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Typologies of crop-drought vulnerability: an empirical analysis of the socio-economic factors that influence the sensitivity and resilience to drought of three major food crops in China (1961–2001)

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ABSTRACT

Why is it that sometimes small droughts trigger serious crop losses while in other cases even large droughts do not have such a major effect? In this paper, we identify socio-economic indicators associated with sensitivity and resilience to drought for each of China's main grain crops (rice, wheat and corn). Provincial harvest and rainfall data (1961–2001) are used to calculate an annual ''crop-drought vulnerability index''. We separate ''sensitive cases'' (where significant harvest losses occurred in years with only minor droughts) and ''resilient cases'' (where harvest losses were minimal despite there being a major drought) and explore the socio-economic characteristics of these different situations. Results show that sensitive cases were particularly common in economically poor landlocked provinces *and* in wealthy coastal areas that have a limited land base. In such ''sensitive cases'', the size of the rural population and the quantity of agricultural inputs were negatively correlated with drought vulnerability, while for resilient cases, vulnerability was negatively correlated with the abundance of land. This leads us to propose a series of drought-vulnerability typologies based on the extent to which land, labour, capital, agricultural technology, and infrastructure buffer or exacerbate the effect of a drought event.

1. Introduction

Climate change policy is based on evidence that is underpinned by mathematical and physical models that project the consequences of increasing concentrations of greenhouse gases. Today, climate models include large numbers of variables and feedbacks, all of which can be calculated to a relatively fine spatial and temporal resolution, covering the entire globe (Intergovernmental Panel on Climate Change, 2007). Despite this extraordinary accomplishment, these models are not yet designed to fully capture one of the most important aspects of the climate system: humanity's ability to respond to changes in regional and local weather patterns. The chapter on agriculture by Working Group II of the Intergovernmental Panel on Climate Change's fourth assessment report is illustrative. It provides a lengthy survey of how crops respond to moisture stress, carbon dioxide fertilization and elevated temperatures. The chapter concludes that if

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global mean temperature rises more than 2 °C, yield declines are likely throughout the globe (Easterling et al., 2007). When it comes to exploring how socio-economic factors may buffer (or exacerbate) the effect of climate change on crop productivity, however, there is a far less robust literature to draw upon. As a result, the IPCC's chapter covers this matter in a few short paragraphs by reviewing how the impact of climate change on food production will also depend on local socio-economic conditions. For example, the chapter looks at how the same meteorological shock had very different effects in adjacent areas of the southern United States and Northern Mexico. The importance of socio-economic context is further backed up by literature that shows what conditions enable farmers to create more or less robust agricultural systems (Fraser, 2003, 2006, 2007; Mendelsohn, 2007; Mendelsohn et al., 2007; Reidsma et al., 2007; Sullivan and Meigh, 2005). Such geographic and economic insights have not yet been integrated into the current generation of coupled global circulation and land use models where human activities are encapsulated by broad 'land use' categories that are themselves defined by only a few parameters such as albedo and soil moisture (see: Heistermann et al., 2006 for a review of land-use models). Similarly, in assessments of climate impacts on agriculture, two types of models are common but rarely joined together: biophysical crop models and econometric/trade models. In the crop models, farmers' decisions are typically represented by simple parameters (such as the assumption that soil moisture determines planting date) and inputs like fertilisers are assumed in models to be used consistently over the growing season (Osborne et al., 2006). In econometric models, farmers are typically treated as an aggregated group of profit maximisers acting in a free market, possibly with parameters representing environmental limitations (Wang and Davis, 2000). In these examples, factors that might influence on-farm activities are unaccounted for (Patt and Siebenhüner, 2005), e.g. risk-reduction strategies. Consequently, we have thus far only a poor understanding of how socio-economic changes may affect land use decisions, and how these may then translate into more or less vulnerable cropping systems.

There are many difficulties associated with incorporating human dimensions into climate change impact models. These are confounded by the need to find a suitable scale and a flexible set of environmental, social, and economic indicators. Regardless of these challenges, it is imperative that integrated climate change impact models capture more socio-economic factors. Take vulnerability to drought as an example. In some historic situations, such as the Ethiopian Famine during the 1980s, the underlying socio-economic and political conditions were such that a minor climatic perturbation had a massive impact (Comenetz and Caviedes, 2002). In other cases, even severe droughts were adapted to without significant problems; for example, a major drought in southern Africa in the early 1990s did not result in significant hunger and famine-related deaths due to a combination of local adaptability, pro-active governmental response and long-range forecasting (Green, 1993). The role of society and economics, therefore, may either counteract or amplify the climate signal, and this has led some development experts to suggest that food shortages almost never emerge due to environmental triggers but are inevitably caused by social phenomena (Sen, 1981).

This is particularly important in terms of drought, which is a slow onset problem (as compared with floods or storms) that we have a reasonable capacity to anticipate based on medium range weather forecasting and our understanding of El Niño/La Niña cycles (Rook, 1997). Since droughts are anticipated to become more pronounced in some of the world's already dry regions as a consequence of global warming (Awosika et al., 1998; IPCC, 2007), and since these areas are among the world's poorest, understanding the underlying socio-economic characteristics of "drought-resilient" regions is critical. Research is needed, therefore, to build more synergies between the crop–climate modelling community and those who focus on food security, poverty and how environmental problems in the past have affected household and community-level coping strategies (Corbett, 1988; Hitchcock, 2002).

To contribute to this debate, we identify cases where relatively small droughts were associated with large harvest losses (we call these "sensitive cases") and contrast these with cases where large droughts were associated with only a small impact on harvests ("resilient cases"). The goal of our research is then to identify spatial and temporal trends and explain the underlying socio-economic factors that characterise resilient and sensitive cases. We do this using provincial scale crop production, rainfall, and socio-economic data for China between 1961 and 2001. In this paper, "vulnerability" refers to the extent to which a drought of a given size (measured meteorologically) has an impact on agricultural production (measured in terms of harvest). In particular, we are interested in those high-vulnerability cases where crop production was "sensitive" (i.e. when a small drought triggered a large harvest loss) to drought and contrast these with low-vulnerability or "resilient" cases (defined as occurring when a large drought seems to have had little or no effect on harvest) with a view to identify factors that contribute to adaptive capacity. This paper is organised around the following four objectives.

- The first objective is to review the literature that: (i) integrates socio-economic and climate factors to assess food production; (ii) discusses the policy and climate change context of Chinese agriculture.
- The second objective is to present a research framework that shows how to identify sensitive and resilient cases by constructing a "crop-drought vulnerability index" and describe the methodological steps and data we used to assess vulnerability for Chinese provincial rice, wheat and corn harvests between 1961 and 2001.
- The third objective is to statistically determine (i) those regions in China where grain harvests were most vulnerable to rainfall anomaly; (ii) trends in vulnerability at the provincial scale over time; and (iii) socio-economic characteristics of provinces and years that have different levels of vulnerability.
- The fourth objective is to use the results to show how indicators of vulnerability vary depending on socio-economic contexts and propose a "vulnerability typology" that could provide the basis for including socio-economic variables in crop–climate models as well as informing interested in promoting climate change adaptability.

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2. Background literature

2.1. Integrating socio-economic and climate factors to assess food production

The literature that links socio-economic factors with climate change impacts and agriculture falls along a qualitative–quantitative spectrum of research. In terms of the more qualitative work, scholars often use a ''livelihoods approach'' to understand local adaptation to past environmental shocks. These studies are generally aimed at understanding how households or communities deployed different types of assets or ''capital'' (e.g. human, social, environmental, political and financial capital) to overcome problems. These methods have been applied in a large range of bio-physical and socio-economic settings including coastal communities (Adger, 1999), small islands (Tompkins, 2005), the Mediterranean (Nicholls and Hoozemans, 1996), flood-prone river basins (Mustafa, 1998), the Arctic (Ford et al., 2006), as well as African farming systems (e.g. Thomas et al., 2007). This literature has exposed the complexity of trying to identify social factors that are linked to climate vulnerability (e.g. see: Reed et al., 2006; Sullivan and Meigh, 2005; Thomas and Twyman, 2005; Thornton et al., 2006). For example, one study has shown that when farmers in Zimbabwe were given the opportunity to interact personally with weather forecasters they were better able to make use of the long-range drought predictions, and obtained statistically higher agricultural yields, than farmers those who had no access to forecasts or those who received forecasts via radio (Patt and Gwata, 2004).

Given the complexity of individual case study based research, a number of other papers attempt to discern common trends from this field research and develop ''vulnerability frameworks'' that situate food production within a global environmental context (Alcamo et al., 2001; Ericksen, 2008; Kasperson et al., 1995; Turner et al., 2003). This literature is summarized by Adger (2006), who concludes that vulnerability analyses need to be placed within a specific spatial scale that is linked to other scales. Many of these papers also build on Watts and Bohle's (1993) food security framework that links local-level exposure to a risk with the capacity of members of a community to adapt to that risk, and the potential of the problem to have severe consequences at a range of scales. With the possible exception of Alcamo et al.'s ''security diagrams'', however, all these frameworks are conceptual and not predictive tools. For example, Turner et al. stress that their framework, ''... is not explanatory but provides the broad classes of components and linkages that comprise a coupled system's vulnerability to hazards.'' (Turner et al., 2003, p. 8076). Others take a less conceptual and more pragmatic approach and construct ''water poverty'' and ''climate vulnerability'' indices based on weighted factors grouped into key components, e.g. resources, access, capacity, use and environment (Sullivan and Meigh, 2005). The way these indices are weighted, however, is not based on replicable quantitative empirical evidence.

In terms of more quantitative approaches, economic modellers have made a significant contribution to the field, showing that agricultural productivity not only depends on climate and biophysical variables but relies on the availability of capital and labour. Economic modellers explore the dependence of net cropland revenues on climate with cross sectional and panel data (Mendelsohn and Reinsborough, 2007; Schlenker et al., 2007) using a ''Ricardian analysis'' that assumes land rents reflect net productivity that itself is a function of soil and climate. Based on data from US counties, researchers show that 39% of crop failure is explained by variations in climate and soil. This economic modelling approach provides evidence that variations in rainfall are correlated to variations in production, and while the studies provide excellent empirical data sets for this type of study, this is not an unexpected result. More importantly, however, some counties/regions are better able to absorb climatic anomalies than others and this suggests that the relationship between climatic and production anomalies is confounded by other factors. Brooks et al. (2005) make a preliminary attempt to define these ''other factors'' and use statistical methods to link national-level socio-economic data with data on mortality due to natural disasters and identify key factors that correlate with the impacts of extreme weather events in the past. Their study, however, uses only country level mortality statistics as its dependent variable and does not control for the size of the environmental shock. As such, Brooks et al.'s study should be seen as an important step towards identifying and quantifying the socio-economic factors that pre-dispose a country to being sensitive to climate but insufficient to base policy on.

2.2. Policy and climate dimensions of Chinese agriculture

Given its size (geographic, economic and population) and its ever-increasing global integration, any changes to Chinese agricultural production will have both national and global implications. Although the increase in China's grain yields over the past 20–50 years has varied somewhat between region, generally speaking, gains have been achieved through state policies that have transferred a certain degree of decision making to the farm level (Wang and Davis, 2000). This has led to new agricultural management practices, land use changes, an increased use of technical inputs notably fertiliser and irrigation and a concentration of agriculture to the plains in the north (Simelton, 2007; Ma et al., 2006; Wang and Davis, 2000; Yang, 1998). These changes make China an interesting place to explore how different underlying socio-economic contexts may influence farm management and allows us to ask the question: what are the key socio-economic variables that allow farmers to take advantage of these new opportunities? Fanfani and Brasili (2003) use the 1997 census to explore this question and they found that two variables (the 'concentration of people engaged in agricultural or non-agricultural activities' and the 'level of mechanization') explained over 60% of the total regional variance in harvest. They also found that GDP was inversely correlated with the ratio of persons involved in agriculture and that geographic factors also play an important role. Although government policies differ little between regions (Wang and Davis, 2000), the census in 1997 revealed a very diverse agricultural geography in China (Fanfani and Brasili, 2003). More detailed overviews of agricultural policies, including trade-related and food economy models have been provided in a number of recent reviews (Huang, 2002; Wang and Davis, 2000; Zhang, 2003).

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As policy makers and scientists try to anticipate how future climate trends may affect Chinese agriculture, the picture that emerges is complex. Water supplies are close to fully, but inefficiently, exploited (Bouman et al., 2007). As a result, serious concern has been raised that climate change will have an adverse impact due to increases in extreme weather events leading to increased agricultural droughts (Cruz et al., 2007). There is evidence that these problems are already emerging with Northern China generally experiencing higher temperatures (Song et al., 2005; Tao et al., 2006) and more droughts (Zhai et al., 1999). For example, some studies project that a 1 °C rise in air temperature expected by 2020, will translate into a 6–10% increase in the need for irrigation water in East Asia (Cruz et al., 2007).

Anticipating the actual impact of these changes, however, is challenging and there is a wide range of estimates for future grain productivity presented in the IPCC-reports (e.g. Cruz et al., 2007). Partly, this uncertainty is because projections are based on linking crop models with climate models that are run for (1) different emission scenarios; (2) rainfed versus irrigated agriculture; and (3) with or without CO_2 fertilization (Erda et al., 2005; Thomson et al., 2006). To summarize this literature, it seems that in the short-term, we may expect increased yields for C_3 crops (wheat, rice) thanks to earlier planting dates and CO_2 fertilization. In the long-term consequences are more tentative and may be negative (Long et al., 2004). For example, irrigated rice yields may decline in the ''B2'' emissions scenario as tropical crops already grow in or above their optimal temperature environment (Xiong et al., 2007). However, these estimates of harvests vary with the socio-economic scenarios and depend on perhaps optimistic (and untested) assumptions about how yields will improve due to technological change (Erda et al., 2005; Thomson et al., 2006).

Research focussing on farmer behaviour (e.g. see: Zhen et al., 2007) suggests a range of agricultural management strategies to adapt to changing climatic conditions. For example, farmers may be able to exploit longer growing seasons by planting crops earlier (Yang et al., 2007), conserve soil moisture by mulching with between plants in semi-arid regions (Zhang et al., 2007) or timing irrigation practices (Feng et al., 2007). However, since farmers respond to input and commodity prices as well as environmental and climate signals, it is unclear how many will be likely to change their management, at least without state intervention. For example, in economically poor regions, agricultural innovation and adaptation is closely linked to farmers' social networks (Wu et al., 2002). Adaptation measures that come out of these networks may be reactive rather than helping farmers take pro-active measures in anticipation of future problems. To date, however, there is little work done on this. As a result, there is a modest or no agreement in the literature on which aspects of China's agricultural system are likely to be vulnerable to changes in the climate.

3. Methodology

In terms of an overall research framework, we draw on the vulnerability literature that suggests a system's vulnerability to climate change is a function of (1) being exposed to a climate related anomaly, (2) being sensitive to this anomaly and (3) being able to adapt to the anomaly (Easterling et al., 2007; Nelson et al., 2007). In this case, we define being ''exposed to a climatic anomaly'' as being exposed in the past to a meteorological drought of a certain intensity and being ''sensitive to the anomaly'' as the extent to which the drought was associated with a harvest loss (this would be considered an agronomic drought). Based on this conceptualization, we hypothesize that in cases where large droughts did not translate into large crop losses there may be underlying socio-economic reasons that explain this resilience to drought and that by identifying these conditions we can identify indicators of ''adaptive capacity'' (or the ''ability to adapt to the anomaly''). To explore trends in crop-drought vulnerability, we contrasted cases, which we call ''resilient'' in that large negative rainfall anomalies (i.e. droughts) were not associated with negative crop anomalies (i.e. harvest losses), with the reverse situation, so-called ''sensitive'' cases where minor droughts were associated with poor harvests. Fig. 1 presents these definitions as a heuristic research framework. To explore trends in crop-drought vulnerability, and to understand the difference between resilience and sensitive cases, we used rainfall, harvest, and socio-economic data from 27 provinces in China, for the period 1961–2001, and conducted the following four steps.

3.1. *Step 1: calculating ''sensitivity'' through a ''crop failure index''*

Provincial scale crop production data for rice, wheat and corn were obtained from the Institute of Geographical Science and

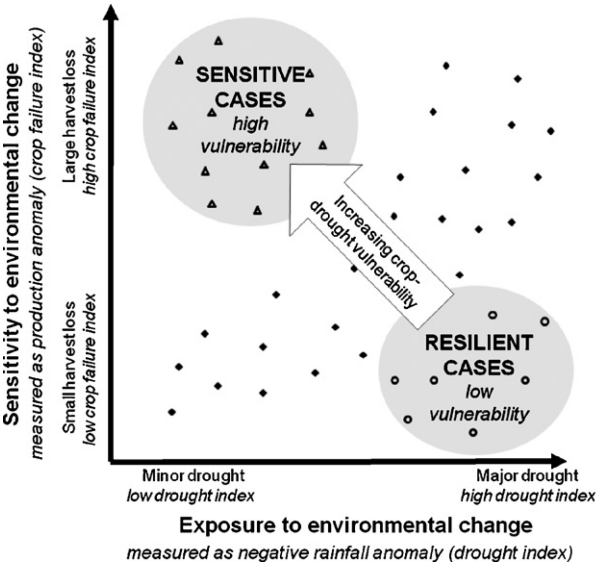

Fig. 1 – Heuristic research framework that stratifies drought events into ''sensitive'' (with a high crop-drought vulnerability) and ''resilient'' (with low crop-drought vulnerability) cases based on the ratio of exposure and sensitivity (here measured as rainfall anomaly and crop production anomaly). Each dot represents a hypothetical drought event where the outliers, that is the sensitive and resilient cases, are represented by triangles and circles respectively. The white arrow indicates increased overall vulnerability to drought.

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Natural Resources at the Chinese Academy of Sciences for the period 1961–2001 (IGSNRR, 2007). To calculate the harvest anomaly, we detrended the yearly harvest data between 1961 and 2001 using an auto-regression function (Schneider and Neumaier, 2001) with 3-year lags in Matlab (version 2007a) software. In effect, this means we studied the period 1964–2001 as the first 3 years are lost in the auto-regression process.

The auto-regression removes the effect of increased technology or consistent mis-reporting, and allowed us to calculate an ''expected'' or ''normal'' harvest, $\hat{H}_i$, for each year, in province *i* (see Eq. (1)). The anomaly was then divided by the actual observed harvest, H_i, to result in an index with a score of one if the actual harvest and the expected harvest were the same, and a score of above one in those years when the harvest was below the expected value. In this paper, we refer to this value as our ''crop failure index''.

3.2. Step 2: calculating ''exposure'' through the ''drought index''

Rainfall data for 1960–2001 was obtained from the Climate Research Unit at the University of East Anglia's TS2.1 dataset which is based on observed weather station data that are averaged over $0.5^\circ \times 0.5^\circ$ grid cells (Mitchell and Jones, 2005). Each grid cell over mainland China was coded by province and analyzed for trends using non-parametric Mann–Kendall test (Gao et al., 2007). The monthly rainfall was detrended per grid then averaged for each province. Given that some months' rainfall are more important than others for crop production, we conducted a paired *t*-test between six different rainfall periods that Cheng (1993) suggests are critical for rice, corn, and wheat production to determine what monthly intervals were most significant. This analysis suggested that a long-term period ending with July of the harvest year and starting from July the previous year (called ''J2J'') explained most of the variance for rice while a spring-drought ''March to May'' explained most of the variance for wheat and corn. This may be because up to three rice harvests are lost if the July to July rainfall is below normal, while two crops of corn or wheat rarely are cultivated in the same year. Both of these rainfall periods have significant linear and quadratic correlations with harvests for all three crops ($p < 0.001$, Spearman correlation coefficient for linear 0.793 with $n = 1056$ for rice, -0.356 with $n = 1101$ for wheat, and -0.375 with $n = 1013$ for corn), where extremely low and high rainfall sums correspond with lower harvests.[1] For clarity reasons, we present only the results relating to the July to July period (*J2J*) for all three crops in this paper. Then, using the accumulated rainfall for *J2J* for all three grain crops, we identified those years in which the rainfall was significantly higher or lower than normal by modifying a rainfall anomaly index (van Rooy, 1965) where the average amount of rainfall, $\bar{R}_i$, for the *J2J* period in province *i* was divided by the ''actual'' amount of rainfall, R_i, that fell during *J2J* in that year (see Eq. (1)). This returns a score of one for a year in which the actual rainfall and the average rainfall equalled each other, and a score of above one for dry years.

3.3. Step 3: identifying adaptive capacity by calculating a ''crop-drought vulnerability index''

For each province and each year, the crop failure index for each crop (rice, wheat and corn) was divided by the drought index. This resulted in a ''crop-drought vulnerability index'' (referred to as the vulnerability index) where a high number indicates that crop failure is high relative to the rainfall anomaly. This is shown in Eq. (1).

$$\text{crop-drought vulnerability index} = \frac{\text{crop failure index}}{\text{drought index}} = \frac{(\hat{H}_i/H_i)}{(\bar{R}_i/R_i)} \tag{1}$$

3.4. Step 4: identifying the socio-economic characteristics of vulnerability

There were three analytical aspects to this step. The first was to identify what provinces had statistically higher/lower vulnerability index scores. The second was to determine what provinces, if any, had a statistically significant trend in vulnerability over time. The third was to determine the characteristics of the resilient and sensitive cases, thereby identifying what socio-economic factors were significant in explaining the vulnerability index.

To identify provinces with statistically different vulnerability indices, we used a one-way analysis of variance (ANOVA) that determined statistically significant differences between provinces in each of the three grain crops' vulnerability index and a subsequent post hoc Duncan pair-wise comparison that divided rice, wheat, and corn vulnerability indexes into a number of overlapping groups. Time trend tests for the vulnerability index were estimated by linear regression on provincial scale and as a national mean for each crop.

To separate sensitive from resilient cases we extracted two sets of data points, one representing evidence of resilient cases and the other representing sensitive cases. We defined ''resilient'' cases as years and provinces where the harvest index was below the first quartile and where rainfall was above the third quartile, i.e. those provinces and years when relatively severe droughts occurred with relatively good harvests. ''Sensitive'' cases were defined as a crop failure index above the third quartile and a drought index between the first and third quartiles, i.e. occurring when harvests were poor while rainfall was relatively normal. The ranking of harvests and rainfall into quartiles was performed on a provincial scale, thus giving each province the same chance for the combination of sensitive, resilient, or disregarded cases. Having identified years and provinces that were statistically more ''vulnerable'' we used secondary statistical data sets available from the Institute of Geographical Sciences and Natural Resources Research (IGSNRR, 2007) to explore what socio-economic variables were significantly correlated with the vulnerability scores in resilient versus sensitive cases. Socio-economic indicators were grouped into five major

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[1] Four other rainfall periods had similar to or poorer correlation results than *J2J* and March to May: (1) July to November in harvest year, (2) December to January, (3) June to August, and (4) April of the harvest year and September of the previous year (these are the two single months that provided the strongest overall correlation with crop harvests).

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categories related to land, population, technical inputs, economic inputs and infrastructure. The socio-economic statistical data were analyzed in two ways: (1) as absolute values to characterise factors that have changed significantly over time, and (2) as standardised anomalies (Fanfani and Brasili, 2003), whereby yearly values were subtracted from the mean values for all years and the resulting difference was divided by the standard deviation of all years to enable cross country comparisons. These types of data were used as independent variables to explain variance in the vulnerability index for each crop and for those provinces/regions and years where harvests were resilient/sensitive to drought. Non-parametric Spearman two-tailed bivariate correlation (Ligon and Schechter, 2004) analyses were used to test the statistical significance between the vulnerability index and the socio-economic indicators as this method does not make assumptions about the distribution of data. The significance level is set to 0.05 for all statistical analyses and only statistically significant results are highlighted and discussed.

3.5. *Data quality issues*

This study excludes analyses of occurrences of pests and diseases, improved crop varieties, environmental degradation, and influences of rainfall intensity and other meteorological changes on harvests. Furthermore, we were unable to derive reliable provincial scale proxy data indicating access to agricultural inputs or health/education status that possibly could help explaining intra/inter-provincial variations. Unavoidably, the coverage of the variables is also inconsistent. The information for technical inputs (such as fertiliser, irrigation or machinery) and economic investments are not specified for a certain crop or farm size. It is also vital to note that we are aware that the results of this analysis can never be better than quality of the data and Chinese official statistics need to be considered with great caution. For example, reconstructions of national total cropland areas suggest State Statistical Bureau data for 1990–1995 is systematically underestimated by 45% and data from Ministry of Land and Resources for 1996–2000 by 10% (Liu et al., 2005). Earlier estimates are more uncertain, and the degree of underreporting likely to be higher in poorer provinces (Smil, 1995). This means that crop yields are almost certainly overestimated. To minimize these problems we have focused on grain harvests (production) rather than yields (productivity) that crop modelling studies have tended to focus upon (Erda et al., 2005; Tao et al., 2006). This is because yield statistics add potential errors from both crop area and harvests. Also, while harvests show the actual outcome, which is relevant for food security, 'yield' may hide areas that have been taken out of cultivation or may be misinterpreted if farmers are producing more than one crop per year (i.e. ''double cropping'') (Kumar et al., 2004). Furthermore, Chinese agriculture is characterised by small plots and perhaps as much as 60–80% of grain production between 1955 and 1995 was for subsistence consumption (Wang and Davis, 2000). These data are not included in official statistics. As a result, we are conscious that vulnerability patterns may look different had home-consumed harvests been included and are planning as the next phase of this research to look in much greater detail at the county level for key provinces. Rural population, and data on the rural labour force in particular, is also assumed to be overestimated as migrating workers frequently remain ''officially'' resident in their home village (Xu et al., 2006). Furthermore the definitions for 'agricultural' and 'rural' have been inconsistent over time (Fanfani and Brasili, 2003) adding other possible problems to the data.

To reduce the impact of chronic over- and under-reporting we de-trended harvest data using a 3-year lag auto-correlation function. To explore the potential influence of economic transition, we cross-checked the standardised relations for all years with those for 1995–2001, during which the statistics is believed to have a higher accuracy, and this demonstrated very similar results for the sensitive cases, while there were too few resilient cases to enable a comparison (not shown). Given these issues, however, we are aware that our results are preliminary and they form part of an on-going research project in which we are working to triangulate the analysis through on-the-ground field work involving collaborations with Chinese research centres with regional expertise. We also plan to expand this analysis to other exposed parts of the world (notably Sub-Saharan Africa) to see if the trends observed here are confirmed elsewhere.

4. Results

The results are divided into three sections. The patterns of crop vulnerability are first examined spatially across China, then as a trend over time. Finally, we identify the socio-economic characteristics of sensitive and resilient cases.

4.1. *Spatial patterns in crop-drought vulnerability*

Across all three crops, provinces with a high mean vulnerability index and high frequency of vulnerable cases, were predominantly located in southern and/or coastal regions. More specifically, when the vulnerability scores were analyzed using a Duncan Pair-wise test, rice vulnerability was divided into five partly overlapping groups of provinces, and corn and wheat into six partly overlapping categories (results for corn are given in Fig. 2). For rice, Heilongjiang in the northeast and Gansu in the west had the lowest mean vulnerability while provinces in the north had the highest. This contrasted with wheat crops, where provinces on the North China Plain had a low mean vulnerability while some northeastern and southwestern provinces had the highest vulnerability. In terms of corn, Ningxia in the west together with Hubei, Guizhou and Hunan the south central had a low vulnerability while a number of provinces along the coast had a higher mean vulnerability score.

4.2. *Temporal trends in crop-drought vulnerability*

Between the 1960s and 2000, a period of time marked by rapid urbanization and a large scale shift from agriculture to urban industry, the overall mean crop-drought vulnerability index decreased significantly suggesting that Chinese crops are better buffered against low rainfall today than they were in the 1960s

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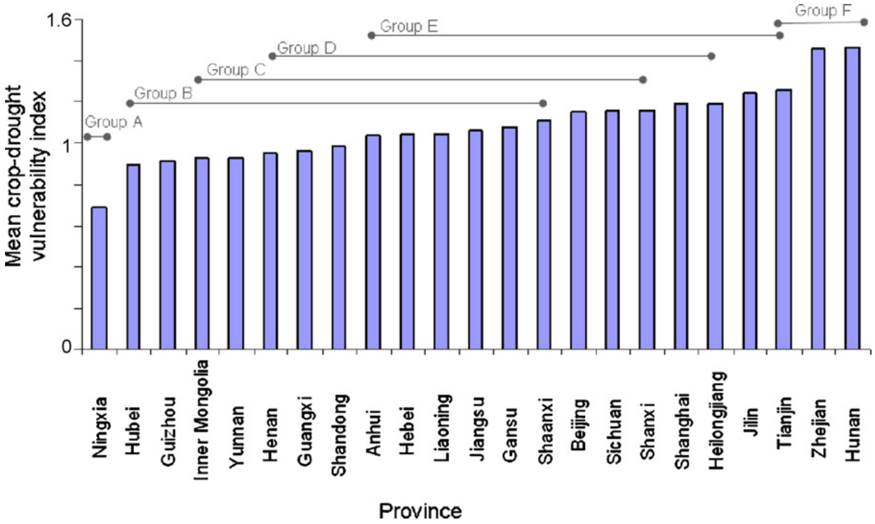

Fig. 2 – Mean provincial crop-drought vulnerability index (1961–2001) for corn harvests. High numbers suggest that corn harvests were more sensitive to rainfall anomalies (drier years) than low numbers. Overall, an analysis of variance indicates that vulnerability varied significantly between provinces ($p < 0.05$). A Duncan pair-wise comparison test placed provinces into six (a–f) statistically significant groups.

($p < 0.05$). At the regional scale, the vulnerability of harvests decreased in growing seasons with below normal rainfall in the north (where the area planted to wheat has declined) for all three crops, and in the west for wheat and corn, in the northeast for rice and on the North China Plain for wheat ($p < 0.05$). On the provincial scale, however, increases in the crop-drought vulnerability for all three grain crops occurred in parts of the rapidly urbanising central coastal zone (in particular Shanghai for rice and Jiangxi for wheat, $p < 0.05$). In addition, the vulnerability index increased for rice in the western provinces, for wheat in parts of the northwest and the south coast (where the amount of land used to produce two crops/year has increased), and for corn in parts of the north and the western regions. Fig. 3 provides a breakdown of these changes in vulnerability by province for each of the three grain crops.

4.3. *Characteristics of resilient and sensitive cases*

The socio-economic factors that are significantly correlated with the drought-vulnerability index for resilient and sensitive cases are listed in Table 1 together with their correlation coefficients. For rice harvests, resilient cases are found where the available agricultural land area is large and the ''double cropping index'' is high, i.e. more than one harvest per year. Resilient rice cases are also related to a high per capita GDP in agriculture. A number of variables were negatively correlated with vulnerability for sensitive rice cases, but broadly speaking population indicators, which measure the size of the rural population, and economic indicators, which show the degree to which capital has been invested in agriculture, were most important. This contrasts with wheat, where resilient cases were negatively correlated with the double cropping index and supplies of electricity. The vulnerability scores for sensitive wheat cases were explained by a similar range of indicators as for sensitive rice though indicators related to the size of the rural population had a larger (negative) correlation than for rice. For resilient corn, the vulnerability score was positively correlated with the land devoted to agriculture, the amount of machinery used, and two economic indicators, the fixed capital per farmer and percent GDP in agriculture (like for rice, these indicators relate to the capital invested in agriculture). Sensitive corn was negatively correlated with the land devoted to agriculture, the urbanization rate, and indicators dealing with the amount of capital invested in agriculture.

Overall, the categories that influence the vulnerability of sensitive cases are related to land, population and economy, while there are fewer categories influencing the vulnerability for resilient cases (see Supplementary Material).

5. Discussion

5.1. *Implications of results*

Overall, this analysis shows that different provinces display a range of abilities to cope with low rainfall, and while it needs to be stressed that this analysis excludes a number of possible reasons for harvest losses (such as pests or storm damages), a number of trends can be observed. For example, the analyses of spatial trends (Section 4.1) suggest that continental semi-arid and temperate areas are better buffered against the impacts of drought events than coastal and sub-tropical/tropical regions. This may be because farmers in these regions are used to poor or fluctuating rainfall and have already adapted to this sort of problem (see: Liu et al., 2005). Similarly, provinces that display low mean vulnerability, such as Gansu in the west and provinces on the North China Plain, make use of extensive irrigation, so it is likely that these irrigation systems buffer crops against the effects of drought. Some sensitive cases had very small areas allocated to the crop in question. For example, Ningxia, which had high vulnerability in corn planted less than 5% of cultivated land to this crop.

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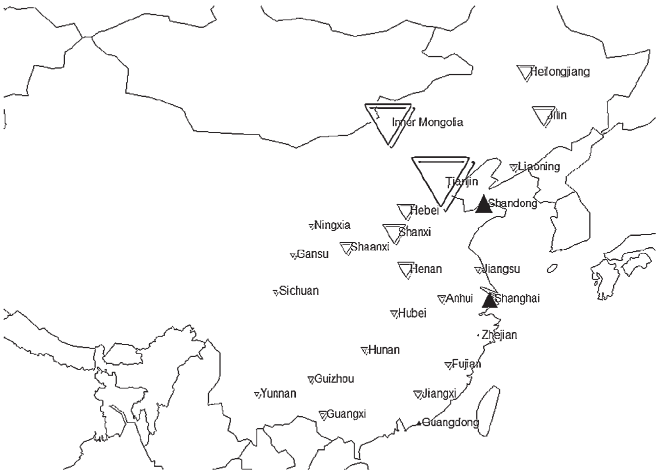
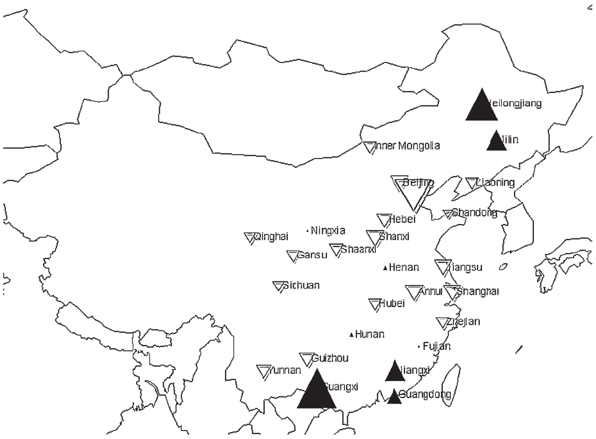
(a) Rice



(b) Wheat



(c) Corn

Fig. 3 – Temporal trends in (a) rice, (b) wheat and (c) corn vulnerability index for each province between 1961 and 2001 when the June-to-July rainfall was below normal. The size of the triangles indicate the slope of the overall trend (large = 0.014, medium = 0.007 and small = 0.0014). Black triangles indicate that the overall vulnerability of crop harvests to rainfall anomalies is increasing. Clear triangles indicate that overall vulnerability is decreasing. The trends are significant ($p < 0.05$) in Inner Mongolia, Liaoning and Tianjin for rice, in Guangdong, Inner Mongolia, Jiangsu, Liaoning, Shanghai and Tianjin for wheat, and in Heilongjiang, Hunan, Jilin, Liaoning and Sichuan for corn.

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Table 1 – Correlation coefficients for provincial scale socio-economic factors that significantly correlate with the crop–climate vulnerability index for sensitive and resilient cases for rice, wheat and corn. Significance at 0.05 level are noted in bold and at 0.01 level in *italics*. The number of data points analyzed (*n*) appears in brackets after the correlation coefficient.

Category	Socio-economic indicator	Rice		Wheat		Corn	
		Resilient	Sensitive	Resilient	Sensitive	Resilient	Sensitive
Land	Total (mu)		**−0.199** (171)		*−0.140* (321)		
	Double cropping index (%)^{b}	*0.249* (67)	*−0.132* (244)	*−0.266* (53)	*−0.137* (250)		
	Agr land (CAS) (mu)	*0.248* (67)	**−0.237** (160)		**−0.283** (191)	*0.260* (34)	**−0.173** (141)
	Total land (CAS) (mu)		**−0.294** (171)		**−0.235** (189)		*−0.209* (151)
Population	Total population (individuals)^{a}		**−0.188** (310)				
	Rural population (individuals)^{a}		*−0.134* (310)		**−0.314** (321)		
	Urbanization rate (%)^{a}		**−0.173** (305)				**−0.257** (267)
	Machinery power (kW)		**−0.164** (310)		**−0.147** (299)	0.263 (63)	
Technical input	Irrigated area (ha)						
	Fertiliser (ton)		*−0.149* (283)		*−0.134* (299)		
	Agr electricity supply (kWh)^{e}		*−0.165* (241)	*−0.277* (54)			
Economy	Agr production capital (Yuan/capita)^{a}		**−0.215** (310)		**−0.143** (321)		
	Fixed capital (Yuan/farmer)^{f}		**−0.393** (310)		**−0.176** (316)	**0.268** (63)	**−0.159** (267)
	Investment in agr (Yuan/capita)^{f}		**−0.200** (310)		**−0.612** (321)		
	GDP in agr (Yuan/capita)^{g}		**−0.200** (310)		**−0.160** (311)		**−0.348** (267)
	GDP in agr cultivation (%)^{h}	0.256 (68)	*−0.145* (300)			**0.374** (60)	**−0.278** (258)
	GDP in other agr activities (%)^{h}		**−0.200** (269)				**−0.207** (267)
	Expenditure (Yuan/capita)^{h}		**−0.182** (279)		**−0.176** (296)		
Infra-structure	Rail density (km/km^{2})^{i}		**−0.163** (242)		**−0.200** (321)		

Unless noted the data covers the whole period. Superscript letters (a–i) indicate that the longest covered period is (a) 1969–2001, (b) 1961–1992, (c) 1995–2001, (d) 1980–2001, (e) 1963–2001, (f) 1982–2001, (g) 1978–2001, (h) 1971–2001, (i) 1978–1997. 1 mu = 0.0.067 ha = 0.1647 acres.

The temporal analysis (Section 4.2) shows that although Chinese grain harvests are not as sensitive to drought today as in the past, there are regions where crop-drought vulnerability has increased. For example, the vulnerability for wheat harvests in the south has risen significantly over time. This may represent a special case, since rainfall there has increased over the period covered by this study and that the share of land area cultivated with wheat is becoming comparatively small. The coincidence of increased crop-drought vulnerability and rainfall may be driven by a switch to more water-demanding crops and a deteriorated irrigation infrastructure that does not conserve the extra water (Tao et al., 2006; Yang, 1998; Yang et al., 2007). On the other hand, the north, which has also had significant rises in vulnerability of wheat has experienced both mean annual warming and reduced rainfall (Gao et al., 2007) suggesting that remaining wheat farmers have not adapted well to these new climatic conditions. The exception to this is found in the northeast, where new rice varieties have been promoted as a direct response to the temperature increases (Yang et al., 2007). As a result, while the vulnerability of wheat increased, for rice it was reduced. This suggests that changing crops was an appropriate adaptation strategy.

In terms of our analysis of the socio-economic characteristics that define resilient and sensitive cases, there are two critical points. The first is that two categories of socio-economic indicators are correlated with the crop-drought vulnerability index for all three crops, suggesting that land use patterns (double cropping or amount of agricultural land) and economic factors (GDP) are consistently associated with crop-drought vulnerability across China. Second, the socio-economic factors that explain vulnerability differ radically between ''resilient'' and ''sensitive'' cases. In other words, although changes in different socio-economic factors may have a relatively similar effect on rice, wheat and corn harvests, the effect on vulnerability depends on whether the farming system is already resilient or sensitive to changing rainfall patterns.

Socio-economic indicators related to land, labour and economic inputs are significantly associated with reduced vulnerability in sensitive farming systems. More specifically, the results suggest that setting aside more land for farming, or increasing investment opportunities in agriculture (e.g. through state funds for extension service or decentralised agri-businesses), can help buffer all three sensitive crops from drought. In the case of already resilient rice and corn, however, more capital invested in agriculture is associated with increases in crop-drought vulnerability. This may be because as an area becomes richer, farmers are able to invest in agricultural technology to reduce risks associated with drought but beyond a certain level of capitalization they start planting more water-demanding crops and over-exploiting water supplies, thus increasing vulnerability (e.g. Yang et al., 2007). The positive correlations between vulnerability and socio-economic variables could also indicate that certain factors can be used more efficiently such as reducing vulnerability for resilient rice and corn by double cropping. Testing this sort of specific hypothesis, however, is beyond the scope of this paper and is identified as a key area for further field-based investigation. For instance, field work is now being planned to develop methods to determine the resilient/sensitive status of farming systems as this is expect to provide

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valuable information for modelling the actual likely impact of climate change on crop yields (Challinor, this issue).

5.2. *Proposed typology of crop-drought vulnerability*

We believe that our findings, and their links to field-based studies, allow us to propose a broad-strokes synthesis of crop-drought vulnerability. Specifically, our results suggest that that regions in China are likely to be sensitive to drought if they: (1) are economically poor and with considerable climatic hardship and topographic constraints (e.g. west and southwest) or (2) if they have a limited amount of agricultural land near industrialised/near-urban regions and an oversupply of rural labour (e.g. coastal region). By contrast, ‘‘resilient’’ cases have (1) higher levels of capital investments in agriculture (e.g. northeast), (2) modest urbanization rates and (3) rising rates of land intensification (e.g. northeast, west). These overall patterns resemble the insights that Fanfani and Brasili (2003) derived from their analysis of how the area sown, agricultural labour and education levels all affect agricultural productivity. These broad types of vulnerability also resonates with early work by Bray (1986) that characterises different economic systems based on whether land is scarce and labour intensive (‘‘rice economies’’), land is abundant (like the agricultural frontier in North America) or where both land and labour are expensive (e.g. intensive agriculture in Europe).

Building on this, we suggest there are generic socio-economic strategies that should reduce vulnerability across a range of cases. Firstly, these strategies need, however, be different in regions that are already sensitive versus areas that are already resilient. For example, in most sensitive areas, policies that promote capital investments into basic agricultural inputs (fertiliser and machinery), extension services and agri-business development should reduce crop-drought vulnerability. For resilient areas, however, policies to reduce crop-drought vulnerability include limiting urban expansion on high-quality agricultural land and improving access to more sophisticated technical inputs (machinery and electricity).

Secondly, policies to reduce vulnerability need to be dynamic in order to respond to changes in the regional economy. This is especially important for a country in economic transition, like China, where measures that will help reduce vulnerability today will be very different in the future as agricultural technological standards develop. As a result, we agree with Fanfani and Brasili (2003) that the traditional regionalisation of Chinese provinces into north, south and west or into regions that produce wheat, grain and corn is insufficient. This is vital because drought vulnerability is fundamentally driven by different factors in already ‘‘sensitive’’ and ‘‘resilient’’ regions. Hence, the same policy may either increase or decrease vulnerability depending on the nature of the local economy, demography and climatic conditions and trends.

To help guide the policy process, we cautiously draw from our results and present a preliminary typology that we suggest explains crop-drought vulnerability in China based on socio-economic factors that seem to limit adaptation (Table 2). Different types of vulnerability seem to occur when:

- *Labour limits adaptation to drought*. This would be typical of the northeast of China (Yang et al., 2007; Zhang et al., 2008) and in this sort of region, a key strategy to reduce vulnerability is through capital investments that would upgrade agricultural technology and possibly increase double cropping with more drought-tolerant crop varieties. This would make more effective use of available labour and help buffer harvests against drought.
- *Land limits adaptability*. This type of vulnerability is represented in the resilient wheat cases in the northeast and sensitive rice growing areas of the North China Plain where technical inputs such as increasing access to irrigation and fertilisers as well as an increasing rural populations reduce vulnerability to drought, but may have serious negative environmental impacts (Zhai et al., 1999). This type of vulnerability seems to overlap with urbanising areas, hence when land becomes too limited, improved water harvesting methods may be required to reduce the vulnerability to drought.
- *Land and labour are limited but there is financial capital available*. In these cases, which include rice production in the south, increases in population and double cropping buffer harvests against low rainfall and strategies to reduce vulnerability further would be to use technological inputs such as fertiliser or fast growing varieties to make production more intensive. Although rice productivity is constrained by small plots and low levels of technology in the south (Yang, 1998), we assume that when the household economy increases, farmers may invest in other crops. Hiring seasonal temporary labour may also offer a more flexible solution to drought.
- *Land and capital are limiting*. In regions belonging to this type of vulnerability (e.g. sensitive wheat cases in all but the southern region) deploying labour more effectively may be a key strategy to reduce vulnerability. This could involve using labour to produce annual crops on flatlands more intensively, while extending conservation agriculture on sloping land and targeting investments so that research reaches farmers through agricultural extension services and short training courses on subject such as water-harvesting methods (Zhang et al., 2007) and integrated pest and fertiliser management.
- *Land, labour and capital are all limited*. This is more typical for certain parts of southern China, particularly for sensitive wheat cases and in north for sensitive rice cases. The location of these crops on their southern and northern limits, suggest that climate (in particular temperature) may be one limiting factor (Song et al., 2005; Tao et al., 2006). Here, preventing out-migration, continuing programmes of land intensification and making capital available for investment may all reduce vulnerability. Investing in extension services that aid climate, environmentally and market adaptable farming systems is a key adaptation strategy in such areas.
- *Capital is limiting*. This type was found for a number of resilient rice and corn regions. Many provinces in north fall into this type because land areas are less constrained, the area devoted to these crops is small, or there is a high degree of state farms that have a better capacity to adopt new technology (Huang, 2002; Wang and Davis, 2000). However, this is not to say that these cases provide a template for a

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Table 2 – Generic "vulnerability typology" that shows how different socio-economic factors will influence crop–climate vulnerability at regional scale. The term 'limiting factor' is used to denote factors negatively correlated with crop-drought vulnerability ($p < 0.05$), such that an increase of this variable should reduce crop vulnerability to low rainfall (see Supplementary Material). Types 2 and 8 were not identified in this study and exploring these types of vulnerability represents an obvious next step in this research. The provinces have been merged into the following regions: NCP = North China Plain, N = north, NE = northeast, W = west, SE = southeast, SW = southwest. See further explanation in the text.

Type of vulnerability	Limiting resources to reduce vulnerability	Identified region for crop			Key socio-economic indicator to reduce vulnerability	Possible strategies to reduce crop-drought vulnerability
		Rice	Wheat	Corn		
1	Land, labour and capital all limiting	N	SE, SW		Increased capital investment, land loss (rice and wheat); population (wheat). Sensitive wheat is particularly technically limited	More effective land use, improve extension service to disseminate technologies, capital investments.
2	Labour and capital				No cases of this type were found in our analysis	
3	Land and capital		NE, N, NCP, W		Increased fertiliser, rail density, per capita investments in agriculture and expenditure per capita. Reduced number of rural households	Create incentives to increase on-farm labour.
4	Capital	W, N, NCP		SW, NE, NCP	Increased capital investment	Although only capital seems to improve this in terms of drought-resilience, there may be other serious problems associated with agriculture such as unsustainable water use, pollution, and habitat loss. Hence before policy makers start using these regions as a template, these other issues should be investigated
5	Land and labour	SE, SW			Increased population, double cropping (resilient rice), infrastructure (sensitive rice)	Capital investments in agricultural management
6	Labour	NE			Increased rural labour	Increase efficiency of available labour and invest capital in upgrading agricultural technology (e.g. machinery)
7	Land	NCP	NE	SE, SW	Increased capital investments, technical inputs; reduced investments in other agricultural activities (all three crops), infrastructure (wheat and corn), double cropping (corn)	Labour or capital investments to intensify land use through irrigation, fertilisers, or terracing
8	None limiting				No cases of this type were found in our analysis	

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resilient farming system since there are indications (e.g. Ma et al., 2006) that some practises are unsustainable in the long-term.

By combining land, labour and capital limited areas we can conceptualize eight generic types of vulnerability to drought (Table 2). As a region's economy, demography or land base changes, however, it is further possible to imagine a pathway from one type of vulnerability to another. More work is needed to further refine the analysis and interpret the results into a more robust typology. This will be done in the next phase of this research by triangulating results obtained at different scales and by exploring more climate change related problems than just droughts. For example, vulnerability to drought coexists with vulnerability to other environmental stresses, and preparing for one type of environmental stress may require trade-offs between resilience and adaptedness to other stresses (Nelson et al., 2007). Such an understanding is crucial for a range of applications. First, this type of analysis provides a tool that can help inform stakeholder discussions on ways to plan, and later monitor, their actions to deal with environmental change. Implementing such policies requires close collaboration across administrative borders to more specifically identify the characteristics of the vulnerability to drought, and prioritise its importance among exposures to other types of environmental changes. Second, crop scientists who model the impacts of climate change (e.g. Osborne et al., 2006; Xiong et al., 2007) need quantifiable parameters as a measure of vulnerability dynamics in order to simulate potential and more realistic yields and to determine different levels of likelihood that farmers will have access to (and actually use) new management practices. As such, this typology presents one way of showing how human dimensions can be better incorporated into crop–climate models. Since farmers have a tremendous capacity to adapt to societal as well as environmental challenges, improving our awareness on how underlying socio-economic processes affect the extent to which agriculture and food production are vulnerable to these changes is crucial.

6. Conclusions

In this paper, agricultural and meteorological records for Chinese provinces were used to identify the socio-economic characteristics of rice, wheat, and corn producing provinces that make their harvests ''sensitive'' or ''resilient'' to rainfall anomalies. The vulnerability to drought was quantified by a crop-drought vulnerability index and correlated with socio-economic factors representing land, labour, technical and economic inputs. Most clearly, we found that economic investments in rural areas generally correlate with reduced vulnerability where harvests were sensitive to droughts. For resilient harvests however, these same factors had no, or the opposite, correlation. Vulnerability to drought seems, therefore, related to underlying population economic, and land-use factors.

Based on these results, we argued that land, labour and capital/technical inputs can be used to define eight different ''types'' of vulnerability and that in each type of vulnerability there will be different strategies to reduce the vulnerability of crops to drought. It is vital to realize, however, that as a region changes in terms of its economy, land use and population, it may move from one ''type'' of vulnerability to another, and different factors will become more or less important in terms of determining vulnerability. This led us to propose the concept of ''crop-drought vulnerability typology'', as a concept that can be of use to both policy makers trying to determine appropriate strategies to reduce climate vulnerability, as well as to crop–climate modellers who need ways of including socio-economic factors in crop models to reduce the uncertainty in yield projections.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.envsci.2008.11.005.

REFERENCES

Adger, W.N., 1999. Social vulnerability to climate change and extremes in coastal Vietnam. World Development 27 (2), 249–269.

Adger, W.N., 2006. Vulnerability. Global Environmental Change 16 (3), 268.

Alcamo, J., Endejan, M., Kaspar, F., Rosch, T., 2001. The GLASS model: a strategy for quantifying global environmental security. Environmental Science and Policy 4, 1–12.

Awosika, L., Diop, E.S., Downing, T.E., El-Raey, M., Le Sueur, D., Magadza, C.H.D., Tour, S., Vogel, C., 1998. Chapter 2: Africa. In: Watson, R., Zinyowera, M., Moss, R., Dokken, D. (Eds.), IPCC Special Report on the Regional Impacts of Climate Change An Assessment of Vulnerability. UNEP, WMO (http://www.ipcc.ch/ipccreports/sres/regional/006.htm accessed: 19th July, 2008).

Bouman, B.A.M., Feng, L., Tuong, T.P., Lu, G., Wang, H., Feng, Y., 2007. Exploring options to grow rice using less water in northern China using a modelling approach II. Quantifying yield, water balance components, and water productivity. Agricultural Water Management 88, 23–33.

Bray, F., 1986. The Rice Economies. Basil Blackwell, Oxford.

Brooks, N., Adger, W.N., Kelly, P.M., 2005. The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. Global Environmental Change Part A 15 (2), 151.

Challinor, A. Towards the development of adaptation options using climate and crop yield forecasting at seasonal to multi-decadal timescales. Environmental Science and Policy, doi:10.1016/j.envsci.2008.09.008, this issue.

Cheng, C., 1993. Climate and agriculture in China. Foreign Language Book No. 108. China Meteorological Press, Beijing, 519 pp.

Comenetz, J., Caviedes, C., 2002. Climate variability, political crises, and historical population displacements in Ethiopia. Global Environmental Change Part B: Environmental Hazards 4 (4), 113–127.

Corbett, J., 1988. Famine and household coping strategies. World Development 16 (9), 1099–1112.

Cruz, R.V., Harasawa, H., Lal, M., Wu, S., Anokhin, Y., Punsalmaa, B., Honda, Y., Jafari, M., Li, C., Huu Ninh, N., 2007. Asia. In: Canziani, O.F., Parry, M.L., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 469–506.

Easterling, W.E., Aggarwal, P.K., Batima, P., Brander, K.M., Erda, L., Howden, S.M., Kirilenko, A., Morton, J., Soussan, J.-F, Schmidhuber, J., Tubiello, F.N., 2007. Food, fibre and forest products. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., Linden, P.J.v.d., Hanson, C.E. (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 273–313.

Erda, L., Wei, X., Hui, J., Xu, Y., Li, Y., Bai, L., Xie, L., 2005. Climate change impacts on crop yield and quality with CO_2 fertilization in China. Philosophical Transactions of the Royal Society B 360, 2149–2154.

Ericksen, P., 2008. Conceptualizing food systems for global environmental change research. Global Environmental Change 18 (1), 234–245.

Fanfani, R., Brasili, C., 2003. Regional differences in Chinese agriculture: results from the 1997 first national agricultural census. Journal of Peasant Studies 30 (3), 18–44.

Feng, L., Bouman, B.A.M., Tuong, T.P., Cabangon, R.J., Li, Y., Lu, G., Feng, Y., 2007. Exploring options to grow rice using less water in northern China using a modelling approach I. Field experiments and model evaluation. Agricultural Water Management 88, 1–13.

Ford, J.D., Smit, B., Wandel, J., 2006. Vulnerability to climate change in the Arctic: a case study from Arctic Bay, Canada. Global Environmental Change 16 (2), 145.

Fraser, E., 2003. Social vulnerability and ecological fragility: building bridges between social and natural sciences using the Irish Potato Famine as a case study. Conservation Ecology 7 (1), 9.

Fraser, E., 2006. Agro-ecosystem vulnerability. Using past famines to help understand adaptation to future problems in today's global agri-food system. Journal of Ecological Complexity 3 (4), 328–335.

Fraser, E., 2007. Travelling in antique lands: studying past famines to understand present vulnerabilities to climate change. Climate Change 83 (4), 495–514.

Gao, G., Chen, D., Xu, C.-Y., Simelton, E., 2007. Trend of estimated actual evapotranspiration over China. Journal of Geophysical Research 112 , doi:10.1029/2006JD008010.

Green, R., 1993. The political economy of drought in Southern Africa 1991–1993. Health Policy and Planning 8 (3), 256–266.

Heistermann, M., Müller, C., Ronneberger, K., 2006. Land in sight? Achievements, deficits and potentials of continental to global scale land-use modeling. Agriculture Ecosystems and Environment 114, 141–158.

Hitchcock, R.K., 2002. Coping with uncertainty: adaptive responses to drought and livestock disease in the Northern Kalahari. In: Sporton, D., Thomas, D.S.G. (Eds.), Sustainable Livelihoods in Kalahari Environments. Oxford University Press, Oxford, UK, pp. 221–236.

Huang, Y., 2002. State Grain Marketing Policy and Farmer Behaviour. Asia Pacific Press (http://ncdsnet.anu.edu.au).

IGSNRR, 2007. Chinese Natural Resources Database. Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences (http://www.naturalresources.csdb.cn/index.asp).

Intergovernmental Panel on Climate Change (IPCC), 2007. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

Kasperson, J., Kasperson, R., Turner, B., 1995. Regions at Risk. United Nations University Press, Tokyo.

Kumar, K.K., Kumar, R.K., Ashrit, R.G., Deshpande, N.R., Hansen, J.W., 2004. Climate impacts on Indian agriculture. International Journal of Climatology 24, 1375–1393.

Ligon, E., Schechter, L., 2004. Evaluating Different Approaches to Estimating Vulnerability, Social Protection Unit, Human Development Network. The World Bank.

Liu, J., Liu, M., Tian, H., Zhuang, D., Zhang, Z., Zhang, W., Tang, X., Deng, X., 2005. Spatial and temporal patterns of China's cropland during 1990–2000: an analysis based on Landsat TM data. Remote Sensing of Environment 98, 442–456.

Long, S.P., Ainsworth, E.A., Rogers, A., Ort, D.R., 2004. Rising atmospheric carbon dioxide: plants FACE the future. Annual Review of Plant Biology 55, 591–628.

Ma, J., Hoeckstra, A.J., Wang, H., Chapagain, A.K., Wang, D., 2006. Virtual versus real water transfers in China. Philosophical Transactions of the Royal Society B 361, 835–842.

Mendelsohn, R., 2007. Measuring climate impacts with cross-sectional analysis. Climatic Change 81 (1), 1–7.

Mendelsohn, R., Basist, A., Kurukulasuriya, P., Dinar, A., 2007. Climate and rural income. Climatic Change 81 (1), 101.

Mendelsohn, R., Reinsborough, M., 2007. A Ricardian analysis of US and Canadian farmland. Climatic Change 81 (1), 9–16.

Mitchell, T.D., Jones, P.D., 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. International Journal of Climatology 25, 693–712.

Mustafa, D., 1998. Structural causes of vulnerability to flood hazard in Pakistan. Economic Geography 74 (3), 289–305.

Nelson, D.R., Adger, N., Brown, K., 2007. Adaptation to environmental change: contributions of a resilience framework. The Annual Review of Environment and Resources 32, 395–419.

Nicholls, R.J., Hoozemans, F.M.J., 1996. The Mediterranean: vulnerability to coastal implications of climate change. Ocean & Coastal Management 31 (2–3), 105–132.

Osborne, T.M., Lawrence, D.M., Challinor, A.J., Slingo, J.M., Wheeler, T.R., 2006. Development and assessment of a coupled crop–climate model. Global Change Biology 12, 1–15.

Patt, A., Gwata, C., 2004. Effects of seasonal climate forecasts and participatory workshops among subsistence farmers in

Please cite this article in press as: Simelton, E., et al., Typologies of crop-drought vulnerability: an empirical analysis of the socio-economic factors that influence the sensitivity and resilience to drought of three major food crops in China (1961–2001). Environ. Sci. Policy (2009), doi:10.1016/j.envsci.2008.11.005

Zimbabwe. Proceeding of the National Academy of Science 102 (35), 12623–12628.

Patt, A., Siebenhüner, B., 2005. Agent based modeling and adaptation to climate change. Vierteljahrshefte zur Wirtschaftsforschung 74 (2), 310–320.

Reed, M., Fraser, E., Dougill, A.J., 2006. An adaptive learning process for developing and applying sustainability indicators with local communities. Ecological Economics 59 (4), 406–418.

Reidsma, P., Ewert, F., Lansink, A.O., 2007. Analysis of farm performance in Europe under different climatic and management conditions to improve understanding of adaptive capacity. Climate Change 84, 403–422.

Rook, J., 1997. The SADC regional early warning system: experience gained and lessons learnt from the 1991–1992 Southern Africa drought. Internet Journal for African Studies 2 (available online at: http://www.ccb.ucar.edu/ijas/ijasno2/rook.html).

Schlenker, W., Hanemann, W., Fisher, A., 2007. Water availability, degree days, and the potential impact of climate change on irrigated agriculture in California. Climatic Change 81 (1), 19–26.

Schneider, T., Neumaier, A., 2001. Algorithm 808: ARfit—a Matlab package for the estimation of parameters and eigenmodes of multivariate autoregressive models. ACM Transactions on Mathematical Software 27 (1), 58–65.

Sen, A., 1981. Poverty and Famines. Claredon Press, Oxford.

Simelton, E., 2007. Climate and human impacts on wheat production and land use in the Loess Plateau region, China. Earth Sciences Centre A115. Ph.D. thesis. Göteborg University, Göteborg.

Smil, V., 1995. Who will feed China? The China Quarterly 801–813.

Song, Y., Simelton, E., Chen, D., Dong, W., 2005. Influence of climate change on winter wheat growth in North China during 1950–2000. ACTA Meteorologica Sinica 19 (4), 501–510.

Sullivan, C., Meigh, J., 2005. Targeting attention on local vulnerabilities using an integrated index approach: the example of the climate vulnerability index. Water Science and Technology 51 (5), 69–78.

Tao, F., Yokozawa, M., Xu, Y., Hayashi, Y., Zhang, Z., 2006. Climate changes and trends in phenology and yields of field crops in China 1981–2000. Agricultural and Forest Meteorology 138, 82–92.

Thomas, D.S.G., Twyman, C., 2005. Equity and justice in climate change adaptation amongst natural-resource-dependent societies. Global Environmental Change Part A 15 (2), 115.

Thomas, D.S.G., Twyman, C., Osbahr, H., Hewitson, B., 2007. Adaptation to climate change and variability: farmer responses to intra-seasonal precipitation trends in South Africa. Climatic Change 83, 310–322.

Thomson, A.M., Izaurralde, R.C., Rosenberg, N.J., He, X., 2006. Climate change impacts on agriculture and carbon sequestration potential in the Huang-Hai Plain of China. Agriculture Ecosystems and Environment 114 (2–4), 195–209.

Thornton, P.K., Jones, P.G., Owiyo, T., Kruska, R.L., Herrero, M., Kristjanson, P., Notenbaert, A., Bekele, N., Omolo, A., with contributions from Orindi, V., Ochieng, A., Otiende, B., Bhadwal, S., Anantram, K., Nair, S., Kumar, V., Kelkar, U., 2006. Mapping climate vulnerability and poverty in Africa. Report to the Department for International Development, ILRI, Nairobi, Kenya, May 2006, 200 pp. (online at http://www.dfid.gov.uk/research/mapping-climate.pdf).

Tompkins, E., 2005. Planning for climate change in small islands: insights from national hurricane preparedness in the Cayman Islands. Global Environmental Change 15, 139–149.

Turner, B.L., Kasperson, R.E., Matson, P.A., McCarthy, J.J., Corell, R.W., Christensen, L., Eckley, N., Kasperson, J.X., Luers, A., Martello, M.L., Polsky, C., Pulsipher, A., Schiller, A., 2003. A framework for vulnerability analysis in sustainability science. Proceedings of the National Academy of Sciences of the United States of America 100 (14), 8074–8079.

van Rooy, M.P., 1965. A rainfall anomaly index independent of time and space. NOTOS. Weather Bureau of South Africa 14, 43–48.

Wang, L., Davis, J., 2000. China's grain economy. In: The Challenge of Feeding More than a Billion, Ashgate Publishing Ltd., Aldershot, 256 pp.

Watts, M., Bohle, H., 1993. The space of vulnerability: the causal structure of hunger and famine. Progress in Human Geography 17 (1), 43–67.

Wu, S.Y., Yarnal, B., Fisher, A., 2002. Vulnerability of coastal communities to sea-level rise: a case study of Cape May County, New Jersey, USA. Climate Research 22 (3), 255–270.

Xiong, W., Lin, E., Ju, H., Xu, Y., 2007. Climate change and critical thresholds in China's food security. Climatic Change 81, 205–221.

Xu, Z., Xu, J., Deng, X., Huang, J., Uchida, E., Rozelle, S., 2006. Grain for green versus grain: conflict between food security and conservation set-aside in China. World Development 34 (1), 130–148.

Yang, H., 1998. Trends in China's regional grain production and their implications. Agricultural Economics 19, 309–325.

Yang, X., Lin, E., Ma, S., Ju, H., Guo, L., Xiong, W., Xu, Y., 2007. Adaptation of agriculture to warming in Northeast China. Climatic Change 84 (1), 45.

Zhai, P., Sun, A., Ren, F., Liu, X., Gao, B., Zhang, Q., 1999. Changes of climate extremes in China. Climatic Change 42 (1), 203.

Zhang, S., Simelton, E., Lövdahl, L., Grip, H., Chen, D., 2007. Simulated long-term effects of different soil management regimes on the water balance in the Loess Plateau, China. Field Crops Research 100, 311–319.

Zhang, T., Zhu, J., Yang, X., Zhang, X., 2008. Correlation changes between rice yields in North and Northwest China and ENSO from 1960 to 2004. Agricultural and Forest Meteorology, doi:10.1016/J.AGRFORMET.2008/01.018.

Zhang, X., 2003. A comparative study of projection models on China's food economy. Journal of Peasant Studies 30 (3), 192–223.

Zhen, L., Xie, G., Yang, L., Cheng, S., 2007. Land use dynamics, farmers' preferences and policy implications in the Jinghe watershed of remote north-western China. Outlook on Agriculture 36 (2), 127–135.

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