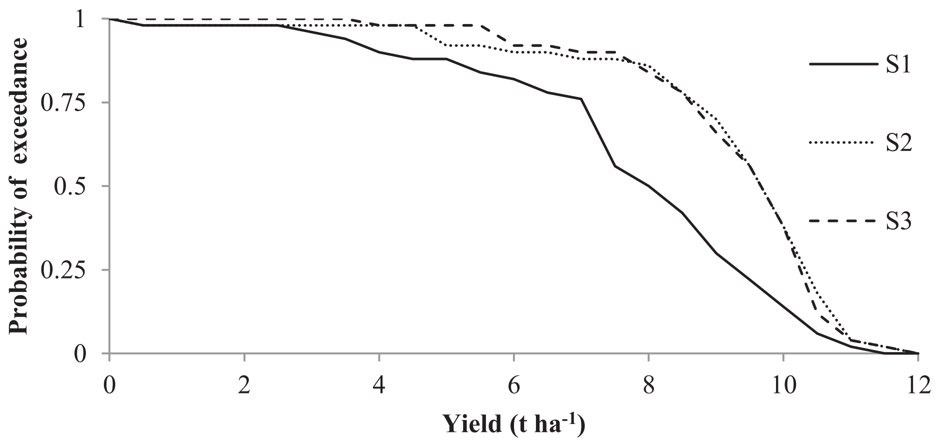


Fig. 5.8 Cumulative probability distribution of maize yields under three scenarios; conventional farming without plastic film mulching (S1, solid line); farming with plastic film mulching's effect of reducing soil evaporation by 50% (S2, dotted line); farming with plastic film mulching's effect of both soil evaporation reduction by 50% and temperature increase with an average increase of 0.77 °C (S3, dashed line).

The distribution of yields between 5% and 95% occupied a smaller range under both S2 and S3 than that under S1 (Fig. 5.7). The yield range is largest under S2 because it shares the minimum yield of 0 t ha^{-1} with S1, however the maximum yield is higher. The 0 t ha^{-1} yield occurred in year 1983 under S1 and S2, and was due to frost stress (<-2 °C in APSIM). Under S3 with the effect of increased temperature, the losses due to frosts were avoided and the lowest yield increased to 3.69 t ha^{-1}, greatly reducing the range of yields under this scenario.

Variability in yield performance is associated with temporal variation of climate and the variation of rainfall is an important consideration. Maize yields are generally higher in wet years than dry years under all three management scenarios (Fig. 5.9).

Although maize yields under S2 and S3 increased in both dry and wet years, the extent of the increase is different. As shown in Fig. 5.9, during dry seasons, the average maize yield increased by 27.3% under S2 compared with the yield under S1, from 7 t ha^{-1} to 8.9 t ha^{-1}. There was no statistically significant difference between average yields under S2 and S3 in dry years ($p > 0.05$). During wet seasons, the average maize yield increased by 10.6% under S2 from 8.5 t ha^{-1} to 9.4 t ha^{-1} compared with the yield under S1. Accordingly, the effect of reducing evaporation from soil by applying plastic film mulching in dry years is approximately twice that in wet seasons. The average yield under S3 is also not significantly different from that under S2 in wet years ($p > 0.05$). When the crop failure year 1983 (yield = 0 kg ha^{-1}) was excluded from the analysis, the variability in yields under S1 and S2 are considerably lower (Fig. 5.9b)

a) b)

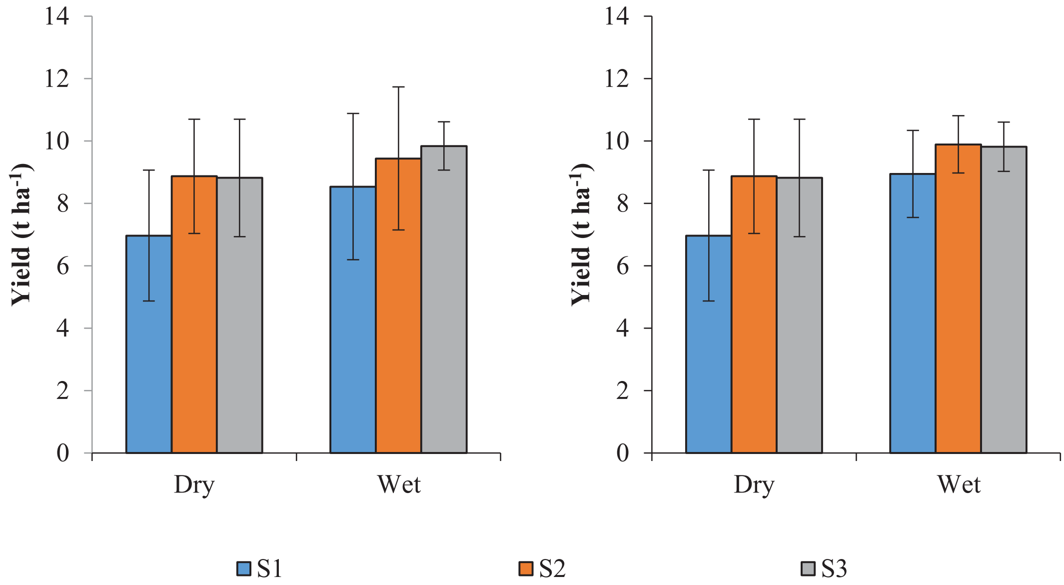


Fig. 5.9 Average simulated maize yield at Changwu under three scenarios for dry and wet years with (a) and without (b) data from 1983, in which a yield of 0 t ha^{-1} was simulated due to low temperatures after sowing. S1 = conventional farming without plastic film mulching; S2 = farming with plastic film mulching's effect of reducing soil evaporation by 50%; S3 = farming with plastic film mulching's effect of both soil evaporation reduction by 50% and temperature increase with an average increase of 0.77 °C; error bars represent standard deviation.

5.3.4 Water use response to the application of plastic film mulch

Calculated WUE during maize growth in response to different plastic film mulching effect scenarios are shown in Fig. 5.10. Average WUE under three scenarios were 2.02 kg m^{-3}, 2.63 kg m^{-3} and 2.68 kg m^{-3} respectively. Similar to maize yields, WUE increased significantly under S2 and S3 compared with conventional farming under S1 ($p < 0.005$). The average WUE difference between the two plastic film mulching scenarios S2 and S3 was not significant ($p > 0.05$). Cumulative probability of exceedance of WUE shows that in more than 86% of years, WUE is above 1.5 kg m^{-3} in all three scenarios (Fig. 5.11). WUE exceeding 2 kg m^{-3} could be attained in 66% of the years under S1. With the effect of mulching, the probability of exceedance at 2 kg m^{-3} WUE level increased to 90% and 94% under S2 and S3 respectively. The effect of plastic film mulching could substantially increase the probability of the higher WUE levels while it has limited effect on lower WUE, which can be seen in Fig. 5.11. The distribution of WUE between 5% and 95% occupied a relatively smaller range under both S2 and S3 than that under S1 (Fig. 5.10). The WUE range is largest under S2 because it shares the minimum WUE of 0 kg m^{-3} with S1, however the maximum WUE is higher. The calculated WUE of 0 kg m^{-3} is because of the 0 t ha^{-1} yield under S1 and S2. Under S3, the WUE increased to 1.5 kg m^{-3} as the lowest yield increased with the effect of increased temperature, greatly reducing the WUE range under this scenario.

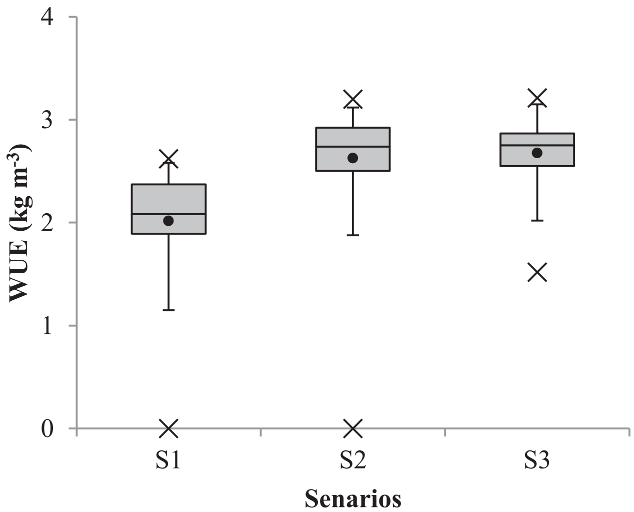


Fig. 5.10 Simulated WUE during 1961-2010 at Changwu under three scenarios; S1 conventional farming without plastic film mulching; S2 farming with plastic film mulching's effect on reduced soil evaporation by 50%; S3 farming with plastic film mulching's effect on both soil evaporation reduction by 50% and temperature increase with an average increase of 0.77 °C.

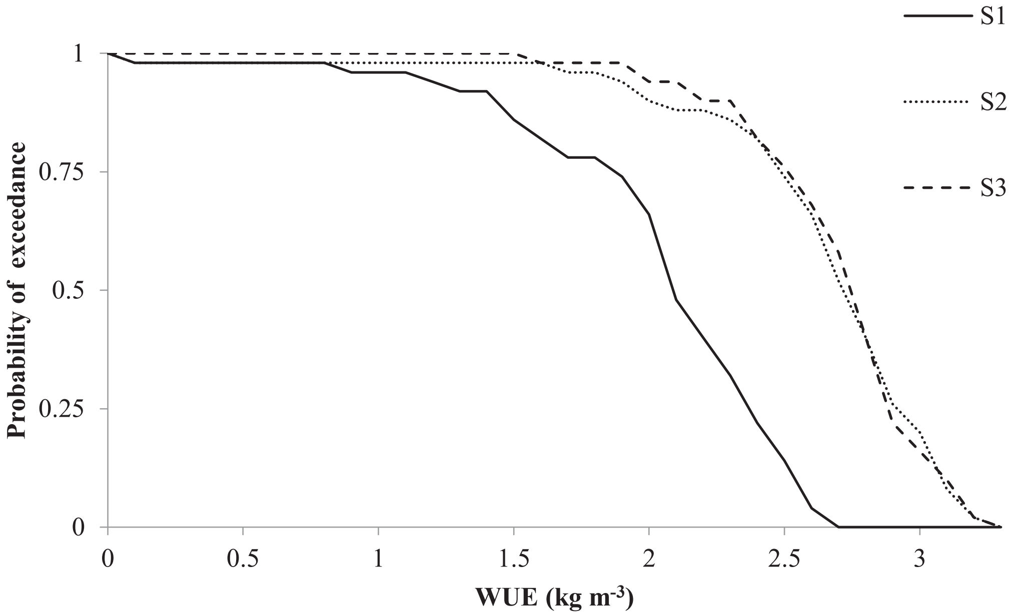


Fig. 5.11 Cumulative probability distribution of WUE under three scenarios; conventional farming without plastic film mulching (S1, solid line); farming with plastic film mulching's effect of reducing soil evaporation by 50% (S2, dotted line); farming with plastic film mulching's effect of both soil evaporation reduction by 50% and temperature increase with an average increase of 0.77 °C (S3, dashed line).

WUE was slightly higher in wet years than dry years under all three management scenarios (Fig. 5.12). Although WUE under S2 and S3 increased in both dry and wet years, the extent of the increase is different. As shown in Fig. 5.12, during dry seasons, the average WUE during maize growth increased by 36.4% under S2 compared with that under S1, from 1.9 kg m^{-3} to 2.6 kg m^{-3}. There was no statistically significant difference between average WUE under S2 and S3 in dry years ($p > 0.05$). During wet seasons, the average WUE during maize growth increased by 23.5% under S2 comparing with that under S1, from 2.1 kg m^{-3} to 2.6 kg m^{-3}. The average WUE under S3 was also not significantly different from that under S2 in wet years ($p > 0.05$). When the crop failure year was excluded from the analysis, the variabilities of WUE under S1 and S2 were considerably lower (Fig. 5.12b)

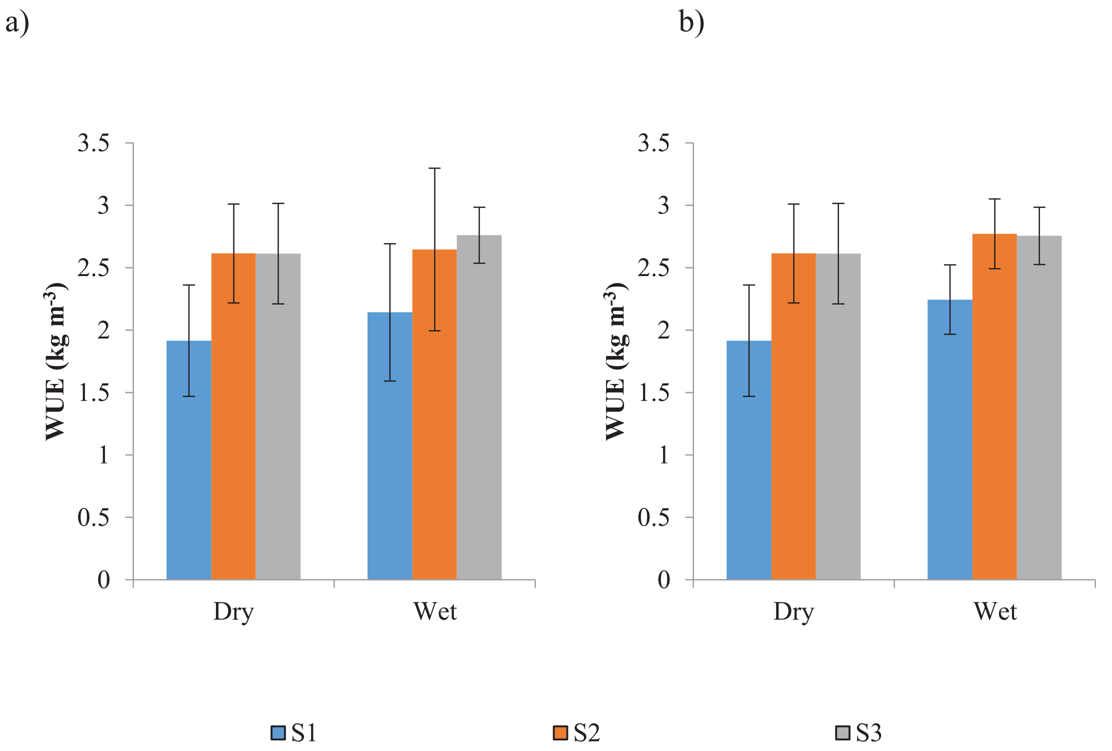


Fig. 5.12 Average simulated WUE at Changwu under three scenarios for dry and wet years with (a) and without (b) data from 1983, in which a yield of 0 t ha^{-1} was simulated due to low temperatures after sowing. S1 = conventional farming without plastic film mulching; S2 = farming with plastic film mulching's effect of reducing soil evaporation by 50%; S3 = farming with plastic film mulching's effect of both soil evaporation reduction by 50% and temperature increase with an average increase of 0.77 °C; error bars represent standard deviation.

5.4 Discussion

The simulation results show that maize yield could be improved significantly (average 1302 kg ha^{-1}, 15.3% more than non-mulching) by applying plastic film mulch, and the potential in dry years are larger than that in wet years. The variability of maize yield could also be reduced by plastic film mulching. The probability of exceedance of maize yields at medium levels could be substantially increased with the effect of plastic film mulching in the context of uncertain climate, while this effect on lower or higher yields are little. The results also indicate that if rainfall can be forecasted over a season to be above or below average, with the decision to apply plastic film mulch made accordingly, the efficiency of the adaptation could be greatly increased.

The simulation showed that of the two pathways by which plastic film mulch can influence crop performance, reduced evaporation of water from soil had by far the greatest effect on crop performance, whereas the effect of temperature was minimal. There is no doubt however that by raising soil temperature during the germination stage, that this effect prevented crop failure. This possibility of crop failure caused by low temperature in 1983 during the maize germination period was identified as a result of the simulation process, which is a demonstration of its value to decision makers.

APSIM performed well in the calibration procedure of this study. The primary limitation was that the modelling of plastic film mulching effect is not readily available in the crop models. Quantifying the effects of plastic film mulching based on its mechanisms and processes are still very challenging, because the effect of plastic film mulching in reality will be affected by mulching itself (width, thickness, colour), operation, and the other farming practices. Although the fact that the addition in of the empirical based mulching effect simulation study has its limitation, it is reasonable that the general conclusions of this study could stand for the dryland agricultural managements on Loess Plateau.

5.5 Conclusion

This study presents a crop growth simulation to quantify the possible effects of plastic film mulching and evaluate its effectiveness on yield increase. Climate-related temporal variability in yield performance was simulated using long-term daily weather data from Changwu station. The yield differences under different plastic film mulching management scenarios have been identified. Results of this study provide various implications for farmers, local governments, policy makers and researchers concerned with improving dryland maize yield by applying of plastic film mulching on Loess Plateau. First, the application of plastic film mulching should be prescribed with care, as it is more beneficial with high probability in dry years than wet years. Second, strategies as plastic film mulching in cold years are needed to avoid crop failure caused by frost during early stage of maize growth. In addition, flexible sowing date is another option to avoid frosts. Last, making use of the weather forecast services can support effective decision making.

Chapter 6: Spatial variation of the effectiveness of plastic film mulching skill to adapt to climate across Loess Plateau

6.1 Introduction

In the previous chapter, the biophysical simulation model APSIM was demonstrated to be capable of quantifying the effects of plastic film mulching on yield and WUE. Climate-related temporal variability in yield performance was simulated using long-term daily weather data from a single climate region, based on weather data at Changwu station. However plastic film mulching is one of the most widely used water saving technologies for dryland agriculture on the Loess Plateau. As mentioned in Chapter 5, there has been some comprehensive experimental research regarding the effects of plastic film mulching on dryland agricultural systems in various locations (Li et al. 2001; Wang et al. 2009, Liu et al. 2009; Zhou et al. 2009, Zhang et al. 2014). These studies are not yet well connected and the examination of the spatial variation in the potential effects of plastic film mulch to change maize yields over a large scale has been rarely undertaken across the whole Loess Plateau. In this chapter, the APSIM model, linked to a Geographic Information System (GIS), was used to provide new insight on where and how climatic variations in the Loess Plateau may influence the effect of plastic film mulch on maize productivity. This chapter will contribute to the identification of areas with suitable climate for maize cultivar 'Xianyu 335' in terms of providing both location-specific information to improve spring maize management, and providing evidence to determine whether or not plastic film mulching is an effective adaptation option for reducing vulnerability to changing climate.

6.2 Materials and methods

6.2.1 The APSIM model

The crop simulation model APSIM has been introduced, calibrated and validated in Chapter 5 (5.2.3 and 5.3.1). In this chapter, the model settings, simulation experiments, and the simulations of plastic film mulching effects on maize yield were undertaken using the methods described in 5.2.4, but applied at 45 individual locations across the entire Loess Plateau. Daily meteorological data, soil data and crop data were used for simulation studies of the maize growth. The differences of yields simulated under three scenarios (S1, S2 and S3 as described in Chapter 6.3) show the potential effects of plastic film mulch on maize productivity.

6.2.2 Climate, soil and crop data

Historical meteorological data from 45 weather stations distributed across the Loess Plateau are available for the period 1961-2010 (Fig. 1) and were used as inputs to drive the simulation. These data were obtained from China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn). The data include daily maximum and minimum air temperatures, rainfall and sunshine duration. Solar radiation was calculated from sunshine hours with a_s=0.25 and b_s=0.50 by using the Ångström–Prescott equation (Prescott 1940).

Silty loam is the dominant soil texture (92.6%) at the 0-500 cm soil layer on Loess Plateau (Zhao et al. 2016), thus soil texture was assumed almost homogeneous. The soil module was parameterised with the experimental data of silty loam soil at Changwu station. As the same soil parameters in Table 5.1 were used at all 45 sites, the differences between sites in the effect of plastic film mulch in this analysis are entirely climate driven.

The same maize cultivar 'Xianyu 335' were assumed to be planted throughout the whole Loess Plateau. Thus the cultivar parameters are the same as those in Table 5.2. Spring maize is sown between mid and late April, and harvested at physiological maturity that is determined by accumulated temperature. The cropping practices at the 45 locations, such as sowing rules, density, depth, and the application of fertilizers, were all set the same as those at Changwu station in chapter 5. The other crop parameters were kept unchanged from APSIM version 7.4.

6.2.3 Spatial analysis

Data from meteorological stations and crop model outputs were used to process and present simulation results. Point data from those 45 sites were interpolated to generate maps for the entire Loess Plateau on total rainfall, averaged daily temperature and global radiation and their temporal variability during spring maize growth season. Spring maize yields under the three scenarios were first simulated at those 45 sites and then simulation results were interpolated to show the spatial yield variation and assess the potential effectiveness of plastic film mulching as an adaptation spatially. The Kriging method of ArGIS 10.1 was used for interpolation. Kriging uses the covariance structure of the field to estimate interpolated values. The resulting interpolated field is optimal in the sense of minimizing the variance among all possible linear, unbiased estimates. This method is commonly used in climate variability analysis (Sluiter 2009) and crop yield mapping (Birrell et al. 1996; McKinion et al. 2010), and has advantages in sparse data interpolation (Sluiter 2009). The spatial analytics tool 'Zonal statistics' were employed to calculate the values for each county unit. Generated maps were stratified at equal intervals according to the statistical value at the county level.

6.2.4 Data analysis

Paired Student's T-Tests were used to test if maize yields under three scenarios differ significantly from each other. The temporal variability of maize yield is associated with temporal variation in climate (rainfall, temperature and radiation). The temporal variability for spring maize yields from 1961-2010 under all three scenarios is analysed. Simulated spring maize yields from four locations in a transect across the spring maize dominant region of the Loess Plateau from central south to north, namely Luochuan, Yanan, Yulin and Baotou (Fig. 6.1), were selected to represent the different combinations of climatic factors and their variable effects on crop production for the purpose of comparison.

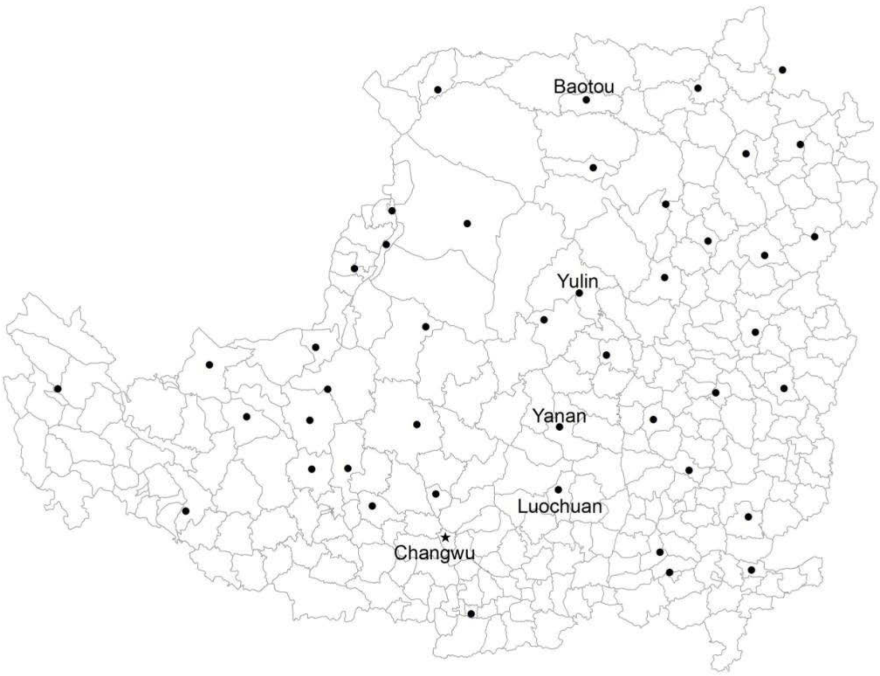


Fig. 6.1 Distribution of 45 meteorological stations over the Loess Plateau, where four sites were selected to show a transect of rainfall and temperature from central south to north.

6.3 Results and discussion

6.3.1 Spatial and temporal variation of climate during maize growing season

Spatial and temporal distribution and variability of total rainfall, daily temperature and global radiation across the Loess Plateau during the spring maize growing season (April to September) are presented in Fig. 6.2. Mean annual rainfall decreases from 481 mm in the southeast to 164 mm in the northwest. Conversely, the coefficient of variation increases from 0.22 in the southeast to 0.40 in the northwest. These results indicate that generally, the rainfall in the northwest of the Loess Plateau is lower with higher variability while that in the southwest is higher with lower variability. The coefficient of variation of total rainfall is much greater than that of daily temperature and global radiation (Fig.

6.2d, e, f), indicating that the inter-annual variation of rainfall on Loess Plateau is much higher. Average daily temperature during spring maize growing season across the Loess Plateau ranges from 14 °C in the north to 22 °C in the south. The warmer region is in the southeast, and the cooler region is in the northeast and the southwest where altitudes are relatively higher. The variability of average daily temperature between years is greater in the north; however temporal variability between years is proportionally much less than rainfall. Solar radiation increases from 18 MJ m^{-2} d^{-1} in the south to 22 MJ m^{-2} d^{-1} in the north. The coefficient of variation for global radiation shows the lowest variability across the Loess Plateau, ranging from 0.035 in the northwest to 0.060 southeast.

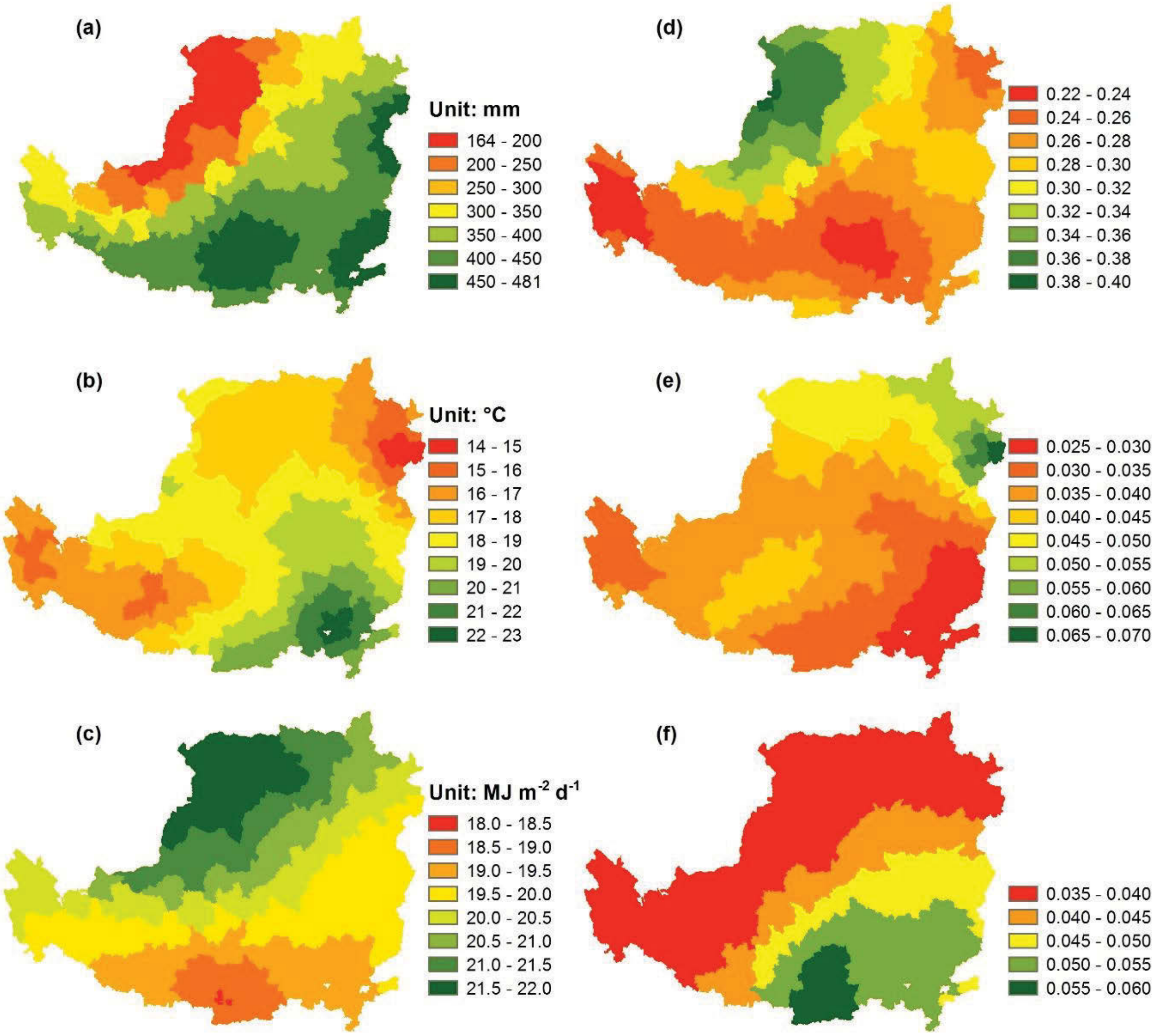


Fig. 6.2 (a) Rainfall, (b) daily temperature and (c) global radiation in the spring maize growing season of Loess Plateau, (d)-(f) respectively indicate the coefficient of variations in rainfall, daily temperature and global radiation.

6.3.2 Spatial variation of maize yield with and without plastic film mulching

Simulated long-term average spring maize yields under S1 vary from 2637 kg ha^{-1} to 7741 kg ha^{-1} spatially on the Loess Plateau (Fig. 6.3a). Several patterns were identified in the spatial distribution of yield and can be explained by the climatic requirements of the 'Xianyu 335' cultivar. The maize yield is highest in central south, where there is relatively high rainfall and mid-range daily temperature, however the solar radiation is not high. The spring maize yield was not as high in the southeast region as the central south, despite having the highest rainfall, due to the shorter growing season caused by relatively higher temperature. The lowest spring maize yielding areas are in the northwest and northeast, however the major causes behind the low yields are different. The low yield in the northwest is mainly due to water limitation from low rainfall, whereas the low yield in the northeast is caused by low temperatures, especially during early germination stage. As those areas are among high altitude mountain areas, for example, Wutaishan with the altitude of 2208 m and total rainfall 620 mm during April-September, the average daily temperature during April and September is only 6.57 °C, which is lower than the base temperature (10 °C) for maize growth (Bu et al. 2013), below which maize germination is greatly reduced. The coefficients of variation of yields range from 0.35 to 0.75 with a general increase trend from the south to the north, which is converse to the distribution of yield levels (Fig. 6.3d). These results indicate that maize productivity in high yielding areas are relatively stable compared to the low yielding regions. The high and stable spring maize producing region is located in the central south of Loess Plateau for maize cultivar ‘Xianyu 335’.

Long-term averaged yields under S2 vary from 4593 kg ha^{-1} to 8870 kg ha^{-1} (Fig. 6.3b). The maize yields with the effect of plastic film mulching on soil evaporation have increased across the entire loess Plateau compared with the yields under S1, although the spatial distribution of yield levels is similar. The highest yielding areas are similar to that under S1, being in the central south and the lowest in the northwest and northeast of Loess Plateau. However, even in the low yield northwest, the average maize productivity rises to above 4000 kg ha^{-1}. The coefficients of variation for yields across the whole Loess

Plateau are reduced compared with that of S1 (Fig. 6.3e), ranging from 0.23 in the south to 0.54 in the north. These results suggest that reducing water losses via evapotranspiration, as may be achieved by plastic film mulching, has large potential to improve dryland agriculture productivity and reduce its instability caused by uncertain climate.

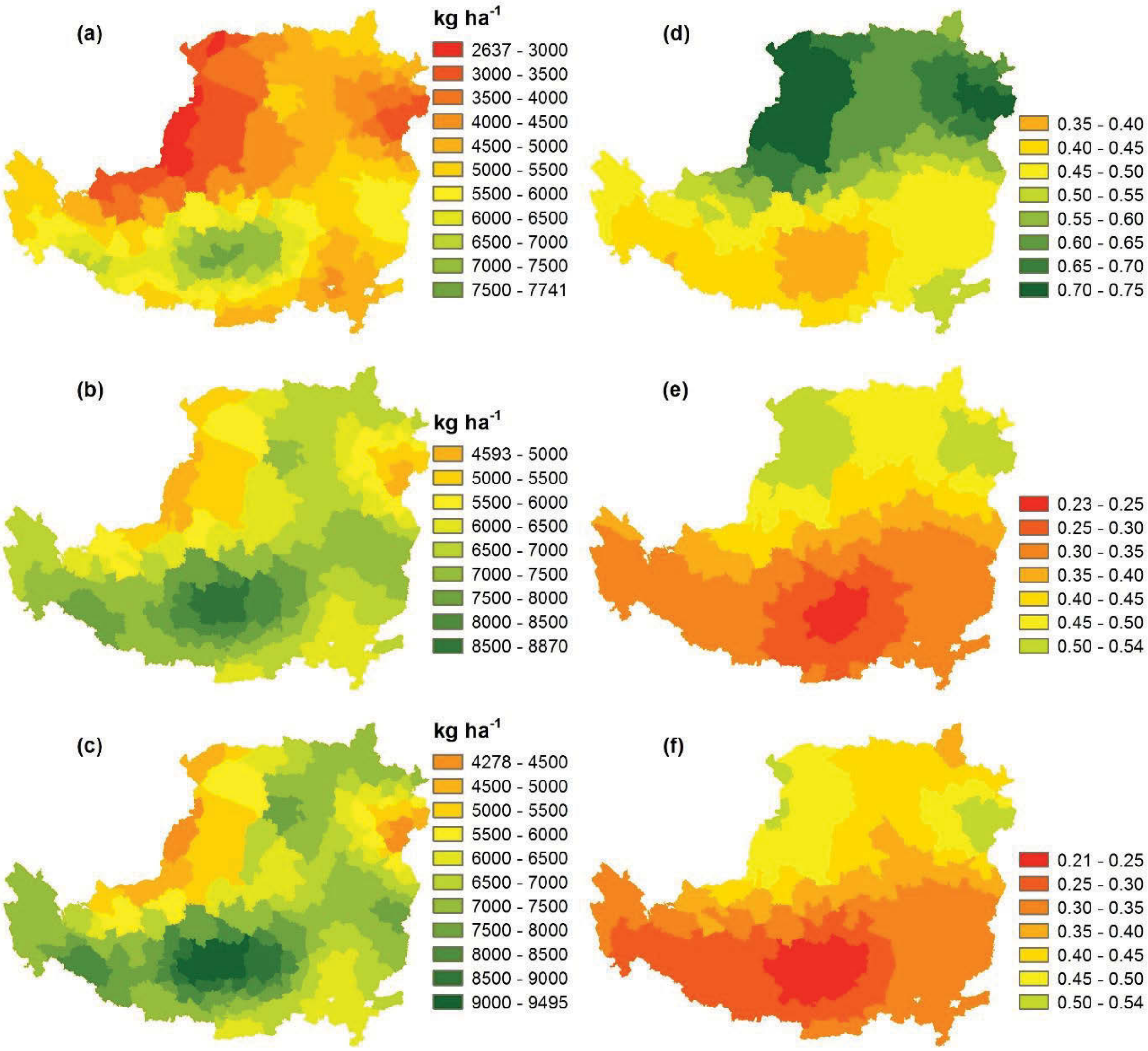


Fig. 6.3 Left (a)-(c) simulated yields and right (e)-(f) the coefficient of variations of spring maize across Loess Plateau under S1 (top), S2 (middle) and S3 (bottom) respectively.

Long-term averaged yields under S3, in which plastic film mulching both reduces evaporation and increases soil temperature, vary from 4278 kg ha^{-1} to 9495 kg ha^{-1} across the Loess Plateau (Fig. 6.3c). The spatial distribution pattern of both yield and coefficient of variation shows little difference with that of S2 (Fig. 6.3). With the effect of increased temperature by plastic film mulching, cold areas with frequent frost events benefit in some years, resulting in the increased average yields in the central-north and reduced yield variability in northeast and northwest. Conversely, the effects of higher temperature shortened the growing period of maize in warmer southern regions, which could even result in yield decrease.

In general, plastic film mulching could increase maize productivity and reduce its instability, but the extent differs. The yield increased the most in the northwest where rainfall is lowest and most variable. With the improvement of water use efficiency by plastic film mulching, the averages yield increase could be up to 2000 kg ha^{-1} (Fig. 6.3). In the southwest area with high rainfall that is suitable for spring maize growth, the yield increase with the effect of plastic film mulching is relatively low at approximately 1000 kg ha^{-1}. The simulated increase in temperature on spring maize production has both positive and negative effects on yield (Fig. 6.4c). Although the yield decreased up to 512 kg ha^{-1} in some areas of the northwest, northeast and southeast regions (Fig. 6.4c), the positive effect of increased temperature on yields was more common than the negative effect in the Loess Plateau. It is also evidenced by the paired t-test results that the mean of maize yields at 45 locations during the 1961-2010 under S3 is slightly higher than that under S2 ($p < 0.05$). The coefficient of variation under S2 and S3 has been reduced the most (up to 0.24) in the northwest (Fig. 6.5), while the reduction of coefficient of variation in the south is only 0.10 compared with that under S1. Similar to productivity, the effect of increased temperature on yield variability has both positive and negative effects (Fig. 6.5c). The negative effects mainly occurred in the southeast, which indicates that the increased soil temperature resulting from plastic film mulching may increase yield variability in the southeast, reducing its value as an adaptation.

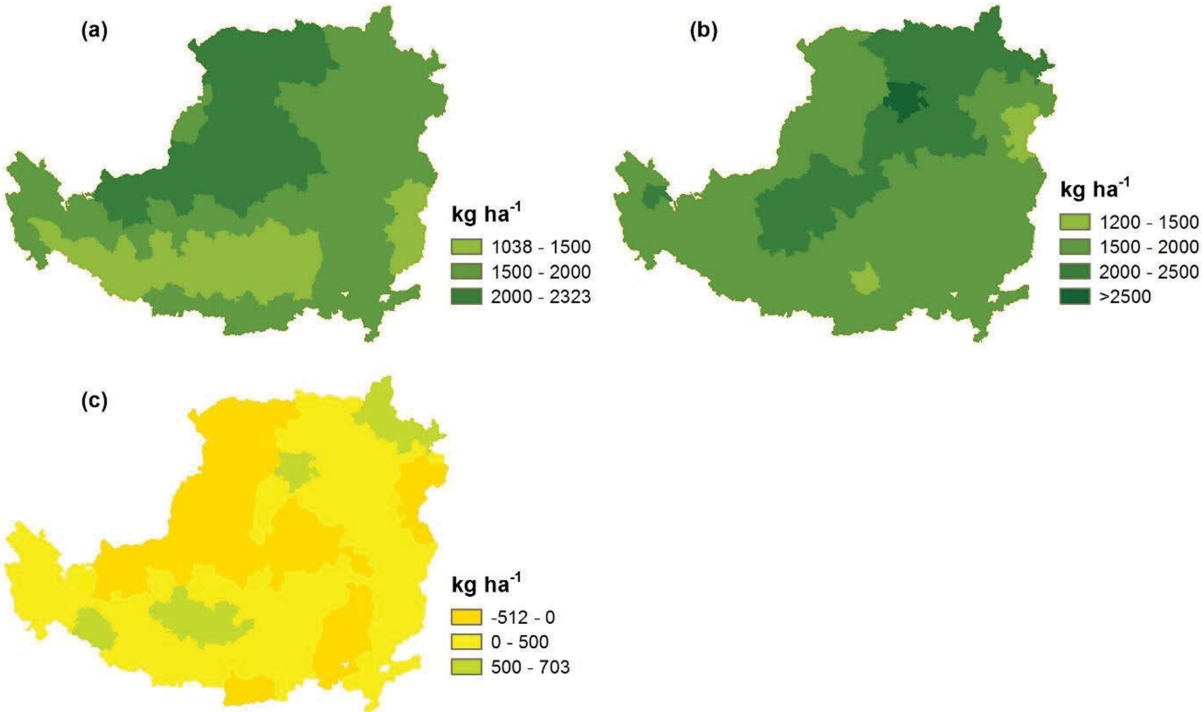


Fig. 6.4 Spatial averaged yield difference between S2 - S1 (a), S3 - S1 (b), S3 - S2 (c).

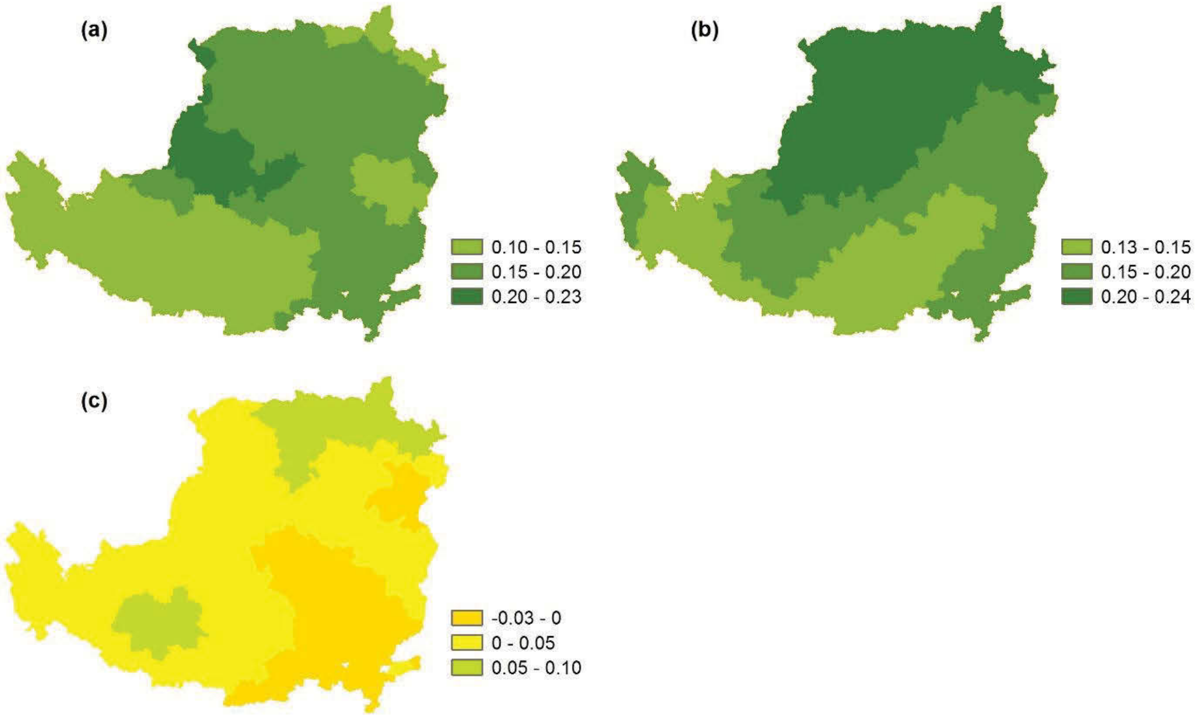


Fig. 6.5 Spatial averaged change in coefficient of variation between S2 - S1 (a), S3 - S1 (b), S3 - S2 (c).

6.3.3 Temporal variability of maize yield

The different slopes of cumulative probability indicate that the temporal variability in maize yield differs throughout the Loess Plateau. In the south part of Loess Plateau, the slopes of the cumulative distribution of yield are steepest, which indicates that the temporal variation of climate between years is relatively stable in the south. The yield range of Luochuan was 3459-12 512 kg ha^{-1} and the cumulative probability of yields above 6 t ha^{-1} is 88% years. In the northern areas, represented by Baotou and Yuyin, the cumulative distribution of yield is shallower and the yield ranges are lager, which indicates that the climate is more variable between years in the north. The yield ranges of Baotou and Yuyin are respectively 0-10 030 kg ha^{-1} and 0-11 776 kg ha^{-1} (Table 6.1). The cumulative probability above 6 kg ha^{-1} is 18% years in Baotou and 20% years in Yulin.

The cumulative probability above 6 kg ha^{-1} in Yanan is 46% years. The probability of cumulative maize yield shows a decreasing trend from the central south to the north (Fig. 6.6). This means the central south has the most suitable climate conditions for high rain-fed maize productivity. The lower probability of exceedance in the north is mainly caused by decreased rainfall.

Table 6.1 Simulated maize growing period, yield range and cumulative probability at four selected sites under conventional farming.

	Sites	**Growing period (days)**	**Yield range (kg ha^{-1})**	**Cumulative probability above 6 t ha^{-1}**
South to North	Luochuan	137	3459-12 512	88%
	Yan'an	124	394-10 552	46%
	Yulin	132	0-11 776	20%
	Baotou	136	0-10 030	18%

With the effects of plastic film mulching, the slopes of cumulative probability became steeper and the probabilities became higher in general (Fig. 6.6b, c). The cumulative probability at mid yield levels all increased largely (Fig. 6.6b, c). Notably, the cumulative probability above 6 kg ha^{-1} under S2 and S3 increased to 100% and 98% years in Luochuan, 76% and 72% in Yanan, 62% and 52% in Yulin, 52% and 46% in Baotou respectively, when compared with that under S1. The lowest yields at Luochuan and Yanan were increased under both S2 and S3, while that at the other two sites Yulin and Baotou remained at 0 kg ha^{-1} under S2 due to subzero temperatures after sowing. With the increased temperature under S3 however, the lowest yields in the Yulin and Baotou were increased from 0 kg ha^{-1}, although they were still low at 1622 kg ha^{-1} in Yulin, and 872.7 kg ha^{-1} in Baotou. Conversely, the lowest yield under S3 in the warmer region of

Luochuan decreased compared to that under S2. These results indicate that the plastic film mulching could reduce year to year fluctuation of maize yield caused by uncertain climate year patterns.

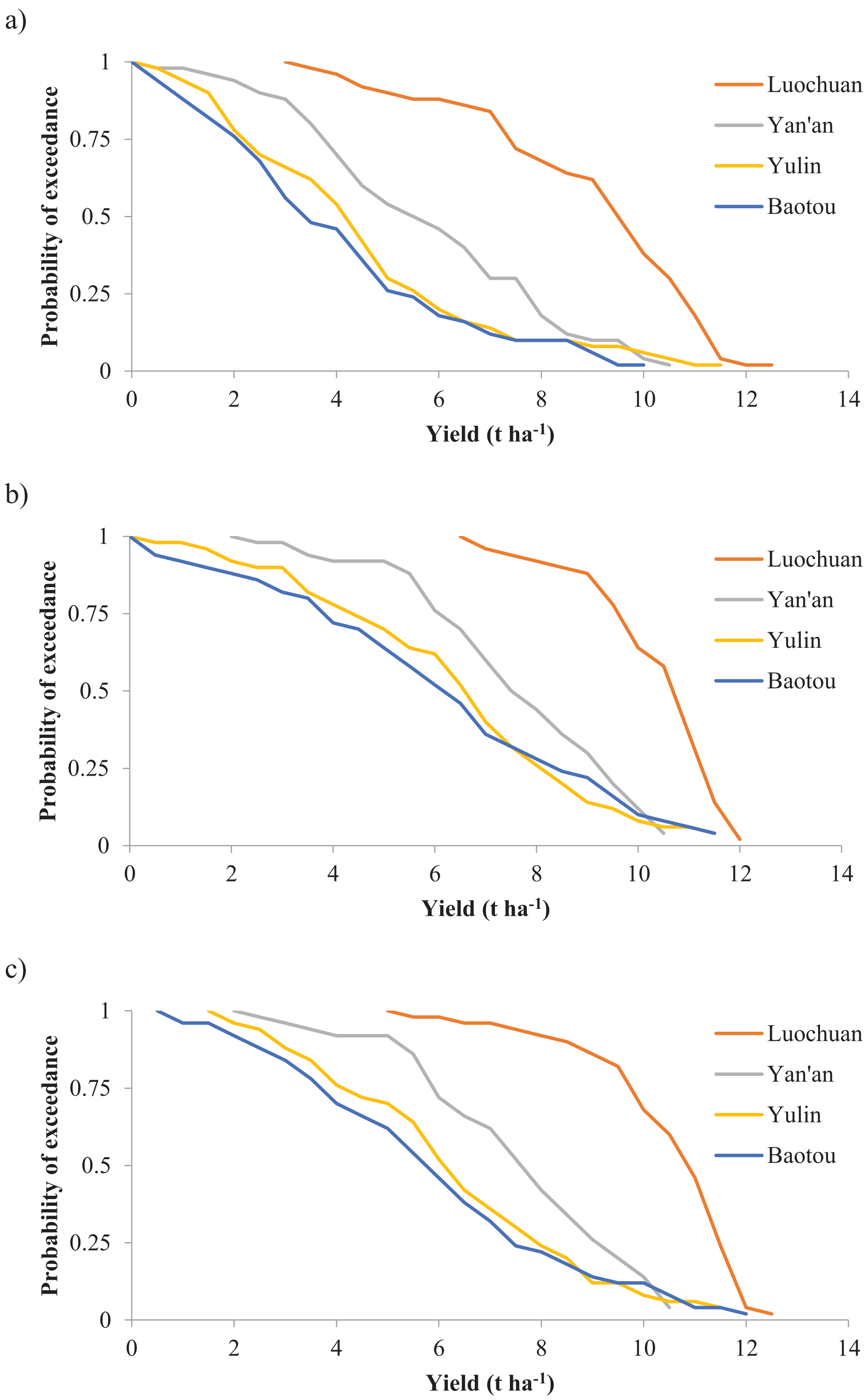


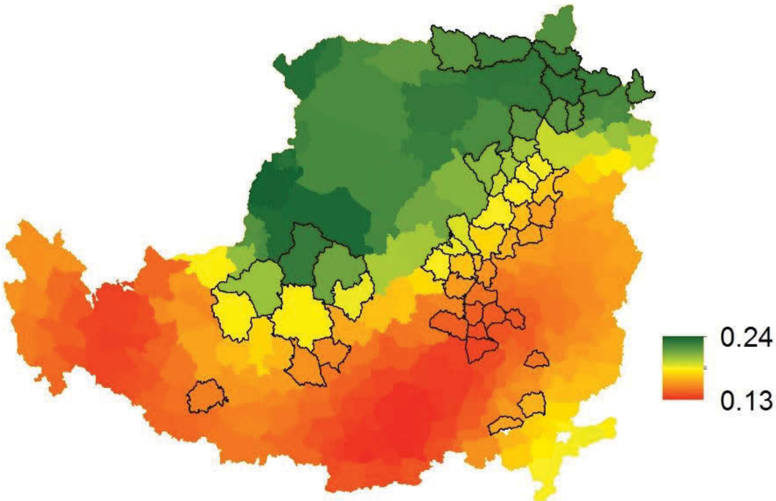
Fig. 6.6 Cumulative distribution of spring maize yield for four locations in the Loess Plateau under three scenarios; S1 (a), S2 (b), and S3 (c).

6.3.4 The effectiveness of plastic film mulching as an adaptation

The productivity of gain sown area was identified as one of the indicators of adaptive capacity in Chapter 4. By the application of plastic film mulching, maize productivity could be increased in the majority of areas on the Loess Plateau. As one of the main crops in use on the Loess Plateau, this increase of maize productivity would result in a general increase in the productivity of gain sown area, proportionate to the share of maize of total grain production, leading to an increase in the adaptive captivity of dryland agricultural systems. The extent of maize yield increase with plastic film mulch differs across the Loess Plateau however. The maize yield increased the most in the north and northwest, with an absolute average increase up to 2611 kg ha^{-1} in the north and up to 60% yield increase when compared with that of simulations without the effect of plastic film mulching under S1. These results indicate that the adaptive capacity in the north and northwest could be increased most using plastic film mulching. Some of the most vulnerable counties identified in Chapter 4, which were characterised by low adaptive capacity, can thus reduce their vulnerability level by increasing adaptive capacity.

The sensitivity index used in the vulnerability assessment undertaken Chapter 4 was represented by the coefficient of variation of climatic yields. In this simulation study, the yield differences are completely climate and management driven. By applying plastic film mulching, the coefficient of variation of maize yields could be reduced by 0.13-0.24 in this study (Fig. 6.7), which suggests that the sensitivity to climate change could be reduced proportionally. However, the relatively more sensitive counties mostly still lie on the southeast of Inner Mongolia on the edge of Shanxi, northwest Shanxi and mid-north Shaanxi, south Ningxia and east Gansu. The sensitivity index of vulnerability assessment would have a new distribution.

a)



b)

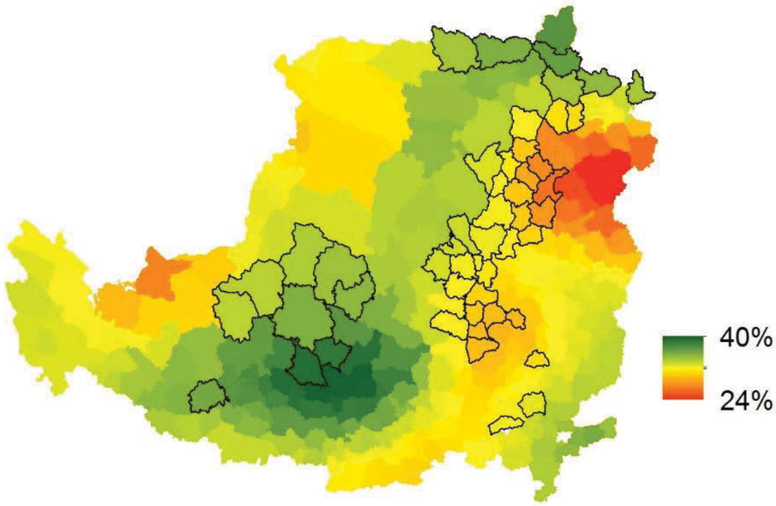


Fig. 6.7 Coefficient of variation reduction under S3 comparing to S1, with 49 most vulnerable counties highlighted, (a) absolute value and (b) by percentage.

6.4 Conclusion

This study assessed the effectiveness of plastic film mulching as a climate change adaptation for dryland agriculture on Loess Plateau in the combination of different geographic locations and temporal variation of climate change. Climate-related temporal and spatial variability in yield performance under different farming practices with and without plastic film mulching based on crop growth simulation studies were conducted at 45 locations and interpolated across the whole Loess Plateau. It was found that the application of plastic film mulching could generally increase the adaptive captivity in the aspect of the productivity of gain sown area and reduce the sensitivity by reducing the coefficient of variation of climatic yields. As a consequence, the agricultural vulnerability is estimated to be reduced. As the maize productivity increased by the greatest amount in the northwest and the coefficient of variation of yields were also reduced by the greatest amount in the same region, this area could see the greatest reductions in agricultural vulnerability as defined and quantified in Chapter 4. The highest vulnerability counties located in the northwest will benefit the most. Thus, subject to local social-economic conditions, the application of plastic film mulching shows promise as an effective adaptation option to reduce agricultural vulnerability on the Loess Plateau, especially for the northwest drier regions.

Chapter 7: Key findings, implications and conclusions

7.1 Overview

In this chapter the key findings of the research are presented as responses to the research questions posed in Chapter 1. The implications of the findings for dryland agricultural management are then explored. The limitations of the work are further discussed and future activities to address them are proposed. Finally, concluding remarks on the present work are provided.

7.2 Key findings

7.2.1 What are the specific challenges for the management of dryland agricultural production?

Three major challenges were identified for the two dryland regions in Chapter 2. For the Australian Wheatbelt, statistical evidence that the production of grains, especially wheat, is stagnating and unstable, was reviewed. This was the motivation to identify the driving forces of Australian wheat production growth and instability. For the Chinese Loess Plateau, which has inherited physical and social-economic restrictions for food security and sustainable development, the necessity for a comprehensive assessment to quantify the vulnerability of agricultural production at the county level was raised. Finally, the importance of identifying suitable adaptations and the challenge of evaluating them was discussed. As an adaption for dryland agriculture, the inconsistent effects of plastic film mulching on crop growth and productivity suggested that the effectiveness of this adaptation needs to be evaluated with consideration of both temporal and spatial differences in climate, prompting further investigation.

7.2.2 What are the driving forces of grain production instability?

In Chapter 3, decomposition analysis was conducted to identify the driving forces in growth trend and instability of Australian wheat production for the period of 1900-2010, at national and state levels. Decadal averages were used to analyse the trend and yearly data were used to analyse year to year fluctuation.

Changes in sowing area were found to be the more influential sources of growth in nine of the eleven decades for total wheat production of Australia. Whilst area was typically the driving force for wheat production growth in New South Wales, Western Australia and Queensland, the results indicate that yield changes contributed proportionally much greater in South Australia and Victoria, especially before the 1960s. The long-term increasing trend of Australian wheat production was mainly due to sowing area increase in the past century. The contribution rate of area to production growth was found to have decreased in all states in recent decades.

The instability of Australia's wheat production has not been reduced significantly in the past century. New South Wales presented the highest year to year production variation with an average annual 3.22 million tonnes difference. The yearly fluctuation of production was mainly caused by highly variable yields in the past 110 year period, with yield contribution rates to the yearly fluctuation of production ranging from 49.8% in Queensland to 72.7% in South Australia.

7.2.3 How can the spatial variation of agricultural vulnerability be quantified?

As vulnerability is a vague concept, difficult to quantify and unequally distributed, a series of activities were conducted in Chapter 4 to develop and apply a methodology for assessing agricultural vulnerability over the Chinese Loess Plateau. Capturing the complex interactions of anthropogenic activities and the environment at the county scale in a holistic manner was undertaken by developing and applying a detailed contextual framework of agricultural vulnerability on Loess Plateau.

The framework was developed based on features from existing frameworks in international research. Indicators representing the climate/agriculture interface were selected to describe exposure and sensitivity, whilst stocks of certain capitals were used to describe adaptive capacity. A vulnerability index for each county of the 243 rural counties on Loess Plateau was calculated. The relationship between vulnerability and its components (exposure, sensitivity and adaptive capacity) were analysed, and their spatial distributions were visualised by applying geostatistical and spatial analysis using ArcGIS. High vulnerability counties and their vulnerability types were identified.

Exposure, sensitivity and adaptive capacity occur independently, with most contributing indicator values concentrated in a narrow range after standardization. Within the 49 most vulnerable counties, which together encompass 81% of the vulnerability index range, 42 were characterized by high exposure and sensitivity but low adaptive capacity. The most vulnerable areas were found to be located in the central northeast-southwest belt of Loess

Plateau. Overall this work demonstrated a compelling approach for quantifying the spatial variation of agricultural vulnerability across the Loess Plateau.

7.2.4 How to assess the effectiveness of plastic film mulching as an adaptation to reduce vulnerability?

The APSIM model was employed to assess the effectiveness of plastic film mulching as an adaptation, because it can simulate cropping systems with different climate, soil and agricultural management practices over time. APSIM was first calibrated and validated by field experimental data from Changwu research station, then used to simulate the effects of plastic film mulching on spring maize growth and water use during the period of 1961-2000.

Simulated LAI, biomass, yield and ESW matched well with the measured values, therefore the performance of APSIM was considered to be satisfactory for modelling the maize cropping system. The application of plastic film mulching could significantly increase maize yields by an average of 15.3% (1302 kg ha^{-1}), and increase the cumulative probability at mid-range yield levels at Changwu. Plastic film mulching was found to be more beneficial with higher probability of exceedance in dry years than wet years. Additionally, the analysis indicated that plastic film mulching in cold years could avoid crop failure caused by frost during early stage of maize growth. Accordingly, greater returns from plastic film mulching could be achieved if its use was targeted towards dry and cold years.

7.2.5 Where and how does climate variation in the Loess Plateau influence the effect of plastic film mulching and its estimated potential to reduce vulnerability?

In response to the widespread application of plastic film mulching across the whole Loess Plateau reported in Chapter 2, the modelling approach developed and described in Chapter 5 was linked to a Geographic Information System to provide new insight on where and how climatic variations in the Loess Plateau may influence the effect of plastic film mulch on maize productivity. Additionally, this activity demonstrated how the technology could be used to inform decisions for the management of dryland regions. APSIM was run at 45 locations with historical metrological data with and without plastic film mulching. Model outputs were interpolated to generate maps for the entire Loess Plateau using ArcGIS.

The results presented in Chapter 6 show that the high and stable production regions of maize with and without mulching are located in the central south of the Loess Plateau. The low yields predicted in the north are limited by decreased rainfall whilst yields in the south are limited by the higher temperature. The simulations predicted that maize productivity could achieve 9495 kg ha^{-1} with the application of plastic film mulching in the northwest, an increase of over 2000 kg ha^{-1}. The coefficient of variation of yields were also reduced by the greatest amount in the northwest. As a contributing indicator to the vulnerability index described in Chapter 4, the improvement in the productivity of grain sown areas may enhance the adaptive captivity of vulnerable counties. Furthermore, by reducing the coefficient of variation of climate yields, the sensitivity to climate change could be reduced, thus the agricultural vulnerability may also be reduced. It was concluded from the analysis that the application of plastic film mulching may be an effective adaptation option for agricultural vulnerability, especially in the northwest regions of the Loess Plateau.

7.3 Implications for dryland agricultural management

7.3.1 Grain production growth and stability

The importance of changes in both area and yield and their interaction effect on grain production when facing regional food insecurity and climate change has been demonstrated in Chapter 3. The production benefits made possible from large scale cropping areas have been found to be decreasing in Australia according to the examination of historical wheat production, a trend which is also evident in other dryland regions (Bruinsma 2011). Although the potential for expansion of cropping areas are limited, it still occurs in some regions such as Brazil and Argentina (Schnepf et al. 2001; Iizumi 2015), and could contribute to total agricultural production increase, albeit with the risk of lowering mean productivity and threatening the environment. Thus the increase in productivity will be the main driver of long term profitability growth in the agricultural production.

Dryland production of grains, particularly in Australia (Grassini et al. 2013), is lower than the world average meaning there is potential to improve the productivity. Improvement of agricultural productivity can be achieved by enhancing management to improve resource use efficiency, close yield gaps, break yield ceilings through new technologies and intensify existing land use where conditions permit. Also of considerable importance to maintaining yield and area of production is avoiding soil and water degradation, and adapting to unavoidable climate change.

7.3.2 Vulnerability assessment

Dynamic and consistent assessment of agricultural vulnerability, as conducted in this thesis, has demonstrated value in that it can identify where, why and to what extent vulnerability occurs. Assessment must continue for long term planning and comparison between dryland locations so that shared needs and more efficient management strategies can be identified. Consistent assessments with clear framework and criteria are needed to provide information for policy-makers. Although scopes and aims of activities may differ, the theory and tools of assessment that are presented in this thesis are universal and may be transferred between locations and different scales. When the sources and extent of vulnerability are identified in these settings, adaptations can be better planned and the effectiveness can be improved.

7.3.3 Adaptation

Whilst some areas have a high adaptive capacity to climate change and therefore high exposure and sensitivity will not necessary result in high vulnerability. In poor and resource limited regions, particularly drylands, high exposure and sensitivity are often overlapped with low adaptive capacity. Adaptation measures for both ecological restoration and economic development are needed for those areas to cope with future climate change, which include investments to improve adaptive capacity and specific adaptations at the farm level.

Farm level adaptations are already naturally selected and conducted during agricultural production, because they generate benefits to producers. However the benefits generated from these practices might be influenced by changing climate, as illustrated by the plastic film mulching studies presented previously. Thus dynamic adaptations according to local weather conditions would be more efficient.

Technology transfer from more developed regions to developing regions (e.g. APSIM from Australia use in China and ridge-furrow mulching system from China use in Africa, Mo et al. 2016), is a quick and economic way to increase the breadth of adaptations available to managers and is made possible by some of the inherent similarities in drylands. New technologies permit the development and evaluation of adaptations on increasingly greater scale, allowing experiments to be revisited under a greater range of environments and scenarios thereby enhancing the ability to pre-empt the impact of climate change.

7.4 Limitations and further work

This study examined two vast dryland agricultural regions at multiple scales, involving large quantities of secondary data combined with empirical analysis, thus limitations exist and further improvements in future studies are proposed. First, the thesis has focused exclusively on dryland cropping systems. Grassland and livestock production are also important components of dryland agricultural systems that contribute to increased dryland productivity, food security and provide development opportunities and reduce adverse impacts of climate change; however they are beyond the scope of this study. Second, multi-scale research requires more comparable studies to be undertaken. Large amounts of comparable data are needed to do more accurate assessments, which is the most apparent limitation of these methods. The availability of compatible data was also a limitation encountered in the present work. Third, in face of changing climate and increasing food demand, the impact of climate change on cropping area and land use warrants future investigation in particular. Forth, concerning the modelling activities undertaken in chapters 5 and 6, it was found that the scenario in which changes in soil temperature were simulated through a compensatory equation affecting air temperature (due to the absence of a separate soil temperature effect in APSIM), had some very noteworthy effects in the analysis. These effects should be confirmed in the field. As plastic film mulching is likely to continue to increase in adoption throughout the Loess Plateau and other dryland farming regions, integrating the effects into crop models to permit better and convenient simulation will likely become a worthwhile endeavour.

7.5 Concluding comments

The present body of work has yielded new insights into dryland agricultural management practical aspects of grain production, vulnerability assessment and effectiveness of adaptation by using two important dryland agricultural regions as case studies. The research was conducted largely in Australia and provided an opportunity to understand Australian dryland agricultural systems in a global context of increasing food demand and changing climate. The main research components were developed and applied to the Loess Plateau dryland agricultural region in China. Although characterised by different farming systems, the shared dryland issues such as dependence on rainfall and soil erosion propose similar challenges which provide the opportunities for one to learn from another. Decomposition analysis was used to identify the driving forces of Australian wheat production growth and instability. A vulnerability framework was developed and applied to identify vulnerable counties in the Loess Plateau of China and to understand their agricultural vulnerability. Field experiments and simulations by the APSIM model were conducted to assess the effectiveness of plastic film mulching as an adaptation for dryland agriculture at site and across the Loess Plateau and found that changes in evapotranspiration and temperature would have largely beneficial impacts on crop production in most regions. The principles, frameworks, technologies and tools can be modified and adopted in other dryland regions. The results can be referenced to location-specific information for policy makers and researchers. The new insights for dryland agricultural managements can provide useful information for the rest of the world as it prepares for the challenges ahead.

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Appendix I

Published research paper: Agricultural vulnerability over the Chinese Loess Plateau in response to climate change: Exposure, sensitivity, and adaptive capacity

Ambio
DOI 10.1007/s13280-015-0727-8

REPORT

Agricultural vulnerability over the Chinese Loess Plateau in response to climate change: Exposure, sensitivity, and adaptive capacity

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Received: 15 June 2015 / Revised: 30 September 2015 / Accepted: 23 October 2015

Abstract Understanding how the vulnerability of agricultural production to climate change can differ spatially has practical significance to sustainable management of agricultural systems worldwide. Accordingly, this study developed a conceptual framework to assess the agricultural vulnerability of 243 rural counties on the Chinese Loess Plateau. Indicators representing the climate/agriculture interface were selected to describe exposure and sensitivity, while stocks of certain capitals were used to describe adaptive capacity. A vulnerability index for each county was calculated and the spatial distribution was mapped. Results showed that exposure, sensitivity, and adaptive capacity occur independently, with most contributing indicator values concentrated in a narrow range after normalization. Within the 49 most vulnerable counties, which together encompass 81 % of the vulnerability index range, 42 were characterized by high exposure and sensitivity but low adaptive capacity. The most vulnerable area was found to be located in the central northeast–southwest belt of Loess Plateau. Adaptation measures for both ecological restoration and economic development are needed and potential adaptation options need further investigation.

Keywords Climate change · Yield variability · Vulnerability analysis · Adaptation · Loess Plateau · County level

INTRODUCTION

The impacts of climate change are expected to be unequally distributed, affecting rural communities in developing countries to a greater extent due to their geographical positions, low adaptive capacities, and dependence on climate sensitive agriculture and natural resource sectors (Stern 2007; Collier et al. 2008; World Bank 2010; Dasgupta et al. 2014). The Loess Plateau of western China (Fig. 1) is one such vulnerable area, where climate sensitive dryland agriculture is the primary economic activity, despite being threatened by a complex interaction of anthropogenic and environmental factors.

The Loess Plateau is home to an estimated population upwards of 108 million, of which more than 70 % are reported to be living and working in agricultural areas (Wang and Li 2010). Agricultural land, including garden plots, forestland, and grassland, accounts for approximate 75 % of the total land area (An et al. 2014). Although the livestock production and forestry sectors have experienced recent growth stimulated by favorable Chinese government policies (Liu et al. 2008; Yin and Yin 2010), subsistence farming of crops is the most common type of agriculture. Wheat and maize are the dominant crops, accounting for about 35 and 30 % of total cultivated area and 30 and 40 % of total crop production, respectively, with potatoes, buckwheat, and other grains also occupying significant shares of cultivated land (An et al. 2014). Agricultural production is heavily dependent on rainfall; however, annual rainfall is both low on average and extremely variable. Annual precipitation decreases gradually from above 600 mm in the southeast to 100 mm in the northwest, with approximately 78 % occurring between May and October. Interannual variation is such that rainfall in wet years can be five times higher than in dry ones (He et al. 2014). Notable climate change has been observed on the Loess Plateau in recent decades, with air temperature rising by 0.6 °C and annual precipitation decreasing by 3 mm per decade (Piao et al. 2010; Turner et al. 2011; Wang et al. 2012; He et al. 2014). Furthermore, extreme events such as

Electronic supplementary material The online version of this article (doi:10.1007/s13280-015-0727-8) contains supplementary material, which is available to authorized users.

Published online: 12 November 2015

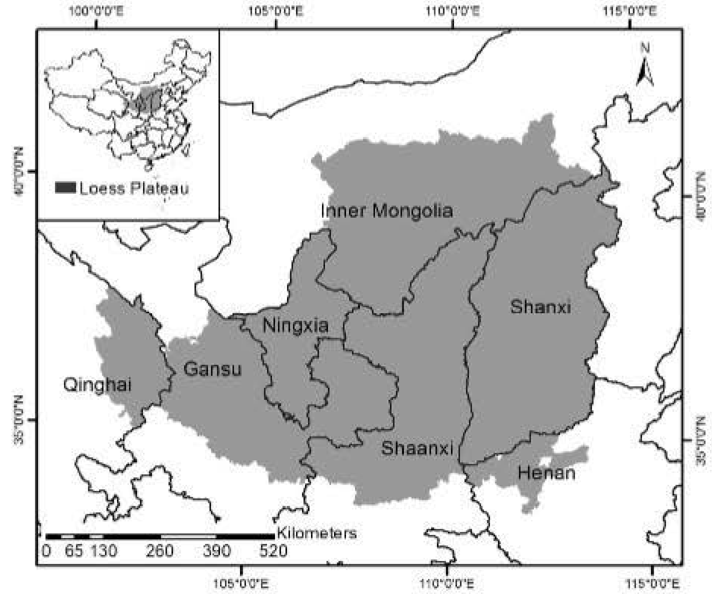

Fig. 1 Location of the Loess Plateau in China

droughts have become more frequent (Piao et al. 2010; Turner et al. 2011; He et al. 2014).

In addition to climate challenges, agricultural production in the Loess Plateau is also threatened by severe environmental degradation, particularly soil erosion, leading to a decline in agricultural productivity and subsequent poverty. Climate change, including increased climate variability, has been identified as a major driving force of this degradation as it exacerbates existing stressors such as naturally unstable soils and low annual rainfall (Li et al. 2003; Xu et al. 2006; Yin and Yin 2010), and it compels local producers to engage in unsustainable land management practices (Li et al. 2003; Lu et al. 2004; Nolan et al. 2008). To compensate for low productivity and meet food demand during periods of poor rainfall, natural land has been reclaimed and cultivated for farming, depriving the fragile soils of vegetation cover and accelerating erosion and water loss. The loss of soil quality leads to even lower productivity and greater susceptibility to damaging weather, further restricting regional agricultural development. In this context, farmers are driven to clear and cultivate even more marginal land to maintain food production, thus perpetuating a spiral of unsustainability on the Loess Plateau.

Adaptation measures are needed for the Loess Plateau in the face of climate change and the expectation of even greater climatic variation in the future (Lu et al. 2004; Nolan et al. 2008; He et al. 2014). Accordingly, a comprehensive management plan has been developed by the National Development and Reform Commission et al. (2010) that prescribes ecological construction interventions based on geomorphic zoning. It has been reported, however, that clarity and rationality of goals during previous ecological restoration and sustainability oriented interventions in the Loess Plateau has been a major area for improvement (Xu 2011). Assessment and mapping of agricultural vulnerability to climate-related stressors is therefore an important process in the formulation and implementation of appropriate adaptation measures and priority setting for agricultural investment (Watson et al. 2013).

Vulnerability assessment usually requires the quantification of biophysical and social-economic metrics of exposure, sensitivity, and adaptation, which has been seldom attempted on Loess Plateau. Studies that assess vulnerability of the Loess Plateau undertaken at the administrative county level are rare. Most notably, Wang and Liu (2003) undertook a vulnerability assessment based on 1990 and 1997 statistical data from 130 counties, although this was restricted to only three provinces which overlap the Loess Plateau, Shaanxi, Ningxia, and Gansu. Counties from Shanxi province, which includes much of the typical hill and ravine terrain that characterizes the Loess Plateau, were not included. Other national scale assessments of vulnerability to climate change have included the Loess Plateau; however, the differences of resolution, focus topics, and indicator selection have caused the findings to differ (Lin and Wang 1994; Simelton et al. 2009; Yin et al. 2009; Li et al. 2015). The incomplete or inconsistent findings of previous vulnerability assessments indicate the need for a novel framework which uses available county-level indicators that are relevant to the specific circumstances in the Loess Plateau and compatible across provinces. The objectives of this study are (1) to develop a conceptual framework for quantifying agricultural vulnerability to climate change in the entire Loess Plateau; (2) to perform a county-level quantitative assessment which analyzes the relationships between vulnerability components; and (3) to map and describe "hot-spots" of the vulnerability distribution.

MATERIALS AND METHODS

Study area

The study area is located between longitudes 100°54′E–114°33′E and latitudes 33°43′N–41°16′N, occupying the geographic center of the People's Republic of China. It spans an area of approximately 648 700 km^2, which includes jurisdictions from seven provincial level administrations, which are further divided into prefectures and then counties. The county was selected as the vulnerability assessment unit as it is the smallest administrative division still included in aggregate national statistics. Fifty-six county-level municipalities with little or no agricultural production were excluded, leaving 243 rural counties to be analyzed in this study.

Vulnerability framework

Capturing complex interactions of anthropogenic activities and the environment in a holistic manner requires the use of frameworks (Angelstam et al. 2013). In this study, features from existing frameworks were adapted according to our study objectives. Vulnerability was defined as the propensity or predisposition to be adversely affected in accordance with the IPCC (2014) AR5 definition. It encompasses a variety of concepts and elements, including the exposure to adverse effects, sensitivity to harm, and lack of capacity to cope and adapt. Exposure together with sensitivity represents the propensity and predisposition of the studied system to be adversely affected by climate change, whereas adaptive capacity reduces these effects (Gallopín 2006; Nelson et al. 2010). Therefore, vulnerability can be expressed as the positive function of exposure and sensitivity, but negative function of adaptive capacity (Li et al. 2015):

$$\begin{aligned}\text{Vulnerability} &= f(\text{Exposure, Sensitivity, Adaptive capacity}) \\ &= (\text{Exposure} \times \text{Sensitivity})/\text{Adaptive capacity}\end{aligned}$$

An integrated vulnerability index was created by combining indicators for exposure, sensitivity, and adaptive capacity (Fig. 2).

Indicators of vulnerability to climate change

The indicators used to create vulnerability index are shown in Table 1. The selection of indicators, their hypothesized

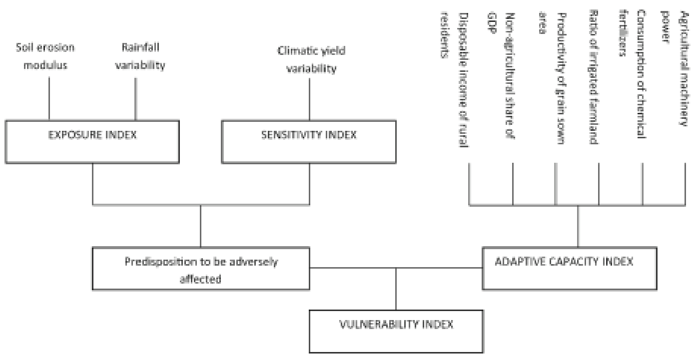

Fig. 2 Conceptual framework for assessing agricultural vulnerability to climate change as a function of statistical indicators

Table 1 Vulnerability indicators, variables, and data sources

Components of vulnerability	Component indicators	Description of indicators	Data source
Exposure	Rainfall variability	The coefficient of variability of annual rainfall during 2001–2010	Chinese Meteorological Bureau
	Soil erosion modulus	Extracted from land resources data	Earth system science data sharing platform of Chinese Academy of Science
Sensitivity	Grain yield variability	The coefficient of variability of annual grain production 2001–2010	China Statistics Bureau
Adaptive capacity	Disposable income of rural residents	Per capita net income of rural residents (yuan person^{-1}) 2010	China Statistics Bureau
	Non-agricultural share of GDP	The ratio of value-added of secondary and tertiary industry to Gross Regional Product (%) 2010	China Statistics Bureau
	Productivity of grain sown area	Total grain yield of each county divided by its grain sown area (kg ha^{-1}) 2010	China Statistics Bureau
	Ratio of irrigation area	The ratio of effective irrigation area to cultivated land area (%) 2010	China Statistics Bureau
	Consumption of chemical fertilizers	Consumption of chemical fertilizers divided by cultivated land area (ton ha^{-1}) 2010	China Statistics Bureau
	Agricultural machinery power	Total power of agricultural machinery divided by cultivated land area (kwh ha^{-1}) 2010	China Statistics Bureau

relationship to vulnerability, and the calculation of each index are described in the following sections.

Exposure index

Exposure is defined by the IPCC as "The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected" (IPCC 2014). On the Loess Plateau, rainfall variability and soil erosion have been repeatedly identified as the driving forces of adverse effects (Li et al. 2003). Accordingly, exposure index (V_e) was represented by the sum/average of the normalized value of the following two indicators.

(1) Rainfall variability: represented by the coefficient of variation of annual rainfall from 2001 to 2010 for each county. Rainfall for each county was obtained by interpolation of rainfall data from 44 meteorological stations distributed throughout the Loess Plateau, using ArcGIS 10.1.

(2) Soil erosion modulus: extracted from land resources data obtained from the earth system science data sharing platform of Chinese Academy of Science. Soil erosion modulus for each county was obtained by zonal statistics using ArcGIS 10.1.

Sensitivity index

Sensitivity measures the responsiveness of a system to climate change; therefore, its indicators should have a demonstrated relationship with agents of exposure and significance to the wellbeing of the vulnerable area. Grain yield variability was identified as the key indicator of agricultural sensitivity to climate change in the Loess Plateau for several reasons. First, rainfall is known to influence the productivity of grain sown land, both directly, through access to water, and indirectly, by influencing farmer practice (An et al. 2014). Second, soil erosion both causes and is exacerbated by low productivity in the Loess Plateau (Li et al. 2003). Third, households practicing subsistence agriculture often have little interaction with markets, and accordingly, income levels are not necessarily coupled with climate variation, nor are they entirely reflective of livelihoods. Fourth, the production of grain is an issue of political significance to China. Sensitivity index (V_s) was represented by the coefficient of variation of climatic yield. As time series of grain yields (2001–2010) consist of a technology-driven trend and variations caused by climate fluctuations (Yu et al. 2001; Zhong and Xing 2004), a detrending model (Zhong and Xing 2004) was employed to eliminate the technologically driven trend component (Y_0) to obtain the variation yield affected by climatic factors (Y_w). Therefore,

$Y_w = Y - Y_0$, here Y is the actual yield. The coefficient of variation of Y_w is for the description of the effects of climate factors on grain production. The indicator, hereafter referred to as climatic yield variability, was normalized and taken as V_s.

Adaptive capacity index

Adaptive capacity refers to the preconditions within a system that are necessary to enable it to execute a deliberate response in anticipation of or in reaction to climate change (Nelson et al. 2007a, b). To represent these preconditions, social characteristics, physical, and economic elements of Loess Plateau counties are necessary to be considered. Six indicators were chosen with the criteria of relevancy, adequacy, administrative practicability, and data availability to represent the adaptive capacity for each county. The significance of each indicator is as follows:

(1) Disposable income of rural residents: provides an approximate indication of the financial capital available for adaptation to detrimental climate change. The significant contribution of financial capital to adaptive capacity arises from the liquidity and fungibility of finances (Nelson et al. 2007a, b), particularly valuable in the face of climatic uncertainty. Furthermore, income is an indicator of the local economic power that can be called upon to resolve emerging threats (Yin et al. 2009).
(2) Non-agricultural share of GDP: represents the potential diversity of non-farm employment opportunities and ability to switch between alternative sources of income as a form of adaptation (Nelson et al. 2007a, b).
(3) Productivity of grain sown area: represents natural capital. Productive land has greater fungibility, being able to accommodate a wider range of farming options than marginal land or wasteland.
(4) Ratio of irrigated farmland: reflects the extent to which farms can access water from alternative sources that are less reliant on rainfall in the event of poor rainfall conditions.
(5) Consumption of chemical fertilizers: reflects the impacts of technological conditions on production (Yin et al. 2009).
(6) Agricultural machinery power: indicates the physical assets available to agricultural producers that may be used for adaptations to climate change.

Adaptive capacity (V_a) was calculated as

$$V_a = \sum_i Y_i \times W_i,$$

where Y_i represents the adaptation ability degree of the i-th indicator and W_i denotes the weight of the i-th indicator. The equal weights method, which is based on the premise that no objective mechanism exists to determine the relative importance of different indicators, was adopted in this paper.

Integrated vulnerability index

Indicators were first normalized as dimensionless values ranging from 0 to 1 using $p_i = [p_i\text{-}min(p)]/[\text{-}max(p) - \min(p)]$. Then, V_e, V_s, and V_a were each calculated. A vulnerability index was calculated as

$$V_v = (V_e \times V_s)/V_a.$$

Classification and mapping

Calculated indexes of exposure, sensitivity, potential harm, adaptive capacity, and vulnerability for 243 counties were ranked from lowest to highest and then divided into five classes by quintile (lowest, low, mid, high, and highest), each containing 48 or 49 counties. The relationship between vulnerability and its components was analyzed and the values of indexes were shown on maps to identify the spatial distribution of vulnerability by ArcGIS 10.1.

Sensitivity analysis

The robustness of our result was analyzed by calculating the average shift in county vulnerability ranks in response to changes in indicator choice and weighting method. The effect of indicator choice was analyzed as the average change in ranking when individual indicators are excluded from the analysis. Where indicators were combined to form a single vulnerability component score, the potential effect of indicator weight was analyzed as the average change in ranking when the weight of each indicator is increased or decreased in proportion to the others.

RESULTS AND DISCUSSION

Relationship between vulnerability components and indicators

The correlation between calculated exposure, sensitivity, and adaptive capacity indexes for all 243 counties was found to be weak (Table 2), indicating that the three components were independent of each other. This suggests complexity in the circumstances of individual counties and the agricultural producers within them.

In general, most indicators contributing to the vulnerability components were concentrated in a narrow range after normalization (Fig. 3), indicating that a small proportion of counties perform extremely high or low rather

Table 2 Pearson's product moment correlation coefficients of calculated vulnerability components from 243 counties on the Loess Plateau

Components	Exposure	Sensitivity	Adaptive capacity
Exposure	1	0.04	0.02
Sensitivity	0.04	1	0.15
Adaptive capacity	0.02	0.15	1

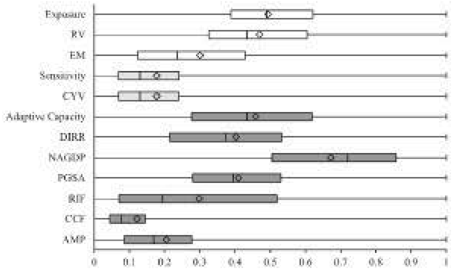

Fig. 3 The distribution of three calculated components (exposure, sensitivity, adaptive capacity) and nine normalized indicators of vulnerability to climate change from 243 rural counties in the Loess Plateau. *Vertical bars* and *left* and *right edges* of *boxes* indicate minimum, maximum, 25 and 75 percentiles of the total data, and *thick black line* and *diamond* are the median and average, respectively. *RV* rainfall variability, *EM* soil erosion modulus, *CYV* climatic yield variability, *DIRR* disposable income of rural residents, *NAGDP* non-agriculture share of GDP, *PGSA* productivity of grain sown area, *RIF* ratio of irrigated farmland, *CCF* consumption of chemical fertilizers, *AMP* agricultural machinery power

than an even distribution across the range of possible scores. Furthermore, as a complex system, some indicators were found to interact with each other.

Among exposure indicators, it is expected that rainfall, which is typically higher in areas with lower rainfall variability, would accelerate and therefore correlate with soil erosion. However, the effect is only present in the top four exposure classes (highest $R^2 = 0.80$, high $R^2 = 0.96$, medium $R^2 = 0.95$, low $R^2 = 0.89$, lowest $R^2 = 0.02$). It is likely that these counties in the lowest exposure class possess advantages such as increased vegetation cover or adaptations that prevent rainfall from causing soil runoff.

Climatic yield variability was very low in the majority of the counties (Fig. 3), resulting in a pronounced skew in the sensitivity index. Notably, 80 % of counties were found to have a sensitivity index less than 0.26. This suggests that for most counties, climatic yield is relatively stable, with only a few counties having highly unstable grain production. The extremely narrow interquartile range highlights the disparity in the effects of climate on different counties and the need to focus on the most vulnerable areas.

Among adaptive capacity indicators, the non-agricultural share of GDP in most counties was proportionally high (Fig. 3), indicating that the interaction of agricultural sectors with the economy is limited despite its significance to livelihoods. By contrast, the values of fertilizer, machinery power, and irrigation were grouped tightly towards the bottom of their respective ranges, showing that the use of these technologies present in the plateau but is relatively low.

Vulnerability to climate change in the Loess Plateau

Upon classification, it was found that the highest vulnerability class accounted for 81 % of the integrated vulnerability index range despite including only 20 % of the counties. Forty-two of the 49 most vulnerable counties had exposure and sensitivity in the high or highest classes, with low or lowest adaptive capacity.

The exceptions among the highest vulnerability class were one county (Fugu) that had a high adaptive capacity index and six counties (Tianzhen, Fengzhen, Zuoyun, Ningwu, Shenchi, Haiyuan) with low or lowest exposure. Fugu county ranked high in adaptive capacity as it has among the highest per capita net income of rural residents and non-agricultural share of GDP. However, the county's serious soil erosion, barren land, and fragmented terrain contributed to higher sensitivity and exposure indexes which carried greater weight in this analysis due to their lower median scores for all counties. For the remaining six counties with comparatively low exposure, all have highest sensitivity and lower adaptive capacity (four lowest and two low), indicating that current structure of agriculture in these six counties may be both poorly suited to the environment and lacking the capital to change. Given the low variability in the integrated vulnerability index of all classes but the highest, those 49 counties (Table 3) that represent the majority of the vulnerability range should be prioritized for adaptations.

Spatial distribution of vulnerability on Loess Plateau

Counties with relatively high exposure indexes were typically located at middle northeast–southwest belt of Loess Plateau, primarily in northwest Shanxi, mid-north Shaanxi, and east Gansu (Fig. 4a). The high exposure can be attributed primarily to serious soil erosion. Some counties located on the northwest and southeast edge of Loess Plateau with lower soil erosion were also classed as high exposure because of high rainfall variability.

High sensitivity indexes were found to be partly overlapped with exposure; the most sensitive counties mostly lie on the southeast of Inner Mongolia on the edge of

Table 3 Identified 49 most vulnerable counties on Loess Plateau

Province	Vulnerability type	County name
Shaanxi	Highest ES/lowest AC	Qingjian, Jiaxian
	Highest ES/low AC	Yanchang, Zizhou, Suide
	Highest ES/mid AC	Wuqi, Dingbian, Mizhi, Wubu
	Highest ES/high AC	Fugu
Shanxi	Highest ES/lowest AC	Loufan, Tianzhen, Youyu, Jingle, Ningwu, Shenchi, Kelan, Xingxian, Pianguan, Linxian, Baode, Shilou, Lanxian, Jixian, Daning, Yonghe, Fenxi
	Highest ES/low AC	Zuoyun, Wuzhai, Hequ, Liulin, Fangshan, Fushan, Yuanqu
	High ES/lowest AC	Xixian
	High ES/low AC	Pinglu
Gansu	Highest ES/lowest AC	Huanxian
	Highest ES/low AC	Qingcheng
	High ES/lowest AC	Tongwei, Zhenyuan
Inner Mongolia	Highest ES/lowest AC	Zhuozi
	Highest ES/low AC	Fengzhen, Qingshuihe, Guyang, Wuchuan
	Highest ES/mid AC	Liangcheng
Ningxia	Highest ES/lowest AC	Tongxin, Haiyuan
	Highest ES/low AC	Yanchi

ES Exposure × Sensitivity = Potential Harm; *AC* adaptive capacity

Shanxi, northwest Shanxi and mid-north Shaanxi, south Ningxia, and east Gansu, where the exposure values are also relatively high (Fig. 4b). Accordingly, counties with the greatest potential for harm consistently lie in the middle northeast to southwest belt where these two indexes overlap, with three areas identified: the southeast of Inner Mongolia on the edge of Shanxi, northwest Shanxi and middle part of north Shaanxi, south Ningxia, and east Gansu (Fig. 4c).

The spatial distribution of adaptive capacity was found to be roughly the inverse of exposure, sensitivity, and potential harm. The highest adaptive capacity was concentrated on the northwestern and southeastern edges of the plateau (Fig. 4d). The northwestern part has high disposable income of rural residents, productivity of grain sown area and ratio of irrigated farmland, whereas the southeastern regions are characterized by high consumption of chemical fertilizers and agricultural machinery power in addition to high productivity of grain sown area. By contrast, the middle northeast to southwest belt, featuring the greatest concentration of counties with high predisposition to be adversely affected, was found to also be made up of counties with the lowest adaptive capacity, aggravating that area's integrated vulnerability score.

In general, counties with high exposure and sensitivity, in addition to low adaptive capacity tended to be close to one another. Therefore, the most vulnerable counties occupy a clearly defined zone, visible in Fig. 4e. A vulnerability belt was identified, running from northeast to southwest across the southeast of Inner Mongolia, the northwest of Shanxi and middle part of north Shaanxi, the south part of Ningxia, and east Gansu.

Our result is consistent with the previous partial assessment of the Plateau conducted by Wang and Liu (2003), in that the counties present in both analyses have similar vulnerability relative to each other. We did, however, find that the highest proportion of vulnerable counties was concentrated in Shanxi province (Table 3), which was not assessed by Wang and Liu (2003). Furthermore, our results appear to validate what is implied by other studies conducted at a lower resolution; where Lin and Wang (1994) reported that Shaanxi, Inner Mongolia, Gansu, Shanxi, Qinghai, and Ningxia all had agriculture which was at an elevated risk of climate change, our study has specifically shown how this vulnerability is concentrated in a middle northeast and southwest vulnerability belt.

Sensitivity of results to indicator choice and weighting

The impact of individual indicator choice on county ranking according to the integrated vulnerability index is shown in Fig. 5a. Climatic yield variability, as the sole indicator of the sensitivity index, has the greatest impact on vulnerability rankings. By contrast, the average shift in ranking is no greater than 7 when any indicator of adaptive capacity is excluded. This is only a small rank change out of total 243.

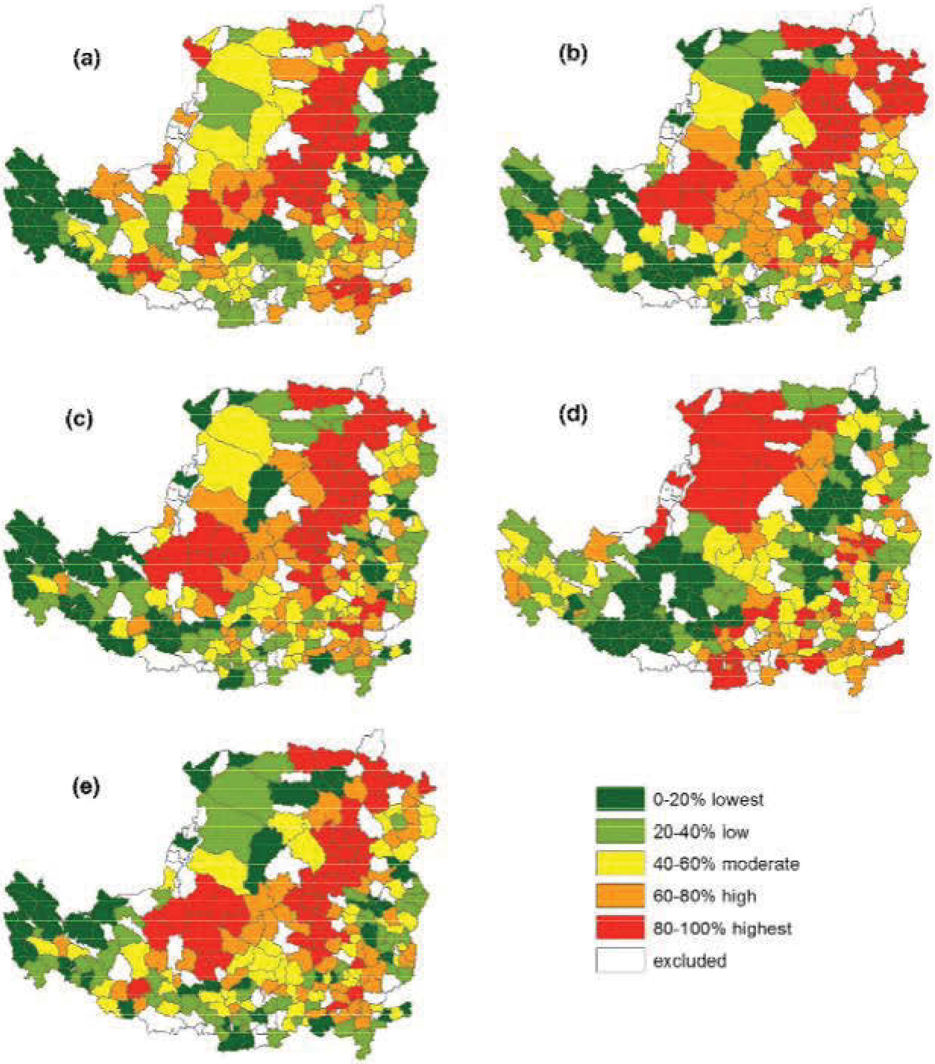

Fig. 4 Spatial distribution of vulnerability to climate variability and its components in the Loess Plateau: **a** exposure, **b** sensitivity, **c** potential harm, **d** adaptive capacity, **e** vulnerability

The effect of potential weighting schemes on county ranking is explored in Fig. 5b, which indicates that an extensive shift in ranks only occurs beyond what is typical for mathematically and opinion-derived weighting schemes. Thus, we conclude that adopting equal weights for adaptive capacity indicators can yield robust results while avoiding

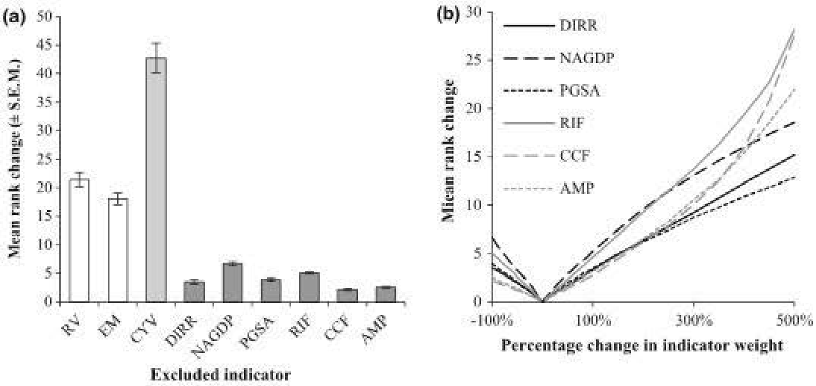

Fig. 5 Mean absolute change in ranking of 243 counties of the Loess Plateau according to integrated vulnerability index when individual indicators are removed from the calculation of the index (**a**) and during one-way sensitivity analysis on the weights of six indicators of adaptive capacity (**b**). *RV* rainfall variability, *EM* soil erosion modulus, *CYV* climatic yield variability, *DIRR* disposable income of rural residents, *NAGDP* non-agriculture share of GDP, *PGSA* productivity of grain sown area, *RIF* ratio of irrigated farmland, *CCF* consumption of chemical fertilizers, *AMP* agricultural machinery power

the pitfalls associated with complex weighting schemes (Saisana et al. 2005).

An interesting revelation of the sensitivity analysis is that 68 % of counties do not change vulnerability class when adaptive capacity is removed entirely from the assessment. This indicates that adaptive capacity in the majority of the Loess Plateau is inadequate relative to the current threat posed.

Policy implications

According to zoning activities undertaken by the National Development and Reform Commission et al. (2010) to guide management decisions on the Loess Plateau, 34 of the 49 counties that we identified as being in the highest vulnerability class are also located within the loess hilly and gully region (Supplementary material, Fig. S1). We therefore suggest the loess hilly and gully region be prioritized for interventions. The current comprehensive management plan prescribed for this region includes extensive ecological construction aiming to minimize erosion and conserve water (National Development and Reform Commission et al. 2010). Judicious use of similar policies has demonstrated value in reducing exposure and sensitivity to climate risks; however, it has been reported that more beneficial sustainability outcomes could be achieved if projects were designed to target specific local problems instead of focusing on achieving area-based quotas for ecological restoration (Xu 2011). In this regard, our results can be used by policymakers to identify priority counties for adaptation and make decisions according to their specific needs.

The need for a greater emphasis on measures which improve the adaptive capacity in vulnerable areas is also evident, as there were few counties analyzed that were found to have both high potential for harm and high adaptive capacity to compensate. To build sustainable agricultural systems that are capable of resisting and adapting to uncertain climate effects as they emerge, the Chinese government should continue its policy of improving rural livelihoods with a focus on the most vulnerable counties identified in this analysis. Specific attention should be paid to promoting investment in productivity enhancing and drought resisting adaptations that will yield a sustainable increase in incomes lasting beyond the intervention period. These measures will provide farmers with alternatives when faced with unfavorable climatic conditions.

CONCLUSION

This study describes and applies a conceptual framework to analyze the vulnerability of 243 counties to climate change on the Loess Plateau. The results indicate that vulnerability to climate change on the Loess Plateau is concentrated to 49 counties and that these counties lie in clearly defined zones. The middle northeast to southwest belt, located at the southeast of Inner Mongolia on the edge of Shanxi, northwest Shanxi and middle part of north Shaanxi, south part of Ningxia, and east Gansu included the most vulnerable counties, which were characterized by high exposure and high sensitivity and low adaptive capacity. We conclude that adaptation measures for both ecological restoration and economic development are needed for those counties to cope with future climate change. Further studies should be undertaken to investigate potential adaptation options on those areas identified as most vulnerable as this is an important issue for future research contributing to sustainable development in the face of changing climate.

Acknowledgments This study was supported by the National Basic Research Program of China (973 Program, No. 2012CB955304). The first author appreciates the financial support from the Chinese Scholarship Council, Ministry of Education, China.

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