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Risk assessment of drought disaster in the maize-growing region of Songliao Plain, China

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Abstract

This study presents a methodology for risk analysis and assessment of drought disaster to agricultural production in the maize-growing area of Songliao Plain of China based on Geographical Information Systems (GIS) from the viewpoints of climatology, geography, disaster science, and environmental science and so on. Crop yield–climate analysis and regression analysis were employed to analyze and quantify relationships between the fluctuation of maize yield and agro-meteorological disasters, and to evaluate the consequences of drought disaster based on historical climate, crop yield, crop sown area, crop damaged area and crop loss data from 41 maize-producing districts of Songliao Plain (1949–1990). The model of risk assessment of drought disaster combined the occurrence frequency, duration and intensity of drought, spatial extent of damage caused by drought and regional production level of maize were developed using a method of quantitative risk analysis. It is shown that drought was the greatest agro-meteorological disaster. Among all agro-meteorological disasters, drought occurs with the highest frequency, covers the largest area, and causes the greatest loss to agricultural production and economy in the region. From 1949 to 1990, the negative value years of the fluctuation of maize yield due to agro-meteorological disasters accounted for 55%, of which 60% was caused by drought. A significant positive relationship between the negative values of fluctuation of maize yield and drought affected area was found, which indicates that the adverse impacts of drought on maize production are similar to the damage extent of drought disaster. According to the risk extent of drought disaster to maize, the Songliao Plain was divided into four sub-regions: high risk zone, medium risk zone, low risk area and slight risk zone by using fuzzy cluster analysis. It showed the risk degree of drought disaster in the Songliao Plain increases gradually from south to north and from east to west. The information obtained from interviewing the district official committees in relation to result compiled was statistically evaluated. The results obtained in this study can provide the basis for developing strategies to mitigate drought and reducing the losses, and to ensure agricultural sustainable development.

Keywords: Drought disaster; Risk assessment; Crop yield–climate analysis; Fuzzy cluster analysis; Maize; Songliao Plain

1. Introduction

China is a great agricultural country. A basic industry of the national economy, agriculture is easily affected by agro-meteorological hazards (particularly drought and waterlogging) (Li et al., 2000). Maize is one of the main crops in China. Songliao Plain is the main maize-growing region of China, and is also one of the major contributors to the Maize Belt of the Temperate Zone worldwide. Although the natural conditions of the plain are favorable to maize growth,

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agro-meteorological hazards frequently occur and maize yield fluctuates greatly from year to year due to micro-topography and unstable monsoon climate. According to statistical analysis, the agro-meteorological disasters that affect maize production in the Songliao Plain are mainly caused by drought, waterlogging and cool summer. Among these agro-meteorological disasters, drought predominated (Zhang, 2000). In the region, the sown area affected by drought accounts for 60% of the total area affected by agro-meteorological hazards, resulting in a serious loss of maize production. For example, the drought in the spring, autumn and summer of 1989 caused a large reduction of total maize production. Moreover, drought has a tendency to occur often, and its degrees of damage on maize production have increased recently with global warming. Consequently, it is important to quantitatively analyze the relationships between fluctuation in maize yield and drought disaster, and to comprehensively assess the potential damage and direct loss of drought disaster to maize in the Songliao Plain. These studies are the basis for making strategies to mitigate agro-meteorological hazards and reducing the losses from them, and adjust the medium and long-term distribution of agricultural activities so as to adapt to environmental changes.

The risk assessment of natural disaster is defined as the assessment on both the probability of natural disaster occurrence and the degree of damage caused by natural disasters (Zhang et al., 2002). Traditional disaster risk assessment is often limited to comparisons of likelihood of a disaster with the dollar value of potential losses or impacts. Theses comparisons are then used to decide whether it is economically favorable to prepare for certain disasters (Knutson et al., 1998). Ewert et al. (2002) assessed the potential effects of elevated CO_2 and drought on wheat for different experimental and climatic conditions based on the different crop simulation models. Pidgeon et al. (2001) described a simulation methodology and its application to investigate the importance of drought across much of Europe. Lansigan et al. (2000) discussed the agronomic impacts of climate variability on rice production systems by distinguishing the impacts of long-term weather variability and short-term weather episodes based on results of systems-based studies and case examples in Philippines. Yamoah et al. (2000) analyzed the long-term consequences of rainfall expressed as a standardized precipitation index (SPI) and fertilizer nitrogen (N) effects on yields risk probabilities of maize. Gu et al. (1993) identified and evaluated drought risk areas based on climatic indexes such as the ratio to the normal of sum of monthly amounts of precipitation for June, July and August using fuzzy cluster analysis. Keating and Meinke (1998) identified and assessed drought impacts on agriculture by using the crop–soil management system. Badini et al. (1997) quantified and mapped agroclimatic indices such as aridity and crop water stress index to assess water stress effect on millet production based on crop simulation model and GIS. Maki and Kurose (1987) evaluated the grades of damage caused by drought to agricultural production using the climatological standards, such as precipitation and evaporation. These studies on impact and risk assessment of drought to agricultural production mainly used two approaches: climatic indices such as precipitation, evaporation, and crop simulation model. However, the damaging effects and crop losses of droughts are not taken into account in two approaches (Agnew, 2000; Lal et al., 1998). Therefore, in this study, drought disaster risk is considered the potential adverse effects of drought as a product of the frequency of drought, the intensity and severity of drought, the spatial extent of damage caused by drought and regional production level of maize from the viewpoints of climatology, geography, disaster science, environmental science and risk assessment and so on. This study presents a methodology for risk analysis and assessment of drought disaster to agricultural production in the maize-growing area of Songliao Plain, China based on Geographical Information Systems (GIS). The main objectives of the present study are to: (1) study the relationships between the fluctuations in maize yield and agro-meteorological disasters such as drought, and to evaluation the consequences of agro-meteorological disasters such as drought by using crop yield–climate analysis based on the historical data such as climate, crop yield, crop sown area, crop damaged area and crop loss data from 41 maize-producing districts of Songliao Plain (1949–1990); (2) assess and zone the degree of drought disaster risk in the Songliao Plain by using a method of quantitative risk analysis and fuzzy cluster analysis. The methodology employed in this study can be applied to the study of other agro-meteorological disasters. The information from this study is potentially useful reference in decision making of drought disaster prevention and agricultural sustainable development planning.

In this context, drought refers to a potentially damaging natural hazard that is caused by the deficiency or absence of precipitation during the growing season. Drought disaster involves a reduction in yield (kg/ha) (less than 70% of the yield expected with temperature and precipitation equal to long-term average values) of one or more of the major food grains (maize, wheat, soybean etc) by drought (MCA, 1995).

2. Material and methods

2.1. Area description and potential analysis of drought hazard

Songliao Plain is situated in Northeastern China, between 38–47°N and 117–131°E, including the southern part of Heilongjiang province, the middle and western part of Jilin province and most of Liaoning province. The total region is politically and administratively divided into 54 districts, 41 of which are maize-producing areas (Fig. 1). The Plain is in warm temperate semi-humid and monsoon-controlled climatic zone with hot, rainy summers and cold, dry winters. Annual mean temperature is 3–8 °C, mean temperature of the coldest month is −12 to −18 °C, mean temperature of the warmest month is 22–24 °C. Annual mean sunshine duration is 2400–2900 h, while annual percentage of possible sunshine is 56–64%. Annual precipitation is 500–750 mm, of which 60–65% concentrates in summer due to monsoon climate. Except for the northwestern area, which is semi-arid, the greater part of Songliao Plain is semi-humid with the annual mean aridity index $((1/12)\sum_{m=1}^{12}(0.0018(T_m + 25)^2(1 - H_m)/P_m)$, where P is monthly total precipitation, T is monthly mean temperature and H is monthly relative humidity, m represents month) ranging from 0.63 to 1.25 (Li et al., 1988).

Maize requires moderate temperatures, a semi-humid climate and plenty of sunshine. In Songliao Plain, the maize-growing season begins with planting in May and continues through September. Early maize is grown. The average temperature during the growing season is 20–25 °C and ≥10 °C accumulated temperature is 2800–3200 °C, the average rainfall during the growing season is 350–650 mm. The frost-free period is 135–155 days.

In summary, the climate of Songliao Plain has many advantages for agriculture: long growing season and frost-free period, plentiful thermal resources, sufficient

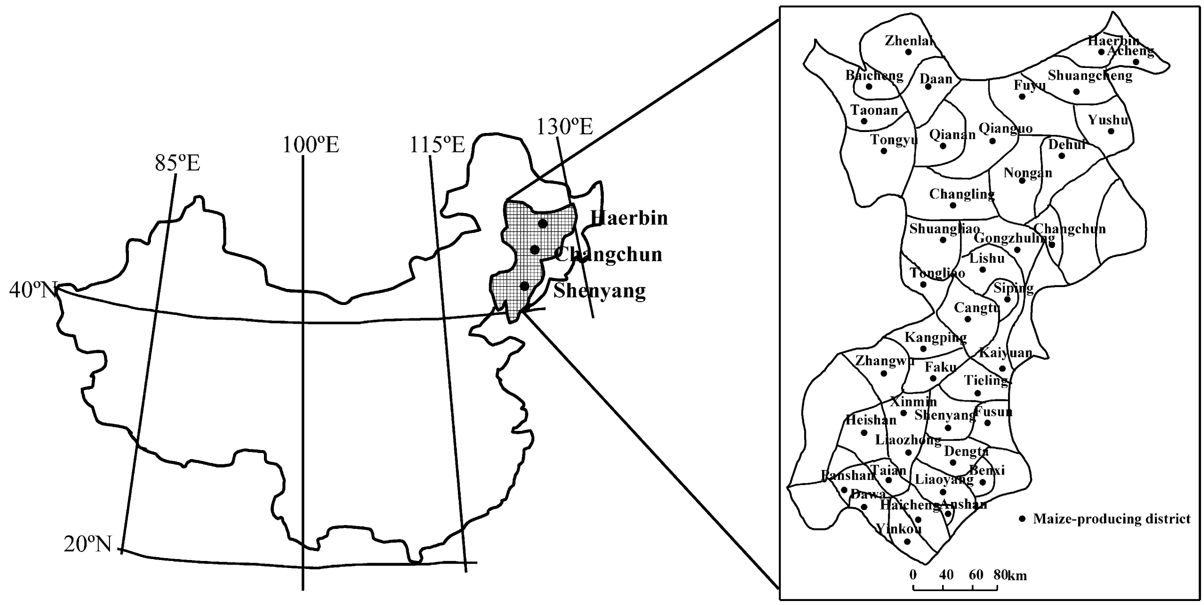

Fig. 1. Location of Songliao Plain in China.

rainfall, and abundant sunshine during the growing season. Songliao Plain enjoys exceptional advantages for the development of maize. However, there are some disadvantages for agriculture in the area, including agro-meteorological hazards arising from drought, waterlogging and cool summer. Since the region is affected by the monsoon regime, the distribution of rainfall is uneven both in time and in space. In addition, there is a large variation of the annual rainfall from year to year. Due to these conditions, the area is susceptible to drought and waterlogging. On the other hand, since the distribution of thermal resources is uneven both in time and space due to micro-topography, the area is also sensitive to cool summer. Among all agro-meteorological hazards, drought hazard occurs the most frequently, has the longest duration, covers the largest area, and causes the greatest loss to agricultural production and economy (Zhang, 2000).

Statistical analysis showed that probability and spatial distribution of drought occurrence are closely connected with the rainfall during maize-growing season (May–September) and aridity index as climatic factors in Songliao Plain (Zhang, 2000). The frequency of drought occurrence increases gradually with reduction of rainfall during maize-growing season from southeast to northwest in Songliao Plain by expression of

$$F_{\mathrm{d}} = 413.99\,\mathrm{e}^{-0.006R}, \quad r = -0.94,\ P < 0.01$$

where F_{d} is the frequency of drought occurrence, R the rainfall from May to September, r the correlation coefficient and P the significant level.

On the other hand, the frequency of drought occurrence increases gradually with increase of aridity index from southeast to northwest in Songliao Plain by expression of

$$F_{\mathrm{d}} = -48.05 + 90.45\mathrm{AI}, \quad r = 0.84,\ P < 0.01$$

where F_{d} is the frequency of drought occurrence, AI the aridity index, r the correlation coefficient and P the significant level.

Fig. 2 shows the spatial distribution of the rainfall during May–September and aridity index in Songliao Plain. From Fig. 2, we can see, rainfall during May–September increases gradually from northwest to southeast. On the contrary, the aridity index decreases gradually from northwest to southeast.

Drought disaster is related not only to climatic factors such as precipitation, temperature and aridity, but also to conditions of the earth's surface such as landform and soil type in various regions. Except for some hills of the east and southwest boundaries that are the non-maize-growing area, Songliao Plain is flat land of average elevation less than 200 m. Landform is classified into accumulation plain, lacustrine plain, lacustrine-alluvial plain, marine sediment-alluvial plain and accumulation-erosion plain. The main types of soil favorable to maize growth are chernozem, grassmarshland chernozem, chestnut soil, grassmarshland soil, and few burozem sequences.

According to the theories of physical geography and field investigation, it can be known that the possibility of drought disaster occurrence on different landforms and types of soil is different. Generally, the types of soil in which drought disaster can easily occur are mountain burozem, plain burozem, chestnut soil, chernozem, grassmarshland chernozem and grassmarsh soil, and the types of landform in which drought disaster can easily occur are accumulation-erosion plain, accumulation plain, lacustrine-alluvial plain, lacustrine sediment plain and marine sediment-alluvial plain.

2.2. Climatic indices of the main agro-meteorological hazards

As previously stated, drought, waterlogging and cool summer are three most damaging agro-meteorological hazards. Climatic indices of agro-meteorological hazards can provide an objective way to define the hazards and assess the current extent and severity of the hazards over a region. Drought is difficult to define and it is not easily characterized either qualitatively or quantitatively. Because of its insidious nature, many definitions of drought have been proposed, the number of indices used to come quantitatively to grip with its climatological aspects being almost innumerable (e.g. Dracup et al., 1980; Wilhite and Glantz, 1985; Wilhite, 2000; Richard and Heim, 2000). Scores of definitions and indices of waterlogging have also been developed within a variety of disciplines (CNHSGSSTC, 1998; Lizaso and Ritchie, 1997a,b). Waterlogging usually specifies when the condition of excessive rainfall and soil moisture is sufficient to have an adverse effect to crops caused by the intense rainfall during the growing season in China (CNHSGSSTC, 1998). Since drought and waterlogging are caused by shortage and surplus, respectively, of rainfall, the intensity of

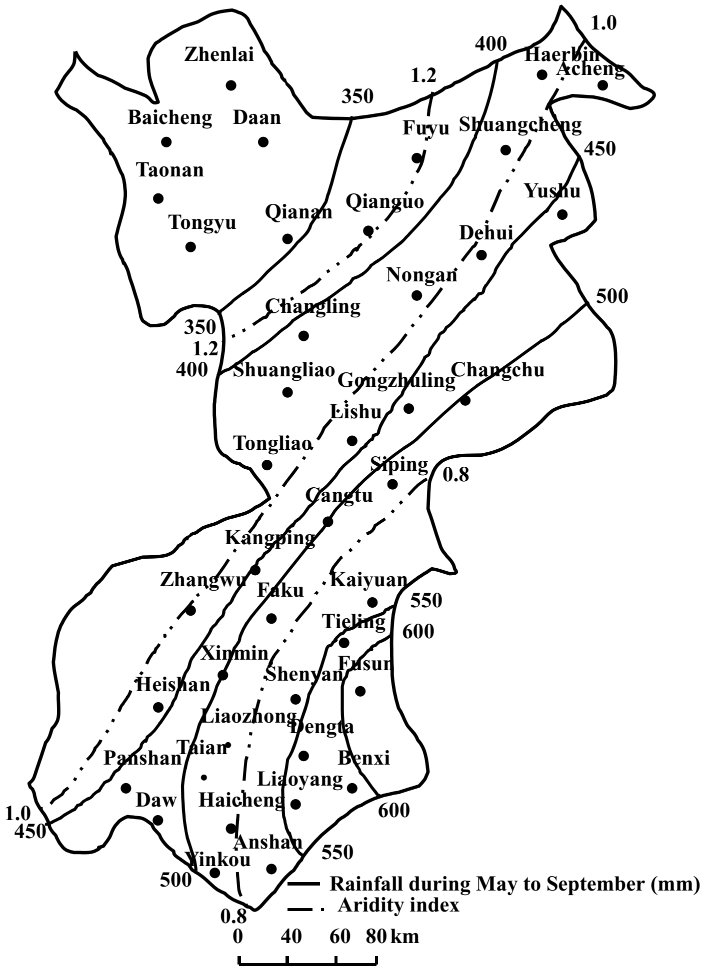

Fig. 2. Spatial distribution of rainfall during May–September and aridity index in Songliao Plain.

meteorological drought and waterlogging in China can be characterized and classified on the basis of the intensity of rainfall deficiency and excess (departure from normal precipitation) (Wang et al., 2000; Li et al., 2000). In China, the sophisticated criterion for identifying and evaluating drought and waterlogging was developed by CAMSNWB (1981) and Zhang and Liu (1993) is expressed as following:

- extreme waterlogging: $R_i > 1.17\sigma$,
- waterlogging: $0.33\sigma < R_i < 1.17\sigma$,
- normal (year): $-0.33\sigma < R_i < 0.33\sigma$,
- drought: $-1.17\sigma < R_i < -0.33\sigma$,
- extreme drought: $R_i < -1.17\sigma$.

where R_i is the rainfall from May until September in the *i*th year, σ the standard deviation for the rainfall in the stated calculated time period.

In this study, the above criterion system was used to identify and characterize the occurrence of drought and waterlogging for each year according to the instrumental data set (1949–1990) of monthly growing season rainfall in Songliao Plain.

Cool summer is a condition of low temperature (more than 0 °C) sufficient to have an adverse effect to crops during the growing season (Wang, 1995). According to this definition, since cool summer is associated with low temperature during the crop-growing season, the seasonal temperature or the normal

Table 1
The standards(ΔT_{5-9}[a], °C) of cool summer at the various $\bar{T}_{5-9}$

	$\bar{T}_{5-9}$ (°C)[b]					
	80.0	85.0	90.0	95.0	100.0	105.0
Moderate cool summer	−1.1	−1.4	−1.7	−2.0	−2.2	−2.3
Severe cool summer	−1.7	−2.4	−3.1	−3.7	−4.1	−4.4

[a] ΔT_{5-9}: the departure of temperature during the growing season (May–September) from the long-term (i.e., over years) mean temperature during the same period.

[b] $\bar{T}_{5-9}$: the long-term (i.e., over years) mean temperature during the growing season (May–September).

departure of seasonal temperature during the crop-growing season is often regarded as the index for identifying the cool summer phenomenon in China (Gu and Hayakawa, 1994; Wang, 1995). In this study, the temperature during the crop-growing season and its departure of from temperature average over some time period (as shown in Table 1) were used to define cool summer year (Wang, 1995).

2.3. Indicators of agro-meteorological disasters

For agricultural production, the damages caused by agro-meteorological hazards such as drought, waterlogging and cool summer clearly indicate the influence and negative impact of these hazards on the growth of crops. It is regarded as a multiple system with natural, social and economic components. The degree of damage caused by these hazards to crop production is mainly decided by such factors as occurrence frequency, duration and intensity of these hazards, the area over which they impact and consequences for the local economy (Zhang, 1995; Zhang and Hayakawa, 1997; Zhao and Yao, 1992). There is no generally accepted criterion for estimating the degree of damage caused by natural hazards. However, indicators commonly used in China consider the covered area and affected area by agro-meteorological hazards, the percentage of the covered area and the affected area to crop sown area, the amount of reduction in crop yields and the economic loss (Zhang et al., 1990; Liang, 1992; Xie and Yang, 1995; MCA, 1995). According to MCA (1995), the covered area refers to the sown area suffered a reduction in yield (kg/ha) (less than 90% of the yield expected with temperature and precipitation equal to long-term average values) of one or more of the major food grains (maize, wheat, soybean etc.) by one or more of the agro-meteorological hazards (drought, flood, cool summer etc.). The affected area (of the covered area) refers to the sown area suffered a reduction in yield (kg/ha) (less than 70% of the yield expected with temperature and precipitation equal to long-term average values) of one or more of the major food grains (maize, wheat, soybean etc.) by one or more of the agro-meteorological hazards (drought, flood, cool summer etc.). Furthermore, it is assumed that the calculation of the covered area and affected area will not be repeated, that is, the severest covered area and affected area will be calculated if several kinds of agro-meteorological hazards successively occurred in a given year for a given region.

The direct effect of agro-meteorological hazards on agriculture is to cause complete crop failure or varying amount reduction in crop yield, so the amount of reduction in crop yield may comprehensively reflect the consequences of agro-meteorological hazards. Since the amount of reduction in crop yield in given region depends on the extent of reduction in crop yield and the magnitude of the damaged sown area by agro-meteorological hazards under given crop yield (kg/ha) level, the damaged sown area suffered various extent of reduction in crop yield is often regarded as the indicator for evaluating the degree of damage caused by agro-meteorological hazards.

Since the percentage of the affected area to crop sown area shows both the degree of damage and the regional differences, the percentage of the drought affected area to maize sown area (PDAA) was used in this study to evaluate the regional degree of damage caused by drought to maize production, as calculated by

$$\mathrm{PDAA}_j = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{\mathrm{DAA}_{ij}}{\mathrm{MSA}_{ij}} \times 100\%\right) \quad (1)$$

where PDAA_j is the percentage of the drought affected area to maize sown area in the district j, DAA_{ij} the drought affected area in the ith year in the district j, MSA_{ij} the maize sown area in the ith year in the district j, n the number of drought years during 1949–1990. Where higher values of PDAA represent greater damage due to drought to maize production.

2.4. Data collection and processing

In this paper, the data consisting of statistical data on the agricultural economy (annual crop sown area and yield etc.), climate (monthly rainfall, temperature and humidity etc.) and main damage condition by agro-meteorological disasters (annual covered area, affected area and crop loss etc.) for each site of the Songliao Plain (1949–1990) and geographical data (illustrated by a meteorological factor distribution map, land-use zonation map, maize yield distribution map, landform zonation map, soil zonation map and so on) collected from the Meteorological Bureau, Agricultural Bureau and Statistical Bureau of Liaoning, Heilongjiang and Jilin province in Songliao Plain. Due to the large amount of available data, Geographical Information System (GIS) is an essential tool to gather, store, handle, update, output and display spatial data. In this study, the Agro-meteorological Disasters Data Base (ADDBASE) was constructed as a GIS database (Zhang, 1994). The ADDBASE was used as a mean of managing all the data, and conducting the potential analyses: the hazard identification of the drought disaster; the risk analysis; and the assessment of drought disaster to maize production. The flow chart in Fig. 3 summarizes the procedure used to assess the risk of a drought disaster to maize.

2.5. Data analysis

2.5.1. Crop yield–climate analysis

Crop yield–climate analysis by using mathematical or statistical techniques provides a simplified representation of the complex relationships between climate/weather and crop yield (Wang et al., 1990). In this study, crop yield–climate analysis was used to study the relationships between fluctuations in maize yield and drought, waterlogging and cool summer. Since the yield of crop per unit area is mainly influenced by climate, cultivation technique and overall standard of management, cultivation technique and standard of management always improved over time. Since climate always fluctuates, the annual actual yield of crop per unit area (AY) was divided into two parts according to the characters and time scales of factors that influence crop yield, that is, the time trend yield (TY, mainly influenced by long-term factors such as cultivation technique and standard of management) and climatic yield (CY, mainly influenced by short-term factors such as climatic factors) (Yu and Li, 1985; Wang et al., 1990, 2000).

Based on the aforementioned crop yield–climate analysis, the following indices are proposed in order to show the relationships between fluctuation of maize yield and agro-meteorological hazards (Zhang and Hayakawa, 1997; Zhang, 2000).

2.5.1.1. Fluctuation term of maize yield. In this study, the climatic yield (CY) was used to analyze the fluctuations in maize yield over time. Technological progress and improvement of societal conditions are responsible for the generally increasing trend of the crop yield. Therefore, the linear trend was removed from the original series, although it is impossible to determine if the trend is linear. Then the residual of the series is examined as the climatic yield, which is postulated to depend mainly on the climatic conditions (Wang et al., 2000). In this study, 5-year running mean of the annual average actual yield of crop per unit area (AY) was adopted to calculated the time trend yield (TY), correspondingly, the climatic yield (CY) can be expressed by

$$\mathrm{CY}_i = \mathrm{AY}_i - \mathrm{TY}_i \tag{2}$$

where CY_i represents the climatic yield, AY_i the actual yield of crop per unit area, TY_i the time trend yield, and i the year.

Using the climatic yield (CY) as a measure of the fluctuations in maize yield, it is possible to reflect changes in the favorable and unfavorable climatic conditions and their impacts on maize production every year. Positive values of CY denote increases in maize yield due to favorable climatic conditions, and negative values indicate a reduction in maize yield due to unfavorable climatic conditions.

2.5.1.2. Climatic index of the fluctuation of maize yield. To analyze the instability and spatial distribution of the fluctuation of maize yield due to climatic effects in different regions, a climatic index of the fluctuations in maize yield (YF) was used to calculate the deviating rang among crop yields and their average value, as expressed by

$$\mathrm{YF}_j = \frac{\sqrt{\sum_{i=1}^{n}(\mathrm{CY}_{ji})^2/(n-1)}}{\overline{\mathrm{AY}}_j} \tag{3}$$

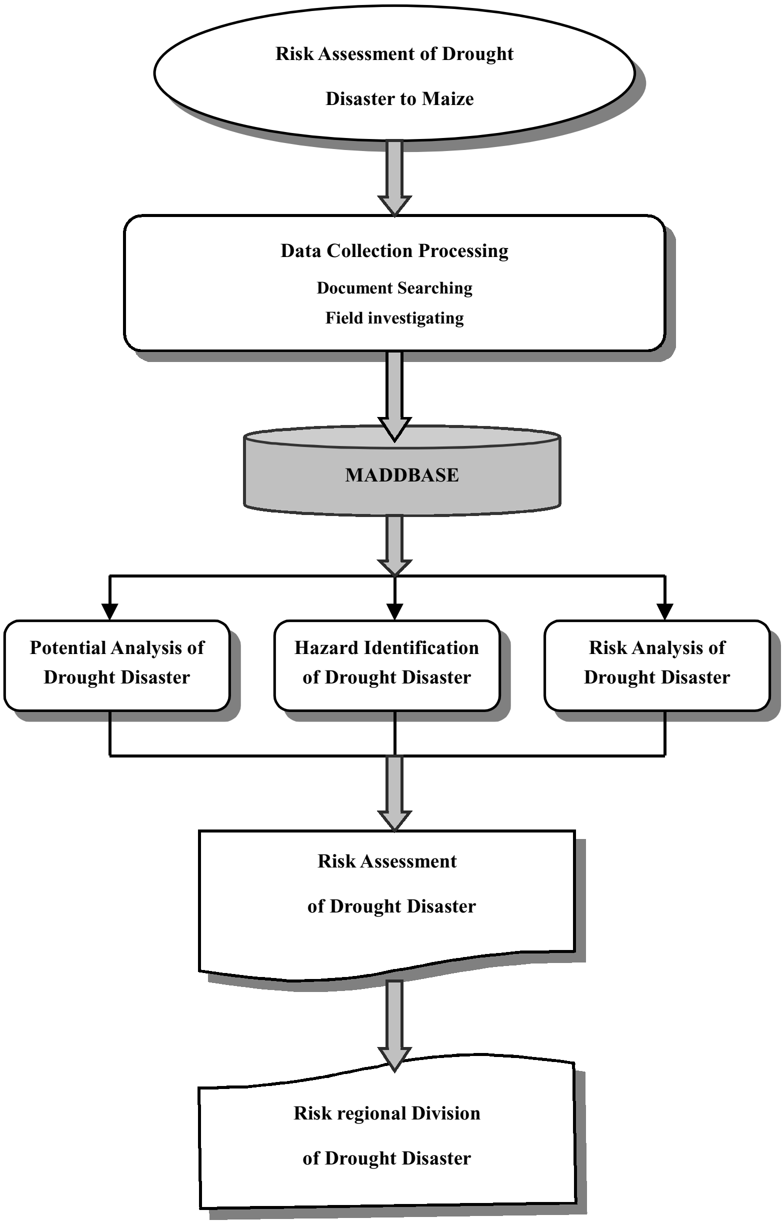

Fig. 3. Flow chart showing the procedure used to make risk assessment of drought disaster to maize.

where CY_{ji} is the climatic yield of the given year i in the given region j, $\overline{AY}_j$ the average actual yield of maize per unit area during the 42 years (1949–1990) in the given region j, n the number of CY in the given region and YF_j the climatic index of fluctuation of maize yield in the given region j. YF_j denotes the relative magnitudes of the yield fluctuation values due to climatic effects, where $0 \leq YF_j \leq 1$. The higher the value, the greater the between-year variability in maize yield.

2.5.2. Model of risk assessment of drought disaster

In this research, a method of quantitative risk analysis (QRA) for the work environment of certain industrial activities in Production Safety Science was used for reference to construct a model of risk assessment of drought disaster to maize production. Typically, QRA techniques are used to obtain a better understanding of the risk posed to people who work in hazardous materials facilities, and to aid them in preparing effective emergency response plans (Heinrich et al., 1980; Luo, 1987). It is based on contrasting the assessed environment with the reference environment, and makes risk assessment to the work environment by giving points to each factor according to class. Zhang (1990) tried to make a study on damage degree of drought disaster using this method. This method considers that the main factors affecting risk potential of the work environment consist of three factors: (1) the likelihood of occurrence of each possible hazardous event as measured by frequency (event/unit time); (2) the frequency of exposure to each hazardous event as measured by exposure times during a given period; (3) the potential consequences of each hazardous event as measured by the people affected by each hazardous event. In order to compute the risk associated with hazards, the product of the above-mentioned three factors is used as a index for assessing the risk potential of the hazardous events to people.

What is called the risk of drought disaster to maize indicates the potential threat and direct endangerment of drought disaster to maize production. Since drought disaster is related to not only climatic factors such as precipitation, temperature, aridity etc., but also to conditions of the earth's surface such as landform and soil type, land-use structure, regional economic development levels and disaster combating capability in various regions, the extent of risk of drought disaster to maize production is mainly decided by such factors as occurrence frequency, duration and intensity of drought disaster, spatial extent of damage caused by drought (i.e., the area affected by drought) and regional production level of maize (Zhao and Yao, 1992; Zhang, 1995; Yang and Zhang, 1996). Therefore, referring to a quantitative risk analysis, in order to make the risk assessment of drought disaster to maize production, time frequency of drought disaster (TF), space frequency of drought disaster (SF), intensity frequency of drought disaster (IF), consecutive intensity of drought disaster (CI) and regional production level of maize crop in the areas afflicted by drought disaster (PL) are parameters needed. If parameters TF, SF, IF, CI and PL are known, the risk extent of drought disaster to maize can be assessed by

$$\mathrm{DDRI}_j = \mathrm{TF}_j \times \mathrm{SF}_j \times \mathrm{IF}_j \times \mathrm{CI}_j \times (1 - \mathrm{PL}_j) \quad (4)$$

where DDRI is the drought disaster risk index to maize, j the district of the Songliao Plain. In the calculation process, TF, SF, IF, CI and PL are shown by percentage, so DDRI values are situated in [0, 100%], and higher value represents greater risk.

According to the situations of drought disaster and the features of maize production in Songliao Plain, parameters TF, SF, IF, CI and PL were decided as followings:

(1) *TF*. It shows the frequency of drought occurrence during 1949–1990. As mentioned previously, drought is an essential prerequisite to drought disaster, so TF can be expressed by

$$\mathrm{TF}_j = \frac{\mathrm{DN}_j}{n} \quad (5)$$

where TF_j is the frequency of drought occurrence in the district j of Songliao Plain, DN_j the number of drought occurrence in the district j of Songliao Plain, n the number of aggregate years (1949–1990). The greater the frequency of drought occurrence is, the greater the probability of drought disaster.

(2) *SF*. It shows the area affected by drought, and is one of the variables describing spatial extent of damage caused by drought to maize production. SF can be expressed by the percentage of the drought affected area to maize sown area (PDAA) as calculated by Eq. (1). The greater the SF value, the more serious the damage.

(3) *IF*. As mentioned above, formation of drought disaster results from the comprehensive action of the varied factors. Except for climatic conditions, conditions of the earth's surface such as landform and soil type, land-use structure, regional economic levels and disaster combating capability in various regions can affect occurrence and intensity of drought disaster, but for field crops, the most important factor affecting drought disaster is still precipitation. Therefore, in the calculation of

IF, the ratio of rainfall during the maize-growing season to water requirement of the corresponding period of maize for the same year was regarded as index of intensity of drought disaster in those years, and marked as IF_i (i shows year). IF in various districts of Songliao Plain can be calculated by

$$\mathrm{IF} = \frac{1}{n}\sum_{i=1}^{n}\mathrm{IF}_i \quad (6)$$

where n is the number of aggregate years (1949–1990).

(4) *CI*. The impacts of drought to crop production vary depending on both duration (as measured by the consecutive drought days in this study) and severity (as measured by the accumulated deficit of precipitation). The consecutive drought days refer to the consecutive days with daily rainfall less than 5 mm during the growing season (Gu et al., 1993). Thus, drought duration is also an important factor deciding the extent of drought damage. If the consecutive drought days are long during growing season, then drought severity is also great, consequently damage caused by drought to crop production becomes even greater, and economic loss caused by it is also even more serious. So in order to evaluate the risk potential of drought duration to maize production in different districts, the consecutive intensity of drought disaster (CI) was proposed, as expressed by

$$\mathrm{CI}_j = \frac{\overline{\mathrm{CD}_j}}{\mathrm{ND}_j} \quad (7)$$

where CI_j is the consecutive intensity of drought disaster in the district j of Songliao Plain, $\overline{\mathrm{CD}_j}$ the average consecutive days with daily rainfall less than 5 mm during the maize-growing season in the jth district of Songliao Plain (1949–1990), ND_j the number of days in the maize-growing season in the jth district of Songliao Plain.

(5) *PL*. It means the regional production level of maize crop. Generally, for field crop, average yield of crop per unit area can indicate both production level of crops and disaster combating capability in various regions. In general, a region with high production level of maize crop has high disaster combating capability greater and low potential loss of maize yield (Wang and Lou, 1997). In this study, the production level of maize was selected as an index estimating disaster combating capability and the risk potential of drought to maize production in the different regions, using the following equation:

$$\mathrm{PL} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{Y_i}{\mathrm{SY}_i}\right) \quad (8)$$

where PL is the regional production level of maize crop of every district in Songliao Plain, Y_i the yield of maize per unit area of every district in Songliao Plain in ith year, SY_i the sum of yield of maize per unit area of every districts in Songliao Plain in ith year, n the number in years of maize yield record (1949–1990).

2.5.3. Fuzzy cluster analysis

Cluster analysis, a major technique in pattern recognition, is a method for organizing a data set into clusters of similar individuals. The conventional (hard) clustering methods restrict each point of the data set to belong to exactly one cluster. Fuzzy cluster analysis which applies the concept of fuzzy sets to cluster analysis gives belongedness to cluster at each point of data set by a membership function (Yang and Liu, 1999). Fuzzy cluster analysis has been widely studied and applied in diverse areas in recent years. See, Yang and Shih (2001), Yang and Liu (1999), Zhen et al. (2000), Gu et al. (1993), Yang and Yang (1998), Zhang et al. (1998, 1999).

Fuzzy cluster analysis is based on a relation matrix such as correlation coefficient, equivalence relation, similarity relation and fuzzy relation, etc. If $U = \{u_1, u_2, \ldots, u_n\}$ is a set of the objects discussed, and $u_i = \{x_{i1}, x_{i2}, \ldots, x_{im}\}$ represents the relationship between each object u_i and m kinds of elements, the fuzzy similarity relationship, which can be represented as a fuzzy similarity matrix $R = (S_{ij})_{n\times n}$, has many methods to consider. In this study, we have used the correlation coefficient method shown in the following equation:

$$r'_{ij} = \frac{\sum_{k=1}^{m}(x_{ik} - \bar{x}_i)(x_{jk} - \bar{x}_j)}{\sqrt{\sum_{k=1}^{m}(x_{ik} - \bar{x}_i)^2 \sum_{k=1}^{m}(x_{jk} - \bar{x}_j)^2}} \quad (9)$$

where

$$\bar{x}_i = \frac{1}{m}\sum_{k=1}^{m} x_{ik}, \qquad \bar{x}_j = \frac{1}{m}\sum_{k=1}^{m} x_{jk}$$

A fuzzy equivalence matrix can be obtained by multiplying R with itself 2^m times. The product operator here is a special one which obeys the rule of fuzzy mathematics (Zhen et al., 2000):

$$R \to R^2 \to R^4 \to \cdots \to R^{2^m}$$

where

$$m = \left\{ \begin{array}{ll} \log_2 n & \log_2 n \in \{\text{integer}\} \\ 1 + \log_2 n & \log_2 n \notin \{\text{integer}\} \end{array} \right\}$$

From the fuzzy equivalence matrix R^{2^m} at each clustering level λ we first create a cut-off matrix $R_\lambda^{2^m}$:

$$(R_\lambda^{2^m})_{nk} = \begin{cases} 1 & (R^{2^m})_{nk} > \lambda \\ 0 & (R^{2^m})_{nk} < \lambda \end{cases}$$

Thus a cluster size λ ($0 \le \lambda \le 1$) will be determined as the cluster criterion and according to cluster requirement. According to the cluster criterion and the cut-off matrix, the cluster results can be determined and shown by partition tree from each cut-off matrix.

Considering this fuzzy cluster analysis method, a computer software had been developed.

The technique has certain distinct advantages, such as having simple processes to study complex systems and providing quantitative, comparative, synthetic, objective and reliable analysis results (Yang and Shih, 2001; Gu et al., 1993; Zhang et al., 1998, 1999). In this paper, fuzzy cluster analysis was used to make quantitative, comparative and objective assessment and classification of drought disaster risk area for maize production in Songliao Plain.

3. Results and discussion

3.1. Drought hazard identification

3.1.1. Temporal and spatial distribution of drought hazard

Since drought is an essential prerequisite to drought disaster, and the greater the frequency of drought occurrence is, the greater the probability of drought disaster occurrence is, the frequency of drought occurrence can reflect the probability of drought disaster occurrence. The statistical incidence of drought hazard during the period 1949–1990 showed that on average Songliao Plain experienced drought for 14 of 42 years with the most frequency among the agro-meteorological hazards. In northwest Songliao Plain areas encompassing Taonan, Baicheng, Fuyu, Qianan, Tongyu, a higher frequency of drought was recorded, where 20–33 times of drought occurred in 42 years.

There are great regional differences in occurrence of drought hazard in Songliao Plain. Fig. 4 shows the spatial distribution of frequency of drought occurrence. The frequency of drought occurrence increases gradually from southeast to northwest. The highest frequency appeared in Taonan of Jilin province and its value was 30 of 42 years. The lowest frequency appeared in Tieling of Liaoning province and its value is 4 of 42 years. The features of spatial distribution of frequency of drought occurrence are mainly results from the above-mentioned features of rainfall during May–September and aridity index.

3.1.2. Regional damage evaluation to maize caused by drought hazard

In terms of drought damage extent, from 1949 to 1990, the annual average drought covered area totaled 4.3×10^5 ha, of which 2.2×10^5 ha was the drought affected area.

Fig. 5 gives the spatial distribution of the percentage of the drought affected area to maize sown area (PDAA). The extent of damage caused by drought shows that the northwest regions have more severe damage, whereas the middle and south regions have only a slight damage. Moreover, comparing Fig. 5 with Fig. 4, it can be seen that there are a number of differences between the spatial distribution of frequency of drought occurrence and the spatial distribution of extent of drought disaster, a reason is that drought is related to only climatic factors such as precipitation, temperature, aridity, landform, soil type etc., but drought disaster is related to climatic factors, landform, soil type, and also to land-use structure, regional economic levels and disaster combating capability of the various regions. In addition, the damage degree of disaster drought to crop production for a region also

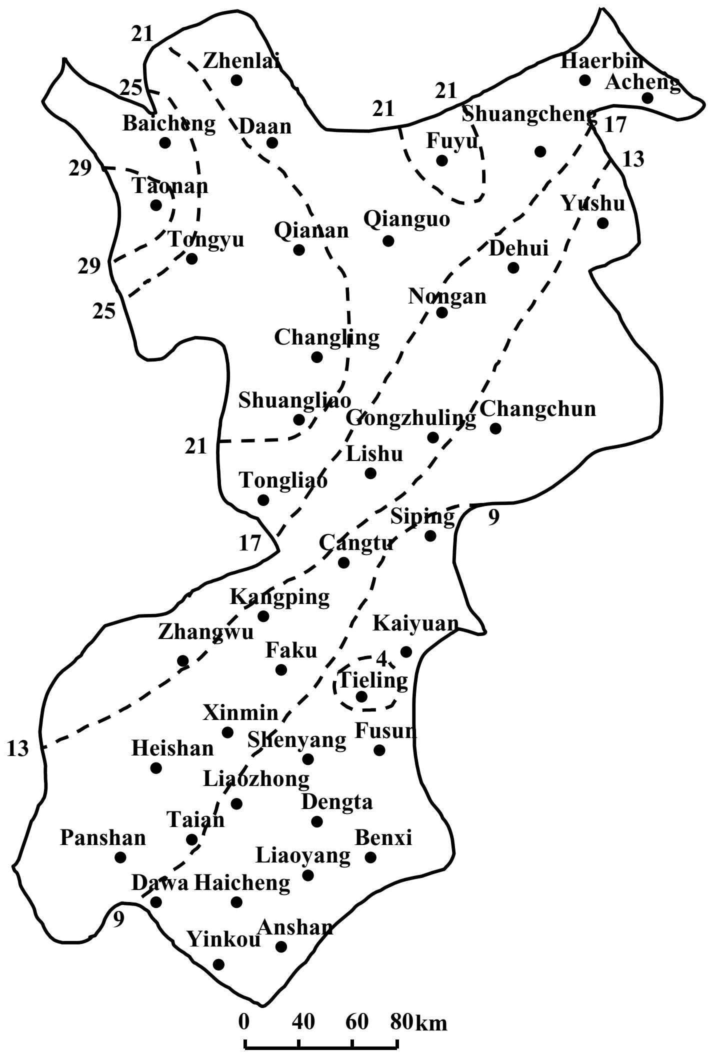

Fig. 4. Spatial distribution of frequency of drought occurrence in Songliao Plain during 1949–1990.

depends on crop varieties, cropping system, various management practices and crop sown area.

3.2. Risk analysis of drought disaster to maize production

In this section, by identifying the relationships between the fluctuation of maize yield and drought disaster based on crop yield–climate analysis and regression analysis, the risk and damage of drought disaster to maize were analyzed.

3.2.1. Characteristics of the temporal and spatial distribution of the fluctuation of maize yield due to agro-meteorological hazards

The variation in the average maize yields from 1949 to 1990 in Songliao Plain is shown in Fig. 6. Maize yield has a basic trend of gradually increasing over time (a dotted line in Fig. 6) accompanied by random fluctuations (a solid line in Fig. 6). The fluctuations in the yield of maize per unit area as influenced by climatic factors from 1949 to 1990 are shown in Fig. 7. The positive value years accounted for 45%, and the

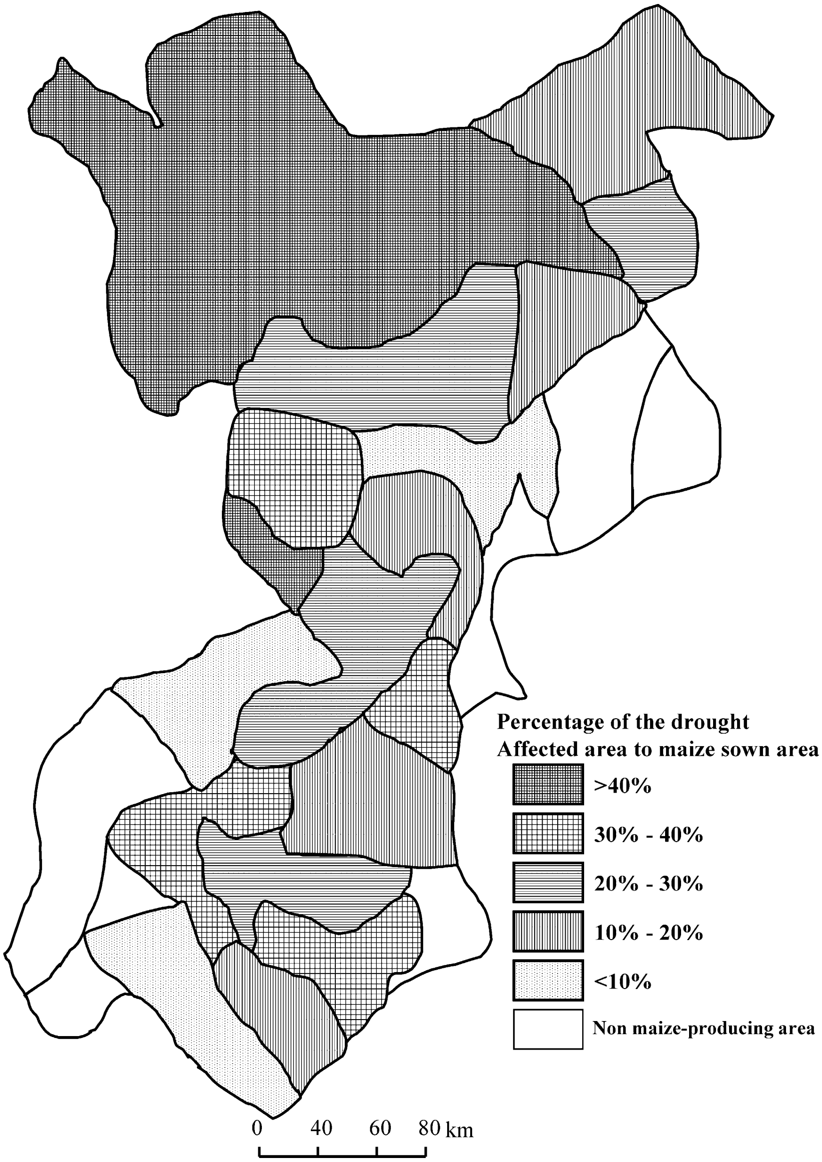

Fig. 5. Spatial distribution of the extent of drought disaster (the percentage of drought affected area to maize sown area) in Songliao Plain during 1949–1990.

negative value years accounted for 55%, of which 60% were caused by drought hazard by comparing the historical maize yield with the agro-meteorological hazard events, so it can be known that drought is the most dominant agricultural disaster which causes the loss of maize yield in the Songliao Plain during this study.

Instability and spatial variation of fluctuation of maize yield due to climatic effects are shown by climatic index of fluctuation of maize yield defined as Eq. (2) in Fig. 8. Climatic index of fluctuation of maize yield is getting greater and greater from southeast to northwest. This means that the southeast part is the most stable area, middle part is the inferior stable area,

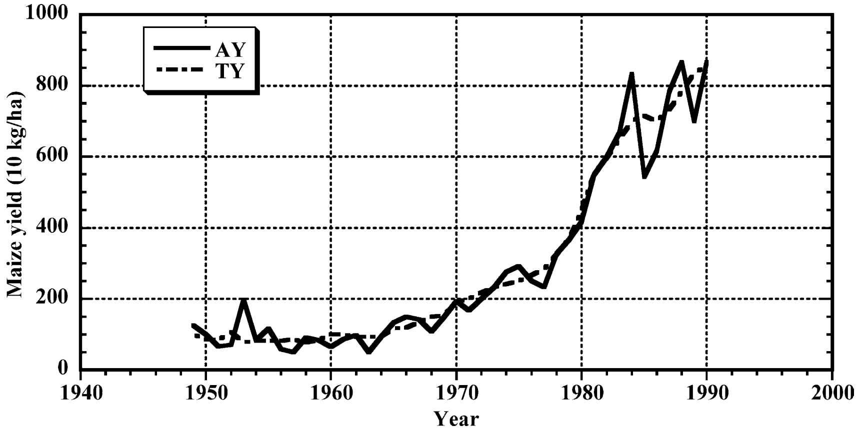

Fig. 6. Annual average maize yield (AY) and 5-year running mean of annual average maize yield in Songliao Plain during 1949–1990.

and northwest part is the most unstable area in maize yield.

3.2.2. Regression analysis on fluctuation of maize yield and extent of drought disaster

Wang et al. (2000) and Zhang and Hayakawa (1997) have shown that there was a closely positive correlation between the climatic yield (i.e., fluctuation term of crop yield) and the damaged sown area by drought. Zhang (2000) compared the climatic yield (i.e., fluctuation term of maize yield) with the damaged sown area by drought in Songliao Plain, it showed that close agreement of climatic yield with the damaged sown area by drought with the negative correlation is obvious. The less the damaged sown area by drought, the greater the positive fluctuations in maize yield relative to the trend in the yield of maize over time. Conversely, the more the damaged sown area by drought, the greater the negative fluctuations in maize yield relative to the trend in the yield of maize over time. It can be seen that fluctuations in the yield of maize are consistent with the damage extent caused by drought every year.

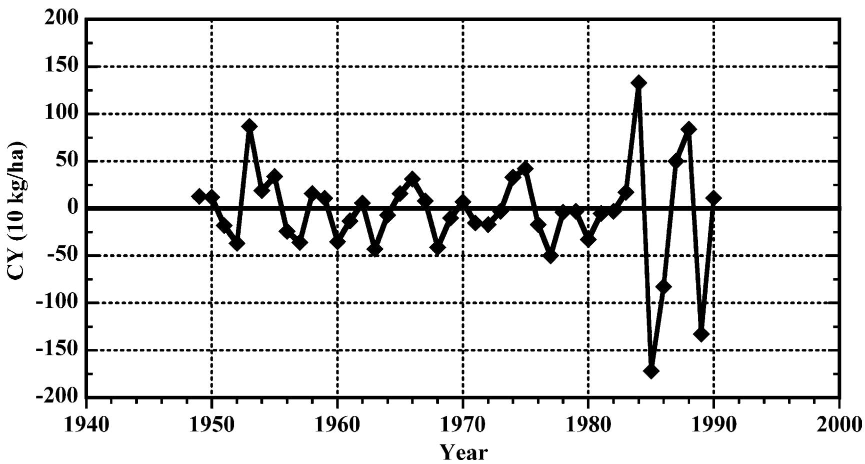

Fig. 7. Fluctuation in per unit yield of maize influenced by climatic factors during 1949–1990. CY = AY − TY (AY means actual maize yield, TY means time trend yield), positive values denote increases in maize yield due to favorable climatic conditions, and negative values indicate a reduction in maize yield due to unfavorable climatic conditions.

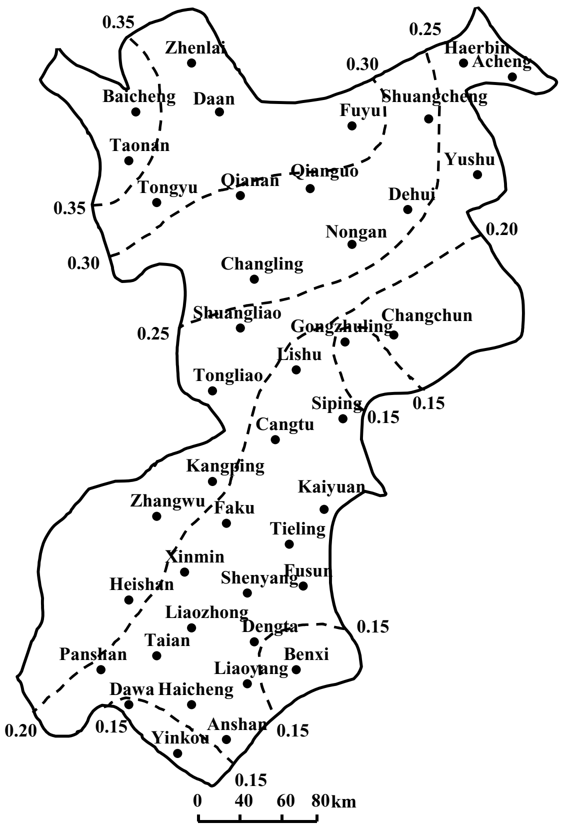

Fig. 8. Spatial distribution of climatic index of fluctuation of maize yield in Songliao Plain during 1949–1990.

Since the negative values of fluctuation of maize yield (i.e., maize yield lower than the time tendency level of maize yield) indicate potential adverse impacts of agro-meteorological hazards, the regression analysis on the negative values of fluctuation of maize yield and drought damaged area was carried out to clarify and estimate the expected maize yield anomalies due to drought hazard in Songliao Plain (Fig. 9). The correlation coefficient between the fluctuation in maize yield and the areas damaged by drought is 0.99, significant at $P > 0.01$ level. This suggests that the greater the areas damaged by drought, the greater the fluctuation in maize yield (lower than the time tendency level of maize yield), and the greater the reduction in maize yield.

3.3. Risk assessment and regionalization of drought in the Songliao Plain

3.3.1. Verification of the model of risk assessment

Table 2 shows the values of drought disaster risk index to maize calculated by Eq. (4) in Songliao Plain. Based on the loss data maize yield caused by drought in Songliao Plain, the model of risk assessment was verified. A regression analysis was carried out to clarify the relationship between drought disaster risk index to maize (DDRI) and percentage reduction yield of maize due to drought (PRYM) (Fig. 10). A linear

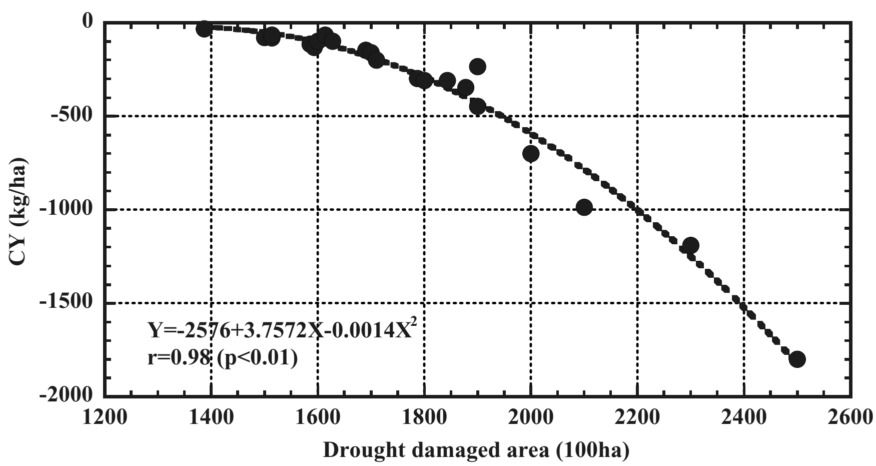

Fig. 9. Relationship between the fluctuation of maize yield and the drought damaged area; r is the correlation coefficient, P the significant level.

Table 2
The values of DDRI for the different districts in Songliao Plain in %[a]

District	DDRI[b]	District	DDRI	District	DDRI
Baicheng	39.7	Acheng	13.9	Kaiyuan	5.9
Taonan	45.9	Shuangcheng	18.6	Tieling	4.5
Daan	37.5	Yushu	14.1	Fushun	4.3
Qianan	35.4	Kangping	15.6	Shenyang	4.7
Qianguo	36.8	Zhangwu	19.8	Dengta	4.9
Fuyu	39.1	Faku	10.5	Liaoyang	5.6
Tongyu	29.9	Xinmin	17.3	Benxi	2.7
Changling	24.3	Heishan	16.5	Haicheng	3.9
Shuangliao	20.5	Liaozhong	12.7	Panshan	4.0
Tongliao	29.6	Gongzhuling	3.6	Taian	6.7
Nongan	25.5	Changchun	6.4	Dawa	3.1
Dehui	23.6	Lishu	6.5	Yingkou	3.0
Zhenlai	43.8	Siping	3.8	Anshan	4.1
Haerbin	19.0	Cangtu	8.1		

[a] Higher values represent greater disaster risk.
[b] The drought disaster risk index to maize.

correlation was found between them ($r = 0.969$, $P < 0.01$). It could be inferred that the reduction extent of maize yield due to drought is similar to the risk extent of drought disaster to maize. Therefore, it may be possible to use the model proposed in this study for the assessment and regional classification of risk degree of drought disaster to maize. The losses of maize yield caused by drought disaster can be evaluated and predicted according to the risk degree of drought disaster to maize.

3.3.2. Risk assessment and regional classification

Classification of damage and risk areas is scientific basis for planning of regional disaster prevention and reduction. The traditional classification of damage and risk areas due to agro-meteorological disasters is often limited to comparisons of the damage condition caused by the disasters with the major climatic and meteorological factors contributing to the disasters. These comparisons are then used to decide the threshold of these climatic and meteorological factors when the disasters occur, their isolines were often used to delimit the damage and risk areas of the agro-meteorological disasters empirically. Consequently, research results have certain arbitrariness of artificial judgment (Gu et al., 1993). Fuzzy cluster analysis based on a relation matrix such as correlation coefficient, equivalence relation, similarity relation and fuzzy relation has been proved to is an objective and reliable mean for identifying characteristics and evaluating disaster areas in the field of agro-meteorological disasters (Gu et al., 1993; Zhang et al., 1998, 1999). In this paper, fuzzy cluster analysis was used to make quantitative, comparative and objective assessment and classification of drought disaster risk area for maize production in Songliao Plain. In the fuzzy cluster analysis, each district of 41 districts shown in Fig. 1 was regarded as an object to be clustered, two indexes DDRI and PRYM were taken as the standard classification. Then following fuzzy similarity a matrix (r_{ij}) was obtained through the fuzzy relationship according to Eq. (9)

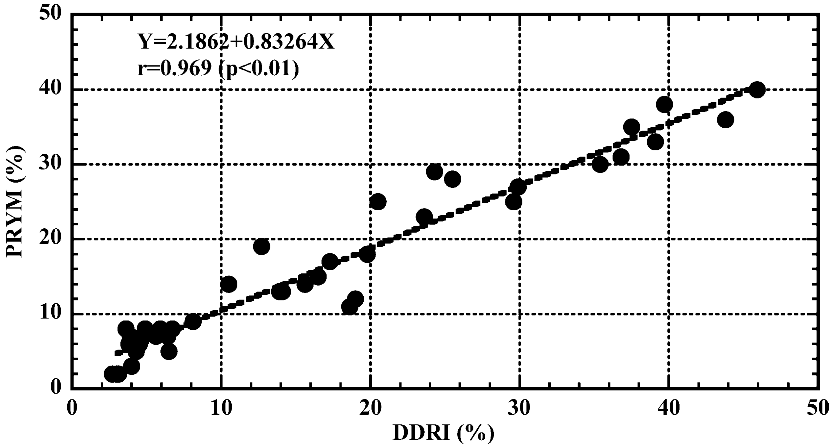

Fig. 10. Relationship between the drought disaster risk index to maize (DDRI) and the percentage reduction yield of maize due to drought (PRYM); r is the correlation coefficient, P the significant level.

(Gu et al., 1993; Zhang et al., 1998, 1999):

$$r_{ij} = 0.5 + \frac{r'_{ij}}{2}, \quad i, j = 1, 2, \dots, 41$$

then a fuzzy equivalence matrix can be created through $R \to R^2 \to R^4 \to R^8 \to R^{16} \to R^{32} \to R^{64}$. Thus, a clustering level λ ($0 \le \lambda \le 1$) will be determined as the clustering criterion according to clustering requirement. In this paper, the clustering level λ was established every 0.02 from 0.99 to 0.87, at last, with each λ given, all clusters can be obtained from each cut-off matrix shown as Fig. 11. As shown in Fig. 11, when λ is 0.89, the clustering result was obtained. Considering the results in Fig. 11, the risk degree of drought disaster to maize in Songliao Plain can be classified into four types. Table 3 shows the risk characteristics of maize caused by drought disaster in four types. From the results shown in Table 3, it can be known that the potential threat (adverse impact) and direct endangerment (loss) of drought disaster to maize-production decrease gradually from Type A to Type D. On the basis of this result, Type A, Type B, Type C and Type D were known as high risk, medium risk, low risk and slight risk, respectively.

Based on the above-mentioned results, four risk areas of drought disaster to maize in Songliao Plain were divided as shown in Fig. 12. The risk extent of drought disaster to maize in Songliao Plain shows the characteristics, which increases gradually from south to north and from east to west. So the characteristics of the areal distribution of drought disaster risk was identified based on the results as shown in Table 3 and Fig. 12. In addition, the information obtained from interviewing the district official committees in relation to result compiled was statistically evaluated and no significantly different. The result obtained by using fuzzy cluster analysis has certain distinct advantages with more quantitative, comparative, synthetic, objective and reliable analysis results than the result obtained by delimiting the risk areas using DDRI and PRYM isolines.

Comparing Figs. 4 and 5 with Fig. 12, it can be known that since Fig. 12 explains both the potential threat (adverse impact) expressed by a combination of the frequency of drought, the intensity and severity of drought, the spatial extent of damage caused by drought and regional production level of maize and the direct endangerment (yield loss) of drought disaster to

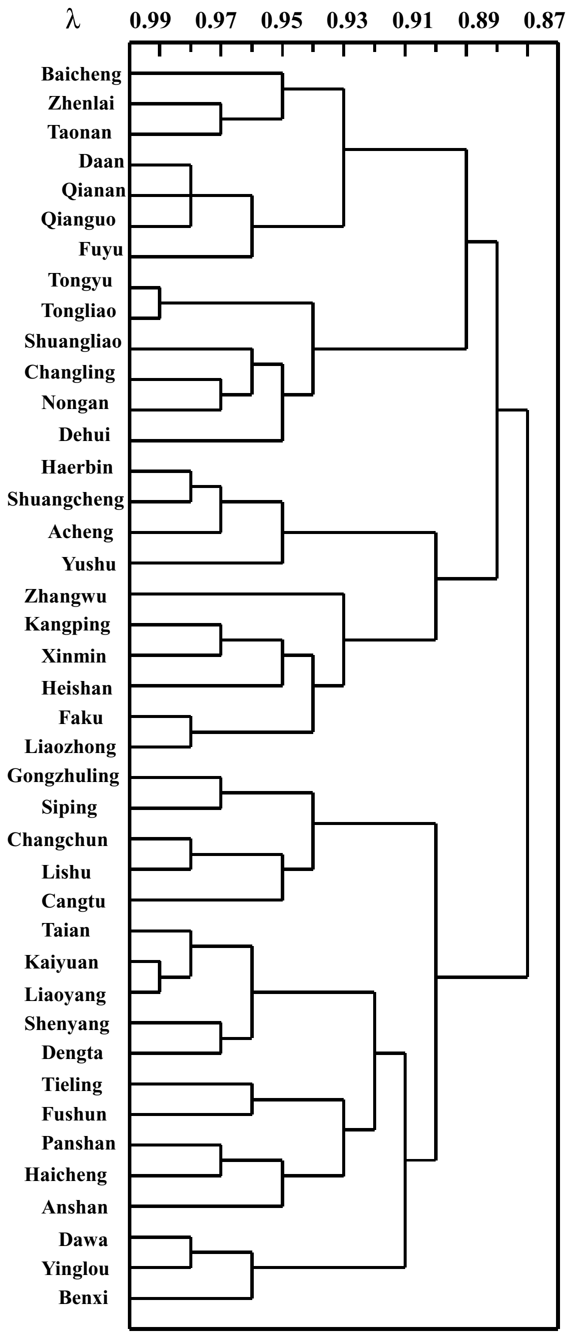

Fig. 11. Partition tree of risk classification of drought disaster with using fuzzy cluster analysis in Songliao Plain.

Table 3
The characteristics of the four types obtained from fuzzy cluster analysis

Type	District	DDRI[a] (%)			PRYM[b] (%)		
		Mean	Maximum	Minimum	Mean	Maximum	Minimum
A	Zhenlai, Baicheng, Taona, Daan, Qianan, Fuyu, Qianguo	39.7	45.9	35.4	34.7	40.1	30.3
B	Tongyu, Changling, Nongan, Dehui, Shuangliao, Tongliao	25.6	29.9	20.5	30.3	21.1	21.1
C	Haerbin, Shuangcheng, Acheng, Yushu, Kangping, Zhangwu, Faku, Xinmin, Heishan, Liaozhong	15.8	19.8	10.5	19.2	11.5	11.5
D	Gongzhuling, Changchun, Lishu, Siping, Cangtu, Kaiyuan, Tieling, Shengyang, Fushun, Dengta,Benxi, Liaoyang, Haicheng, Panshan, Dawa, Yingkou, Anshan, Taian	4.8	6.7	2.7	9.4	2.6	2.6

[a] The drought disaster risk index to maize.
[b] The percentage reduction yield of maize due to drought.

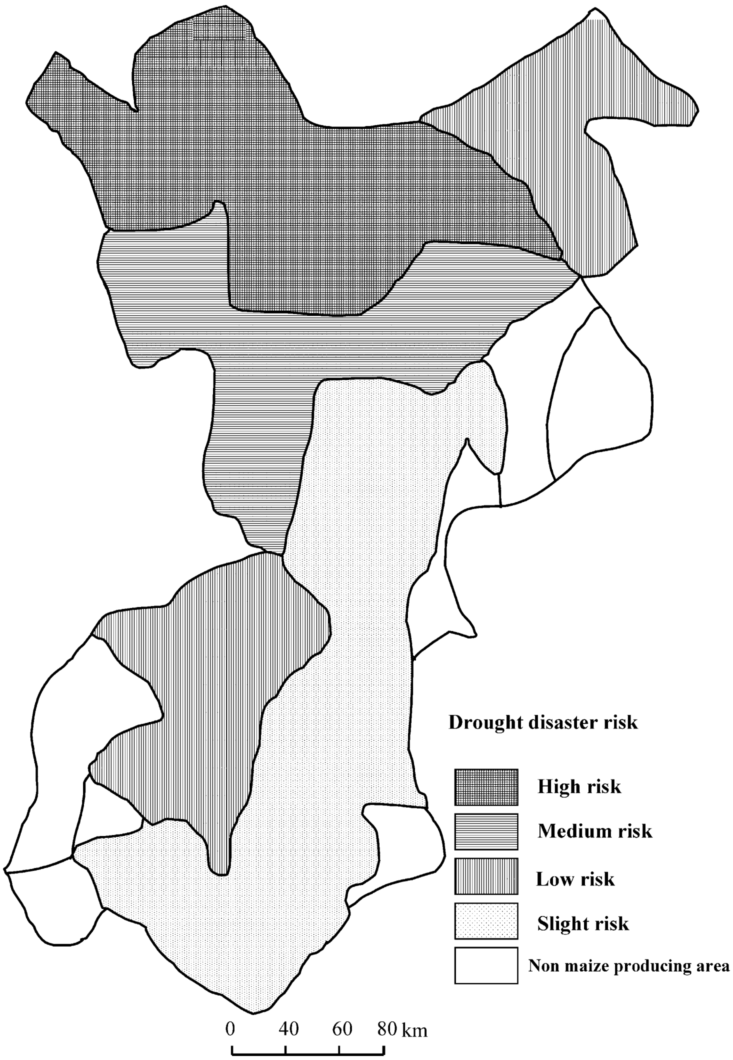

Fig. 12. Regional classification of drought disaster risk in Songliao Plain.

maize production, in conclusion, mapping of areas on basis of their risk to drought obtained by the integration of a number of variables concerned can provide practical guidelines and basis for the regional drought mitigation plan and agriculture planning.

4. Conclusions

An increasing number of studies are focusing on extreme climatic events such as drought hazard and relationships between climate changes and agricultural production (e.g. Dracup et al., 1980; Wilhite and Glantz, 1985; Lal et al., 1998; Agnew, 2000; Wilhite, 2000; Lansigan et al., 2000; Richard and Heim, 2000; Pidgeon et al., 2001; Abaurra and Cebrián, 2002). In contrast, less attention has been focused on influences of these extreme climatic events on agricultural outcomes. Furthermore, the previous studies on impact and risk assessment of drought to agricultural production mainly based on indices such as precipitation, evaporation, and crop simulation model (e.g. Maki and Kurose, 1987; Gu et al., 1993; Badini et al., 1997; Keating and Meinke, 1998; Yamoah et al., 2000; Ewert et al., 2002). However, the damaging effects and crop losses of droughts and socioeconomic factors contributing to drought risk are not taken into account. Data to use in the crop simulation model are not easily available. However, a clear understanding of the vulnerability of food crops as well as the agronomic impacts of drought hazard enable one to implement adaptive strategies to mitigate its negative effects. In this study, drought disaster is regarded as a multiple system with natural, social and economic components. Drought disaster risk is considered the potential adverse effects of drought as a product of the frequency of drought, the intensity and severity of drought, the spatial extent of damage caused by drought and regional production level of maize from the viewpoints of climatology, geography, disaster science, environmental science and risk assessment and so on. This paper presents the a risk assessment framework for the characterization and quantification of the agronomic impacts of drought hazard based on historical climate, crop yield, crop sown area, crop damaged area and crop loss data. Application of the proposed methods to maize-growing region of Songliao Plain, China has shown that they are useful in performing the impact and risk assessment associated with drought hazard, and that the resulting drought disaster risk map may be used by the different district authorities to develop drought disaster risk protection plans. The methods have certain advantages, such as having simple processes and easily available data, and providing quantitative, comparative, synthetic, objective and analysis results. The methodology employed in this study can be applied to the study of other agro-meteorological disasters. The information from this study is potentially useful reference in decision making of drought disaster prevention and agricultural sustainable development planning. Two further researches remain to assess impacts of drought hazard on maize yield in order to determine their consequences for maize yield by developing agronomic models as described by Keating and Meinke (1998), and to develop an effective and realistic drought disaster reduction and mitigation program based on the results of drought disaster risk assessment.

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