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DOI 10.1007/s13280-015-0727-8

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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

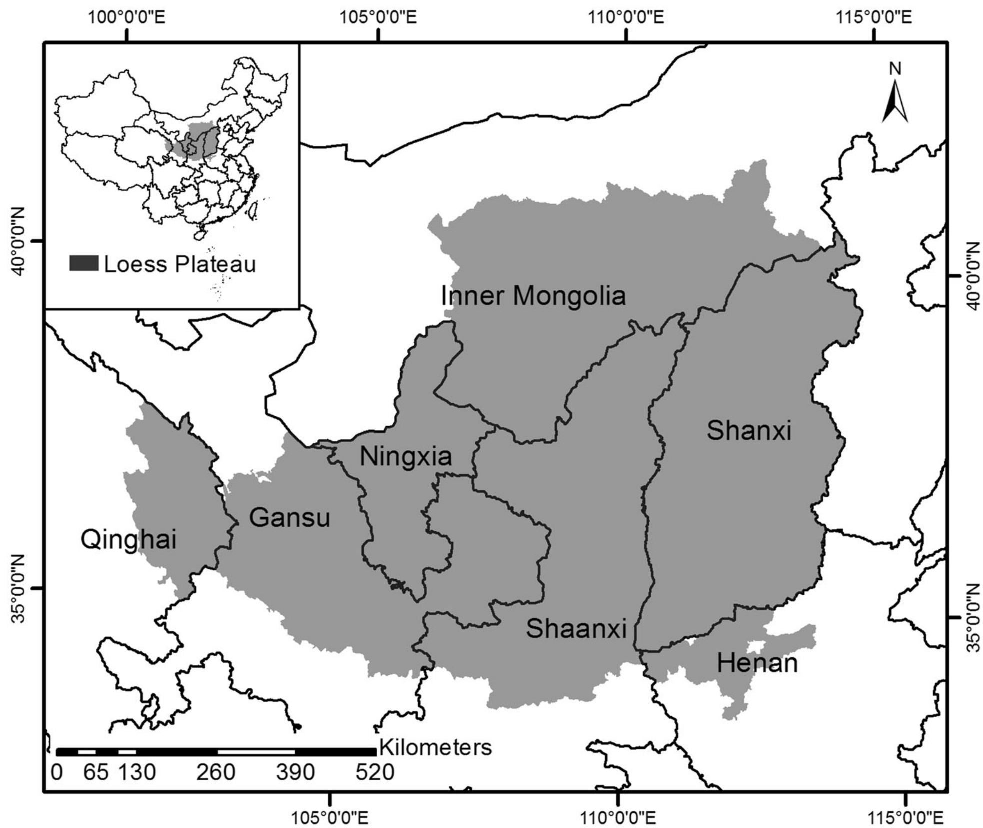

Fig. 1 Location of the Loess Plateau in China

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

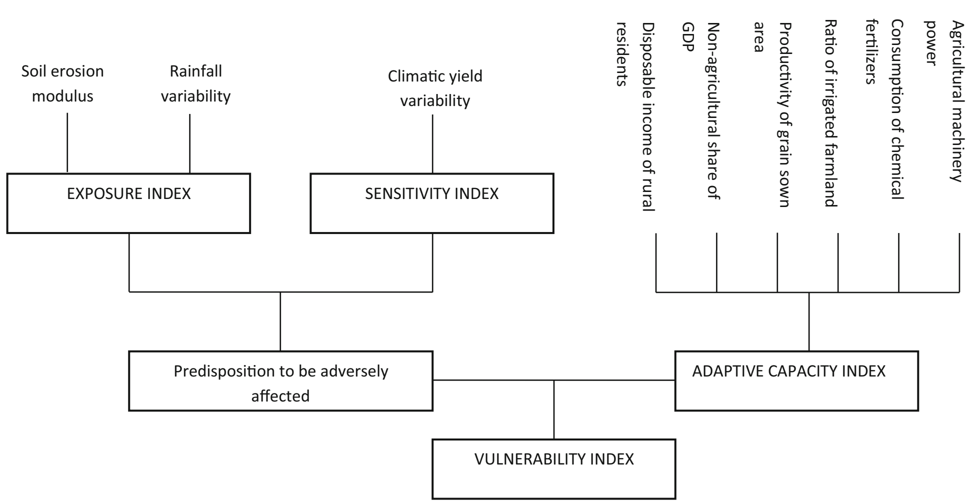

Fig. 2 Conceptual framework for assessing agricultural vulnerability to climate change as a function of statistical indicators

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

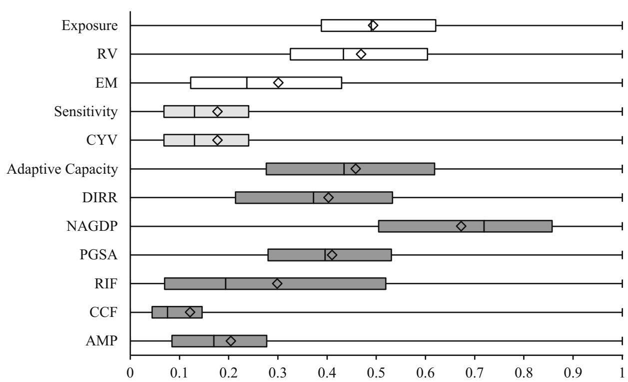

Fig. 3 The distribution of three calculated components (exposure, sensitivity, adaptive capacity) and nine normalized indicators of vulnerability to climate change from 243 rural counties in the Loess Plateau. *Vertical bars* and *left* and *right edges* of *boxes* indicate minimum, maximum, 25 and 75 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 $\times$ 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.

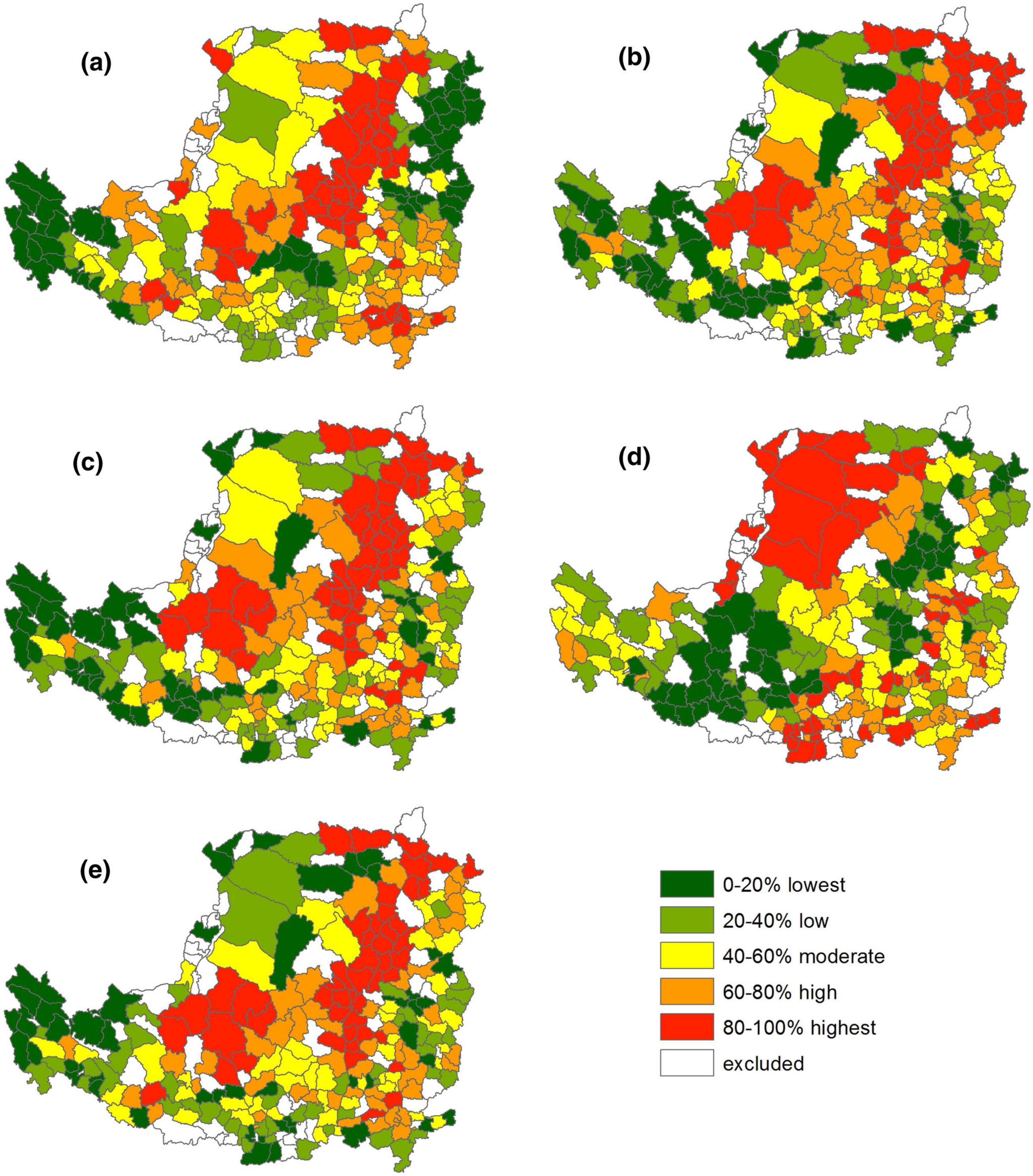

Fig. 4 Spatial distribution of vulnerability to climate variability and its components in the Loess Plateau: **a** exposure, **b** sensitivity, **c** potential harm, **d** adaptive capacity, **e** vulnerability

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

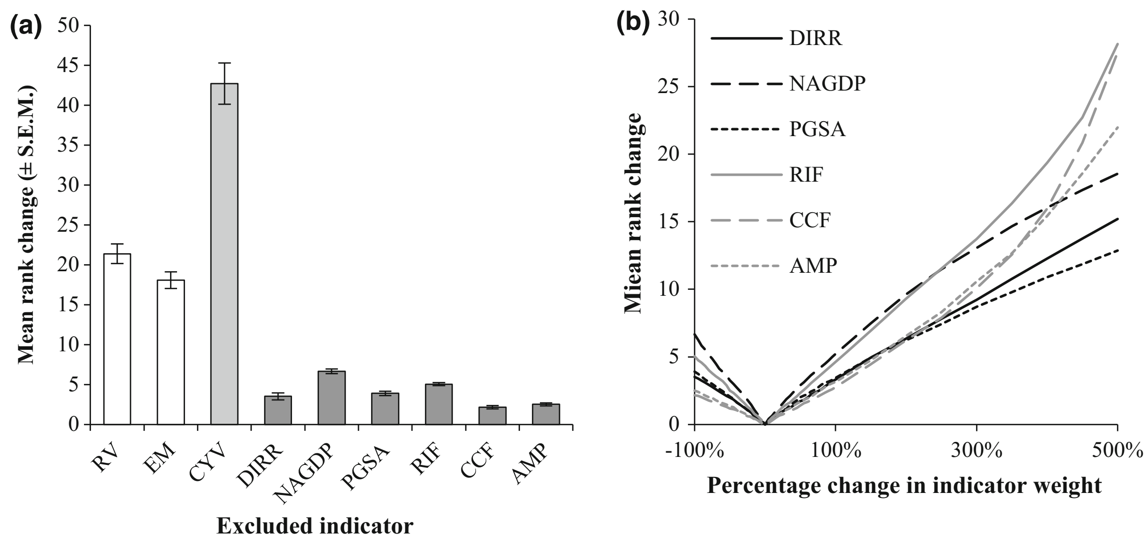

Fig. 5 Mean absolute change in ranking of 243 counties of the Loess Plateau according to integrated vulnerability index when individual indicators are removed from the calculation of the index (**a**) and during one-way sensitivity analysis on the weights of six indicators of adaptive capacity (**b**). *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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