GIS-Based Climate Change Adaptation Decision Support Tool (ADST): Indices to Assess Agricultural Vulnerability

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Abstract: There is a need to address the issue of how climate change and water resource and agricultural impacts assessment can be transformed into useful information for use by agricultural decision-makers to reduce climatic risk in agricultural production and explore approaches to bridge the gap between the assessment process and decision-making endpoints. A GIS-based Climate Change Adaptation Decision Support Tool (ADST) can help agriculture decision-makers in considering climate change adaptation in future plans and strategies. This tool builds up a few GIS databases covering key climate-water-agriculture information under current and future climate (2050s) along with a list of agricultural adaptation options. For the case study area - Ningxia, China – a series of ADST indices were computed for describing agro-climatic vulnerability, agricultural adaptive capacity and an agricultural investment plan. The approach to developing the vulnerability maps is based on the IPCC definition of vulnerability as a function of adaptive capacity, sensitivity, and exposure. Indices of adaptive capacity, climate and non-climatic sensitivity, and climate change exposure were constructed to examine the vulnerability to climate change in the region. The analytic hierarchy process (AHP) method is used to prioritize indicators to assess the potential contributions of various aspects to systems' coping capacities. Adaptive capacity for agriculture is considered to be an outcome of biophysical, socio-economic, and technological factors. Climate exposure is determined through the use of scenario results from the Hadley Center's PRECIS regional climate model and Environment Canada's scenarios network (CCCSN).

Keywords: Geographic Information Systems, Climate Change, Adaptation Decision Support Tool, agriculture

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1. Introduction

Geographic Information Systems (GIS) allow for interdisciplinary efforts to foster collaborative science, spatial data interoperability, and knowledge sharing in climate change impacts and adaptation studies. The use of GIS has made data sets compatible, and created a bridge between the atmospheric sciences, geography, ecology, other more spatially-based sciences, and the natural resource management and planning communities. There is a need to address the issue of how climate change and water resource and agricultural impacts assessment can be transformed into useful information for use by agricultural decision-makers to reduce climatic risk in agricultural production and explore approaches to bridge the gap between the assessment process and decision-making endpoints. GIS-based Climate Change

Adaptation Decision Support Tool (ADST) can help agricultural decision-makers in considering climate change adaptation in future plans and strategies. This tool builds up a few databases covering key climate-water- agriculture information under current and future climate in (2050s) along with a list of agricultural adaptation options.

ADST can link agro-climatic Indices with Global Climate Models/Regional Climate Models Originated Climate Change Scenarios. Key agro-climatic indices for crops (e.g., crop heat units, growing degree-days, effective growing degree-days, precipitation deficits, seasonal crop coefficients of water demand) can be defined and used together with other indices (adaptive capacity and vulnerability in agricultural production) to measure the changes of climatic risk. Vulnerability assessment is a key aspect of anchoring assessments of climate change impacts to present development planning. Methods of vulnerability assessment have been developed over the past several decades in natural hazards, food security, poverty analysis, sustainable livelihoods and related fields. These approaches - each with their own nuances - provide a core set of best practices for use in studies of climate change vulnerability and adaptation (Chambers, 1989; Bohle and Watts, 1993; Adger and Kelly, 1999; Downing *et al.,* 2001).

While social determinants of adaptive capacity are difficult to observe and measure, some aspects of adaptive capacity, including physical infrastructure, resources and the distribution of those resources, may be assessed relatively easily both at national scales and at lower or higher levels of aggregation. A number of sets of national-level indicators developed within the UN system are used to build up a picture of national performance or status in areas as diverse as human health and economic trade (e.g data assembled by World Health Organization, World Bank, United Nations Development Programme, United Nations Conference on Trade and Development, International Labour Organization and others). Some proxies for generic adaptive capacity at the national level can be borrowed easily from other data sources for an initial holistic assessment of generic adaptive capacity. Adaptation efforts by governments and civil society must be targeted at specific groups within vulnerable countries, and further research into the underlying causes of vulnerability at the sub-national scale are necessary (Burton, 2001).

ADST can help to address one or more of the following questions: 1) how will agricultural investment decision processes be affected by climate information and how feasible is it for decision makers to make changes based on this information? What additional climate-water-agriculture information is needed by these decision processes to modify or adapt agriculture responses to make the water resource management and agricultural development more resilient to climate variability and change? What levels of risk and certainty are required to base decisions on modifying or adapting agricultural infrastructure and investments? 2) What are potential agricultural adaptations to climate change and what is the effectiveness of these options? How can the effectiveness of these adaptations be measured? What are the costs and benefits of these adaptations? What are the barriers to successful adoption of these measures?

This paper develops a series of ADST indices computed for describing agro-climatic vulnerability and agricultural adaptive capacity and an agriculture investment plan in a case study area – Ningxia, China – in order to identify proper adaptation options and measure the effectiveness of these adaptations. The methodology and data sources used to create the regional agricultural vulnerability maps are presented in section 2. Detailed definitions of indices are also provided in this section. Results of our case study are given in Section 3. Different indices were computed with local socio-economic and climate data including scenario results from the Hadley Center's PRECIS regional climate model and Environment Canada's scenarios network (CCCSN). Discussion and conclusions are presented in Section 4.

2. Methodology – computation of ADST Indices

The ADST Indices include those summarizing factors of agriculture adaptation mainly by profiling climatic stress, sensitivity and a system's adaptive capacity. Indices representing regional agroclimatic conditions are usually integrated with crop impact models which will not be discussed here.

2.1 Construction of an index of adaptive capacity (IAC)

Adaptive capacity includes three broad sets of vulnerability factors: social, technological, and biophysical (Chambers 1989; Bohle *et al.,* 1994). We have constructed a composite index for each these factors based on data from 2000 and 2001 (China Statistical Yearbook).. The final index of adaptive capacity for each district (county and county-level city) is calculated as the average of these three indices.

Each of the three indices is the average value of a set of normalized variables. Concerning normalization, all of the variables in the vulnerability profiles are normalized based on the method in the UNDP's Human Development Index (UNDP

2002). In some cases, the index values are reversed by using 100 – the index value to ensure that high index values indicate high vulnerability in all cases. Each indicator was evaluated in this manner prior to construction of the composite indices.

Social Vulnerability Index

Agricultural dependency is measured by the percentage of the district workforce employed in agriculture. A high level of agricultural dependency will increase the district's vulnerability to climate variability.

Table 1 | Social Vulnerability Index

DIMENSION	INDICATOR	DIMENSION INDEX
Agricultural dependency	Percentage of agricultural workforce	Agricultural Dependency Index
Human capital	Gross Domestic Product per capital	Gross Domestic Product index
Literacy	Literacy rate	Education Index [100 – index value]

Note: All data for the social vulnerability index is taken from the 2000 –2001 China yearbook.

Increased overall literacy levels reduce vulnerability by increasing people's capabilities and access to information and thus their ability to cope with adversities.

Technological Vulnerability Index

The Technological Vulnerability Index of a district uses indicators that measure a district's technological capacity or access to technology.

Table 2 | Technological Vulnerability Index

DIMENSION	INDICATOR	DIMENSION INDEX
Vulnerability to rainfall variability	Irrigation rate	Technological Vulnerability Index
Infrastructure development	Composite index of infrastructure development	Infrastructure Development Index

Irrigation rate is the net irrigated area as a percentage of net sown area. Water scarcity is the main productivity constraint for Ningxia agriculture. Our case studies show that an assured supply of water for irrigation reduces farmers' vulnerability to low and erratic rainfall.

Infrastructure Vulnerability Index

Quality of infrastructure is an important measure of relative adaptive capacity of a district, and districts with better infrastructure are presumed to be better able to adapt to climatic stresses. The index is published as a single composite index number for each district based on the following indicators and weights:

Table 3 | Infrastructure Development Index

SECTOR	WEIGHT
Transport Facilities	30
Energy	28
Banking Facilities	10
Communication Infrastructure	8
Educational Institutes	12
Health Facilities	12
Total	**100**

Biophysical Vulnerability Index

Areas with more productive soil and more groundwater available for agriculture are assumed to be more adaptable to adverse climatic conditions and better able to compete and utilize the opportunities of trade.

Table 4 | Biophysical vulnerability Index

DIMENSION	INDICATOR	DIMENSION INDEX
Soil quality	Depth of soil cover	Biophysical Vulnerability Index
Groundwater availability	Replenishable groundwater available for future use, in million cubic meters	Groundwater Scarcity Index

Indicators for soil quality are the depth of the soil cover in centimetres and severity of soil degradation. The soil cover map polygons were converted to a grid with a cell size of 50 km to maintain the same scale as the output from the PRECIS Regional Climate Models. By converting the polygon data to grid level it was possible to create fuzzy boundaries between soil cover classes and interpolate new cell values for areas on the borders of polygons. The gridded data was then averaged up to the district (polygon) level where each district was given an average soil cover value.

The same procedure followed for soil cover was used to convert the polygon data to a grid, and then back to district-level polygons. Data on ground water resources was calculated as the total amount of groundwater which is replenishable annually, measured in million cubic meters/year (MCM/Yr). This depends on the amount of rainfall, recharge from the canals, surface water bodies and change in land cover.

2.2 Construction of Climate Sensitivity Index (CSI)

The Climate Sensitivity Index (CSI) is an average of two indicators which were calculated for two time periods:

a) The observed climate period of 1961-1990 (called Observed CSI)
b) A future scenario climate period of 2041-2070 (called Exposure CSI)

Observed CSI portrays current or near current climate sensitivity in Ningxia. Exposure CSI builds upon Observed CSI. It represents the combination of both climate sensitivity and potential exposure to climate change by incorporating Global Climate Models/Regional Climate Models scenario results with the observed CSI data.

The Dryness Index (Table 5) is normalized and averaged to create the final CSI. The higher the CSI value (either Observed or Exposure), the higher the relative climate sensitivity for a district.

Table 5 | Dryness Index

DIMENSION	INDICATOR	DIMENSION INDEX
Vulnerability to Dryness (Observed and Exposure)	The ratio of annual potential evapotranspiration to precipitation (average over the normal or scenario time period).	Dryness Index

Observed CSI

The indicators used for Observed CSI were calculated using climate data from the 'China Meteorological Administration's (CMA) website. For the purpose of this study, only the temperature (degrees Celsius * 10) and precipitation (mm per month) parameters were used. To capture the borderless changes in the climatic variables, it was important to construct the CSI indicators at grid level. The final analysis, which involved combining the individual CSI indicators, was conducted and presented at the county level.

Monthly and daily data from 1961 to 1990 for Ningxia were extracted for the construction of Observed CSI. It is believed that this time period adequately reflects the current or near-current climatic conditions in Ningxia.

Dryness Index (DI) (Table 5) is used to give a relative impression of the dryness of an area. It is the ratio of average annual potential evapotranspiration to precipitation for the time period 1961-1990. Areas with the highest DI value are considered to be the most sensitive because a lack of adequate rainfall can be detrimental for agriculture. Although some areas with high DI values may have adapted agricultural practices to the drier conditions, it is thought that even with drought tolerant crops and irrigation, if little to no rain is received, most adaptation efforts will have little effect. The higher the Observed CSI value, the higher the relative climatic sensitivity.

Exposure CSI

Exposure CSI is based on the same indicators as outlined in Table 5. However, this version of CSI is the combination of climate sensitivity and exposure. Climate sensitivity in observed CSI is represented by the original China Meteorological Administration climate data. Climate exposure is determined through the use of scenario results from the Hadley Center's PRECIS regional climate model and Global Climate Models from the Canadian Climate Change Scenarios Network (CCCSN). Exposure CSI is based on the time period 2041-2070.

Exposure is defined here as the difference or ratio between the two scenario datasets for each climate parameter (temperature and precipitation). For each dataset (Control and Green House Gas Forcing), the daily data for temperature and precipitation were averaged to produce monthly values for the time period 2041-2070. The monthly difference between the Control and the Green House Gas Forcing datasets was then calculated for temperature while the ratio between the Control and Green House Gas Forcing was determined for precipitation. The temperature difference was then added to the observed monthly climate dataset (1961-1990) to create average monthly scenario temperature datasets for 2041-2070. The precipitation ratio was multiplied with the observed monthly climate datasets to create average monthly scenario precipitation datasets for 2041-2070. The scenario datasets were then used to calculate Exposure CSI (Dryness Index (Table 5) indicator) in the same fashion as described above. Districts with the highest Exposure CSI value have the highest climate sensitivity under the modeled scenarios of climate change exposure.

3. Assessing climate risks on agriculture using ADST-Indices: a case study of Ningxia

3.1 Background: Ningxia and its climate and agriculture

Ningxia is located in northwest China (Figure 1) and is one of the poorest regions in China. It is particularly exposed to extreme climatic events such as drought. Ningxia's climate is dry and highly seasonal – annual mean temperature ranges from 5-9°C. Annual precipitation decreases from south to north – the mountainous area in the south receives around 600mm, which declines to only 100mm in the north, with an overall average of 262mm. Winters are dry and very cold, summers are hot and receive most of the precipitation. The Yellow River is the main surface water source in the region.

The human population is close to six million, with 65% in rural areas. In 2004 the regional Gross Domestic Product was 6.57 billion US$ and GDP growth was around 11% per year. The population below the absolute poverty line in the southern mountainous areas of Ningxia is nearly 150 thousand in 2004.

Ningxia has three main types of agricultural production, each related to a different set of climatic and other factors, such as topography, traditional customs, and availability of water from the Yellow River:

1) Southern mountainous area: rain fed cultivation in the more humid climate, but still fairly dry, with an average annual rainfall above 400mm. Potato is the

major crop grown over a large area. Cattle, sheep, pigs, and chickens are the major livestock.

2) Central arid area: a mix of rain and riverfed irrigation with some extensive grazing. Average annual rainfall between 250-400mm. The dry conditions only allow corn, spring wheat, potato, and some cattle and sheep husbandry.
3) Northern irrigation area: primarily irrigation, using water diverted from the Yellow River, with an averaged annual rainfall of <250mm. Intercropping is the major planting system. The main crops in this area are corn, spring wheat, paddy rice, and potato. Cattle, sheep, pigs, and chickens are the major livestock.

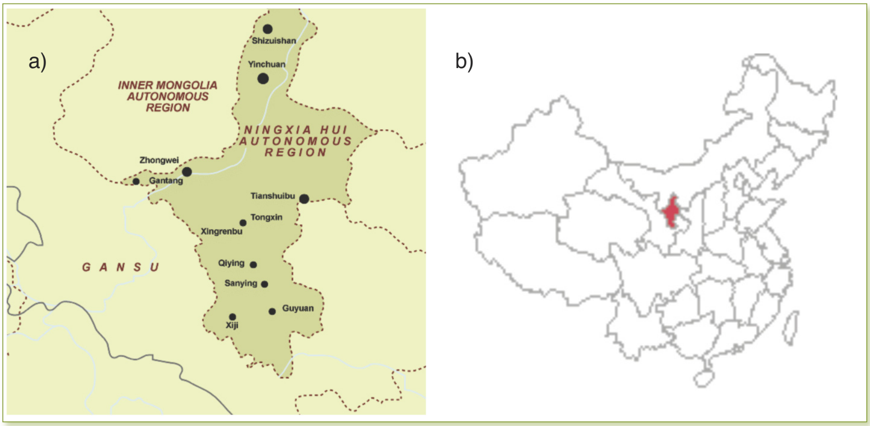

Figure 1 | Ningxia, location in China (b right panel) and main urban areas (a left panel).

Each sub-region has specific vulnerabilities and risks related to climate change. Agriculture in Ningxia depends heavily on irrigation and is very sensitive to climate change. The purpose of this case study was to evaluate the vulnerability of agriculture to climate change in Ningxia by mapping the socio-economic adaptive capacity and exposure. This case study describes an example of creating the maps of adaptive capacity (IAC), climate sensitivity (CSI) and climate change exposure using a set of ADST Indices.

To assess the main climate-related risks to rural communities and agriculture system in Ningxia, it is necessary to document the characteristics and impacts of current climate variability and extreme events and define the range of future climate change in the region based on the use of computer climate models. It consisted of a number of activities illustrated in following sections.

3.2 Characterising the extent and impacts of recent climate variability and trends

Lin *et al.* (2008) analyzed observed datasets from roughly 23 stations distributed throughout Ningxia with records dating back to the early 1950s. These provided an overview of the presence and magnitude of trends or changes in temperature, precipitation and other climate variables. Figures 2 and 3 show, respectively for temperature and precipitation, long term annual values. The mean annual temperature of Ningxia was fairly stable from the early 1950s to the 1980s but then developed a modest positive trend which is consistent with the global average temperature increase. Temperatures in winter months show increasing trend (roughly 0.5°C/decade) which has increased in most recent decades (with a range of 0.6-1.2°C/decade during 1991-2007).

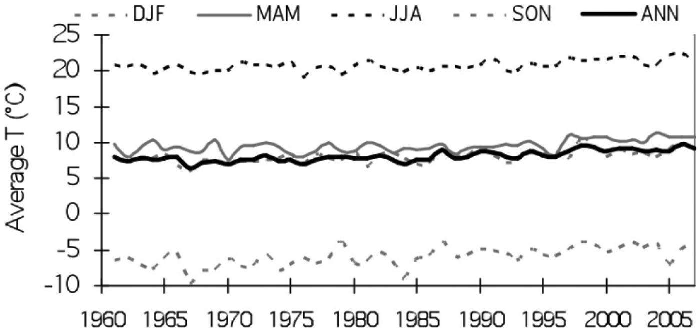

Figure 2 | Seasonal and annual temperature series for the whole of Ningxia, 1961-2007 (Lin *et al.*, 2008)

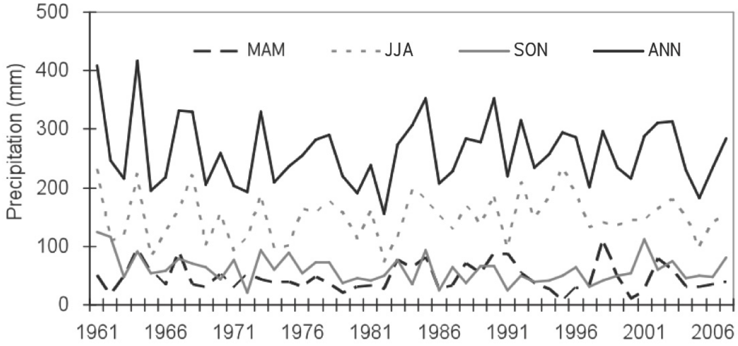

Figure 3 | Seasonal and annual precipitation series for the whole of Ningxia, 1961-2007 (DJF not shown as <10mm) (Lin *et al.,* 2008).

Precipitation in most months shows very modest evidence of a trend with a slight increase in Summer (JJA) (roughly 1.0-5.4mm/decade) and a slight decrease during Autumn (SON) to (roughly 1.0-4.5mm/decade). A marked feature of recent climate in Ningxia has been a major drought, due to three very dry years from 2004-2006, which was similarly experienced in 1981-82.

Recent studies have documented precipitation changes in China. Using daily precipitation dataset of 740 stations in China, Zhai *et al.* (2004) analyzed trends in annual and seasonal total precipitation and in extreme daily precipitation for the period 1951–2000. Results suggested that annual total precipitation has significantly increased in western China (including Ningxia) and has increased for both cold and warm seasons. The precipitation increase in western China is due to increases in both precipitation frequency and intensity.

3.3 Projections or scenarios of future climate

To estimate potential risks that climate change represents to agricultural production and activities it is important to provide guidance about the rate and magnitude of future climate change during the short to medium term future and to give measures of confidence to projections of future change. In this study, the Canadian climate change scenarios network (CCCSN) was used to provide detailed projections of how Ningxia's climate may change in the near future. Table 6 shows the changes in temperature and precipitation for mid-term future periods in central arid Ningxia, based on the Intergovernmental Panel on Climate Change – Fourth Assessment Report, Global Climate Models from the CCCSN website. Changes include shifts in the average conditions (such as warmer temperatures) but will also include changes in the frequency and severity of more extreme weather events (heatwaves, rainstorms) which are likely to cause greater socio-economic impacts. Computerized climate models represent the most reliable means currently available for describing the future climate, however, such models are not predictions; it is important to recognize that the 'scenarios' they produce are associated with large uncertainties.

Table 6 | Changes from (2041 - 2070) annual mean temperature and precipitation using Global Climate Models (GCMs) from the IPCC 4th Assessment Report from the Canadian Climate Change Scenarios Network (CCCSN). Models labelled CSIRO from Australia; NCARPCM from the Untied States; HADCM3 from the United Kingdom and CGM3 from Canada. A2 refers to a high greenhouse gas emission scenario; A1B to a medium scenario; and B1 to a low scenario – Tongxin (Central Ningxia)

MODEL RUN	TEMPERATURE (°C)	PRECIPITATION (%)
AR4.CSIROMk3.5.SR-A2	1.58	-22.98
AR4.CSIROMk3.5.SR-A1B	1.57	-27.96
AR4.CSIROMk3.5.SR-B1	1.26	-25.51
AR4.NCARPCM.SR-A2	1.77	-2.97
AR4.NCARPCM.SR-A1B	2.11	-8.08
AR4.HADCM3.SR-A2	2.91	-11.19
AR4.HADCM3.SR-A1B	3.21	-13.29
AR4.HADCM3.SR-B1	2.59	-14.14
AR4.CGCM3T47—Mean.SR-A2	3.48	-27.09
AR4.CGCM3T47—Mean.SR-A1B	3.26	-25.90
AR4.CGCM3T47—Mean.SR-B1	2.55	-19.89
Average	**2.39**	**-18.09**

Table 7 | Changes in future annual maximum and minimum temperature and precipitation using PRECIS the Hadley Centre's Regional Climate Model – results averaged across Ningxia (Lin *et al.,* 2008)

DIFFERENCE FROM BASELINE	TMAX °C		TMIN °C		PRECIPITATION (%)	
	B2	A2	B2	A2	B2	A2
2011-2040	1.6	1.8	1.6	1.8	+3	+5
2041-2070	2.6	3.6	2.7	3.7	+4	+8
2071-2100	3.5	6.0	3.7	6.4	+6	+12

In some cases it may be appropriate to prepare more detailed scenarios of future climate (better resolution using dynamical downscaling techniques), for example in relation to decisions about very large investments for infrastructure such as reservoirs and coastal defence. Lin *et al.* (2008) projected the changes in temperature and precipitation for three periods in the future, based on the regional climate model PRECIS (Table 7). In other cases it may be sufficient to use already available sources of information such as the Intergovernmental Panel on Climate Change's recent reports alongside analysis of recent climate trends that can be used as a crude guide to conditions over the next five to fifteen years for near-term decision-making.

Finally, an important source of uncertainty in scenarios of climate change is that different climate models can produce different results for the same regions. For Ningxia most climate models show increases in temperature so we have reasonable confidence in this result, but there is a wide range in the magnitude of warming which affects the level of confidence. However, results in Tables 6 and 7 can be used to identify critical areas of climate risks important to Ningxia. Risks relating to higher temperatures were prioritized because there is high confidence that warming will continue in the future. Droughts and changes in extreme events were also prioritized due to the significance of their current impacts and threat of greater impacts in the future.

3.4 Assessing vulnerability and adaptive capacity under climate change in Ningxia

Lin *et al.* (2008) subjectively ranked risks across sub-regions with a simple method. As the three sub-regions of Ningxia possess very different agricultural production systems, it was important to treat them separately. The approach used here combined a simple ranking from High to Medium to Low for three aspects of climate risk: L = likelihood of change occurring in the future; I = Potential significance of the impacts; and C = Confidence in the direction and detail of the future change. By combining these indices an overall assessment of the level of risk priority based on expert-judgement and local consultation was obtained. Table 8 present the results of the analysis.

Datasets from Ningxia Statistical yearbook were used to calculate present regional capacity to adapt to the identified climate risks. The adaptive capacity is divided into five grades according to the calculated relative values of the indicators. A preliminary result for current and future period was mapped in Figure 4. Observed and Exposure CSI was also calculated for each county for three sub-regions in Ningxia.

Figure 5 shows climate data for estimating the Dryness Index (DI) in central sub-region. Changes of DI are projected to the future to give hints on the rate and extent of future hazards. Exposure CSI was computed both with PRECIS and downscaled Global Climate Models data to allow comparison.

Table 8 | Summary of climate risk prioritization by sub-region*(Lin *et al.*, 2008)

MAIN CLIMATE RISKS/ SUB-REGION OF NINGXIA	DROUGHT	SURPRISES / EXTREME	DRYING	CHANGES IN YELLOW RIVER FLOWS
North	M	M	H	H
Central	H	M	H	M
South	H	H	M	L
All Ningxia	H	M	M	H

**Colours refer to; Red – High risk, Brown – Medium risk, and Green – Low risk.*

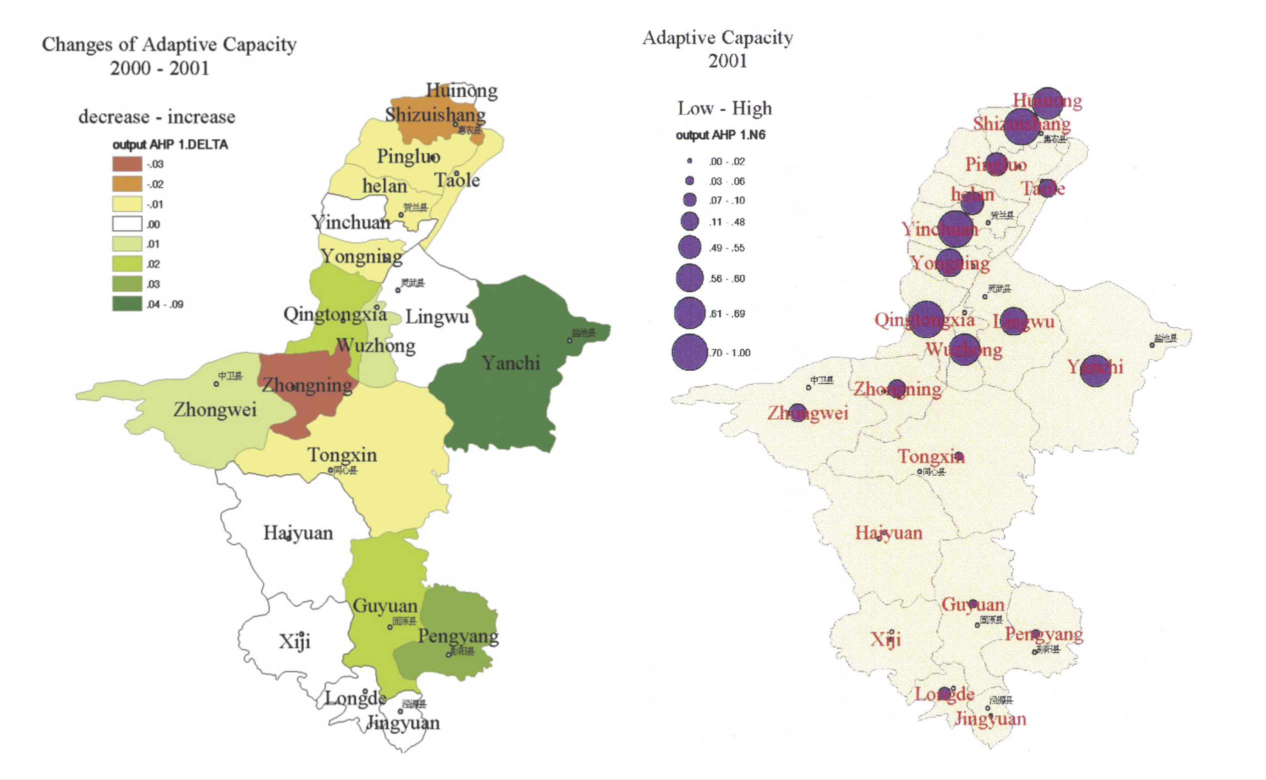

Figure 4 | Adaptive capacity to climate risk in Ningxia (right: present – 2001, left: changes to baseline in 2041-2070).

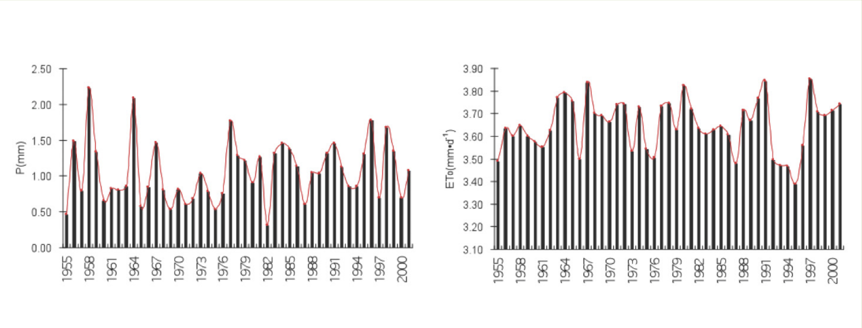

Figure 5 | Present CSI data: left panel - Precipitation and right - Daily Potential evapotranspiration (ET0) in Center Ningxia (Tongxin station, 1955-2000).

4. Conclusion

The preliminary results of this study using ADST indices indicate that counties in northern Ningxia generally have stronger adaptive capacity than those in the south. The northern counties have good irrigation facilities and general infrastructure except for industrially-developed cities like Qingtoongxia and Shizuishan. The strong industry and trade give these two counties a higher adaptive capacity, where Gross Domestic Product and gross industrial output are higher than in other regions in Ningxia. The worst area appears in the central arid sub-region where less precipitation and low irrigation rate were observed. Under climate change scenarios, the drought in the spring and hazard weather events is foreseen to increase dramatically.

This study has shown that economic, institutional, political and social factors are likely to play an important role in enabling the agriculture sector to adapt to climate change. It suggests that different sub-regions should adopt different prioritized adaptation measures to carry out adaptation actions. Climate risk and adaptation objective analysis are foundations to ensure adaptation is appropriate for local development. Next steps for future research include integrating policy-relevant indicators to assess the effectiveness of adaptation actions.

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