Research Article

Trends in Moisture Index, Farmland Area, and Their Combined Effects on Grain Production in Northern China

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China policies and Grain-for-Green Project have led to changes in farmland area and grain production. Climate change was also occurring during this period. To analyze the effects of land use and climate change on grain production, the area of farmland in northern China during 1988–2008 was determined from remote sensing images, a moisture index (MI) was calculated from daily meteorological data obtained from weather stations, and unit grain production was obtained from statistical yearbooks. Using statistical and spatial analyses, we determined that MI decreased across most of the study area during this period. This decrease in humidity caused humid zones to decrease and semiarid areas to increase. Combined effects of decreased humid area and conversion of farmland resulted in a decrease in agricultural land in humid areas and an increase in semiarid and arid areas. Increases in unit grain production, machine power, and irrigated farmland area led grain production to increase from 122,799,081 to 188,532,597 ton in humid areas, from 28,875,900 to 115,976,814 in semiarid areas, and from 7,622,100 to 15,490,026 in arid areas, respectively. Increased unit grain production and farmland resulted in increased importance of semiarid areas for grain production.

1. Introduction

Grain production is one of the top priorities for the Chinese government, who has issued a number of policies aimed at maintaining and improving grain production, including "Ten Policies to Further Promote Agricultural Economic Development" in 1985 and "Guidelines to Strengthen Works in Rural Areas" in 1986. These policies encouraged farmers to expand farmland by considering unused land areas. In 1999, the government stopped collecting tax from agricultural products and began to provide subsidies to farmers who planted grains.

In general, those policies caused grain production to increase continuously in China from 1978 to 2000 [1]. However, rapid urbanization caused a significant decline in farmland area. About 17750 km^2 farmlands were converted to urban use from 1990 to 2010 [2]. The central government launched the Grain-for-Green project in 1999, resulting in

conversion of eroded farmland on slopes to forest or grass-land [3–5]. The Ministry of Land Resources has also taken various measures (e.g., farmland replenishing programs) to compensate for loss of farmland by land reclamation [6].

Climate change has also affected agricultural areas in recent decades. The average global surface temperature has increased over the past century by 0.6°C, and precipitation has increased in some regions and decreased in others in the Northern Hemisphere [7]. In China, precipitation increased by 2% from 1950 to 2000 in the south and decreased by 4–11% in the north, while temperature decreased by 1.2°C in the south and increased by 2.5°C in the north [8–10].

Climate zones in northern China are primarily humid, semiarid, and arid. The dynamic spatial patterns of the humidity index in northern China and of farmland character-istics in various moisture zones have not been fully clarified. Grain production is affected by many factors, including climate, chemical fertilizer application, irrigation, cropping

index, and farmland area [11–14]. The combined effects of these factors on the dynamics of grain production remain to be elucidated in northern China. The purpose of this study was to analyze the spatial patterns of the humidity index, changes in farmland area, and their possible effects on grain production.

2. Study Area

Northern China, with ten provinces, three autonomous regions, and two major cities, comprises $5.6 \times 10^6 \, \text{km}^2$ and was populated by 0.55 billion inhabitants in 2008 (Figure 1). The average annual temperature varies from −5.5 to 15.3°C, and average annual rainfall is between 5 and 1400 mm. The largest desert (Taklimakan Desert) is located primarily in Xinjiang Autonomous Region. Cropping systems consist mainly of single and double cropping. Single-cropping systems are primarily distributed in the northern part, and double-cropping systems are found in the southern part of this area. The major crops in northern China include rice, corn, wheat, and millet.

3. Data and Methodology

3.1. Data Sources. Three main datasets were used to analyze the effects of humidity and farmland area on grain production. The humidity index was calculated using the Penman-Monteith equation and the Thornthwaite moisture index. The input data were daily maximum and minimum temperatures, daily precipitation, wind velocity, and actual water vapor pressure from 1988 to 2009. Those data were obtained from the 174 weather observation stations in northern China and recorded by the State Meteorological Bureau. The second dataset, comprising farmland cover data in the late 1980s and 2008, was interpreted from Thematic Mapper/Enhanced Thematic Mapper (TM/ETM) images acquired from the United States Geological Survey (USGS) (http://www.usgs.gov/). The third dataset, unit grain production, and grain planting area at the district level in 1989 and 2008 were collected from local and state Statistical Bureau yearbooks [15–18]. No grain-production data were available for Inner Mongolia Autonomous Region in 1989, so 1988 data were used.

3.2. Methodology. The moisture index (MI) at each station for each year was calculated by combining the improved Penman-Monteith equation and the Thornthwaite Moisture Index (1) as follows:

$$\text{PET} = \frac{0.408\Delta \left(R_n - G \right) + r \left(900 / \left(T + 273 \right) \right) U_2 \left(e_s - e_a \right)}{\Delta + r \left(1 + 0.34 U_2 \right)},$$

$$\text{MI} = 100 \times \left(\frac{\text{Precipitation}}{\text{PET}} - 1 \right),$$

(1)

where PET is potential evapotranspiration ($\text{mm} \, \text{d}^{-1}$), R_n is net canopy radiation ($\text{MJ} \, \text{m}^{-2} \, \text{d}^{-1}$), G is soil heat flux ($\text{MJ} \, \text{m}^{-2} \, \text{d}^{-1}$), T is air temperature at 2 m height (°C), U_2 is wind velocity at 2 m height ($\text{m} \, \text{s}^{-1}$), e_a are actual vapor
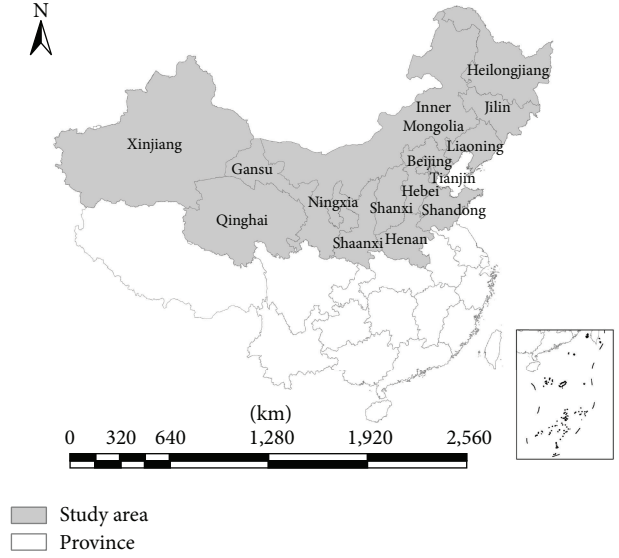

FIGURE 1: Location of study area.

pressure (kPa), Δ is the slope of the saturation vapor pressure curve ($\text{kPa} \, ^\circ\text{C}^{-1}$), r is the psychrometer constant ($\text{kPa} \, ^\circ\text{C}^{-1}$), and MI represents the moisture index. The values of T, U_2, and e_a were obtained from daily weather station data. Recommended FAO values for G, Δ, r, and R_n were used. These values have been widely used for calculating PET.

The MI for all meteorological data in each year was interpolated with ANUSPLINE software to a raster resolution of 100 m. The linear slope of MI in northern China from 1989 to 2008 was calculated using the least-squares method for each pixel in the Economic and Social Research Institute's (ESRI) ArcGIS and was used as the indicator of an average year-to-year trend for each pixel. Positive and negative slopes indicate an overall increase and decrease, respectively, as calculated using

$$S = \frac{n \sum_{i=1}^{n} m_i x_i - \sum_{i=1}^{n} m_i \sum_{i=1}^{n} x_i}{n \sum_{i=1}^{n} m_i^2 - \left(\sum_{i=1}^{n} m_i \right)^2},$$

(2)

where S is the slope, X_i is the value of precipitation for year i ($i = 1, 2, 3, \ldots, n$), and m_i is the sequence number of the year ($m_1 = 1, m_2 = 2, m_3 = 3, \ldots$, and $m_n = n$). Positive and negative values indicate increasing and decreasing trends, respectively.

Landsat images covering northern China were preprocessed by correcting for geometric and radiometric distortion. In our previous study, we collected and applied geometric correction to multispectral scanner (MSS) data from the 1980s; these MSS data were used for geometric correction of the Landsat data (late 1980s and 2008). Human-machine interaction interpretation was performed on remote sensing images using ESRI's ArcGIS 9.3 platform. Land cover was classified into six categories: farmlands (cultivated for crops), woodlands (covered with trees including arbors, shrubs, and forestry plantations), grasslands (covered by herbaceous plants), water bodies (natural or facilities for irrigation and water containment), unused lands (areas not
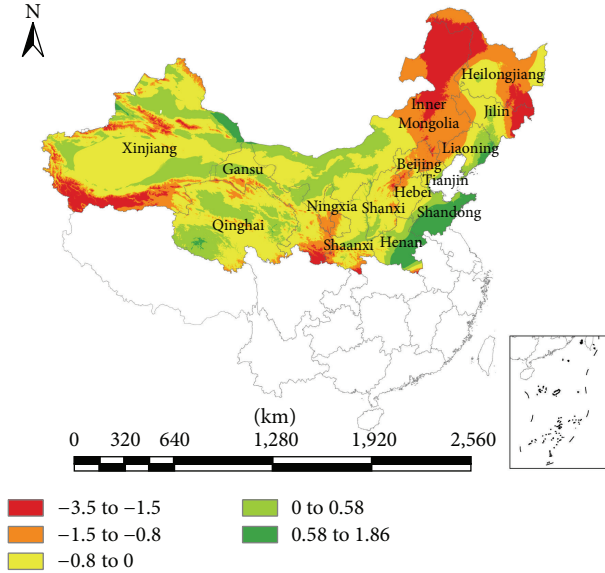
FIGURE 2: Slope of moisture index in northern China from 1989 to 2008.

Legend:
- −3.5 to −1.5
- −1.5 to −0.8
- −0.8 to 0
- 0 to 0.58
- 0.58 to 1.86

TABLE 1: Area of humid, semiarid, and arid zones in northern China.

Humidity region	1989 (ha)	2008 (ha)	Percent change
Humid areas	283,915,219	219,482,992	−22.7
Semiarid areas	105,227,195	153,469,562	45.8
Arid areas	173,833,567	190,023,428	9.3

Note: minus means decrease.

TABLE 2: Area of farmland in humid, semiarid, and arid zones in northern China.

Humidity region	The late 1980s		2008	
	Area (ha)	Percent (%)	Area (ha)	Percent (%)
Humid	70,778,220	72.0	52,196,864	51.0
Semiarid	20,403,300	20.8	40,440,571	39.5
Arid	7,088,430	7.2	9,663,439	9.4
Total	98,269,950	100	102,300,874	100

put into practical use or that are difficult to use), and built environment areas (urban and rural settlements, factories, and transportation facilities). Farmland area in the late 1980s and 2008 was extracted from these combined data.

Total grain production is affected by unit grain production and planting area. Farmland area and grain cropping index are the main factors that determine grain planting area. The grain cropping index was calculated using

$$\mathrm{PI} = \frac{A_g}{A_f}, \tag{3}$$

where PI is the cropping index, A_g is the grain planting area (ha), and A_f is the area of farmland in a certain area (ha).

Northern China was classified into three moisture regions according to Feddema [19] and Grundstein [20]. Regions with MI less than −66 were classified as arid, those with MI between −66 and −33 were classified as semiarid, and those with MI greater than −33 were classified as humid. The spatial analysis function of ESRI's ArcGIS was used to analyze the individual and combined effects of moisture index, farmland area, unit grain production, and planting index on grain production.

4. Results and Analysis

4.1. Moisture Index. Daily weather observation data were input into (1) to obtain MI data for 1988–2009 for northern China, and the linear slope of MI from 1989 to 2008 was calculated. MI tended to decrease in most areas (Figure 2), with the most rapid decrease mainly occurring in northeastern areas. Increases in MI occurred in the southeast, north, and some middle areas of northern China.

Annual MI values in northern China for 1988–1990 were considered as the 1989 MI value, and MI values for 2007–2009 were considered as the 2008 value. The mean 1989

and 2008 MI values were used to classify areas into humid, semiarid, and arid zones (Figure 3). Humid zones were mainly concentrated in the southern and eastern parts of the study area, with only a small portion in the far northwestern part.

Trends in MI during the study period revealed that humid zones decreased and semiarid and arid zones increased (Table 1 and Figure 3). Humid areas decreased from 283,915,219 ha in 1989 to 219,482,992 ha in 2008, with a decrease of 22.7%. The decrease in humid areas occurred mainly in the middle and northeastern parts of northern China. The area of semiarid zones in 1989 was 105,227,195 ha and increased to 153,469,562 ha, with an increase of 45.8%. The increased semiarid areas mainly occurred in the middle and northeastern parts of northern China. The area of arid zones in 1989 was 173,833,567 ha and increased to 190,023,428 ha in 2008, with an increase of 9.3%. The increase in arid areas occurred mainly in the western part of northern China.

4.2. Farmland Changes. The results of visual interpretation of remote sensing images are presented in Figure 4 and Tables 2 and 3. Farmland is distributed primarily in the eastern and southern parts of northern China. The area of farmlands in the late 1980s was 98,269,950 ha (Table 2), with 70,778,220, 20,403,300, and 7,088,430 ha in humid, semiarid, and arid areas, respectively (Table 2). The net effect of the expansion of farmland and loss of farmed area to urbanization was an increase in agricultural area to 102,300,874 ha in 2008. This net increase suggests that the area of farmland expansion was greater than that of farmland loss.

The rapid expansion of urban areas occurred mostly in eastern China (Figure 5(a)). Approximately 3,808,569 ha of farmland were converted to urban area from the late 1980s to 2008 (Table 3). Most conversion of farmland to urban areas occurred in humid areas because these areas have a greater proportion of the population and a stronger economy.

The area of other land-use categories converted to farmland from the late 1980s to 2008 was 19,078,701 ha (Table 3). In the 1980s, urbanization and industrialization in China were
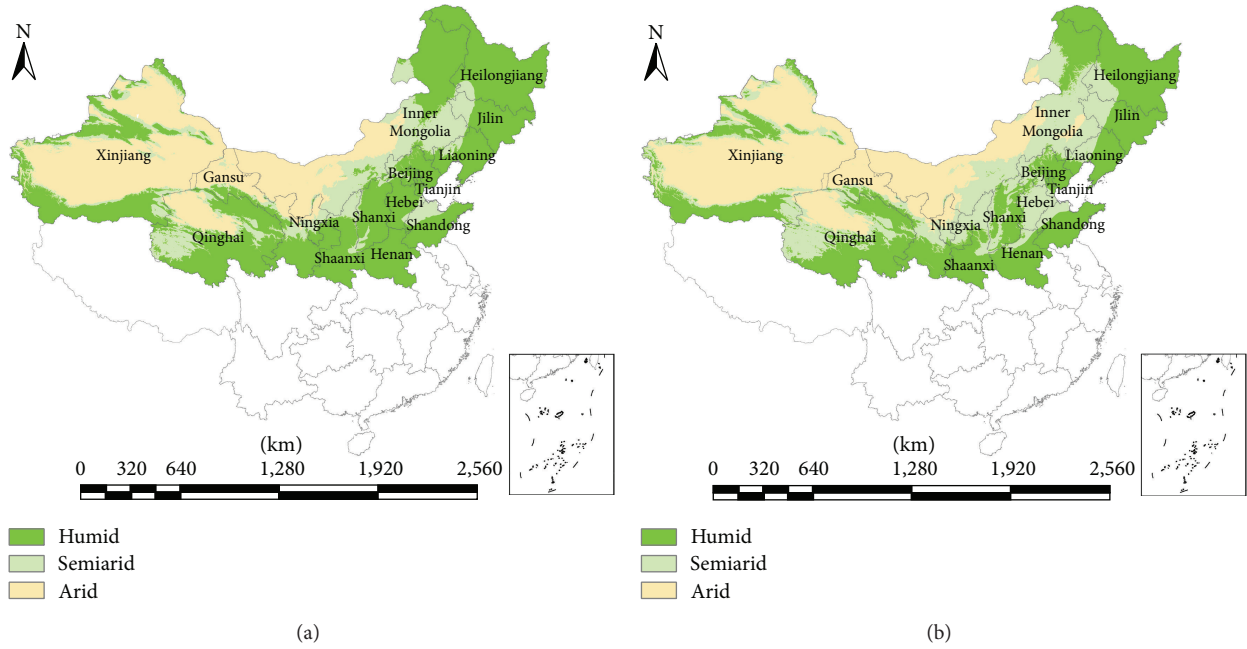
(a)

(b)

FIGURE 3: Humid, semiarid, and arid zones in northern China: (a) 1989 and (b) 2008.
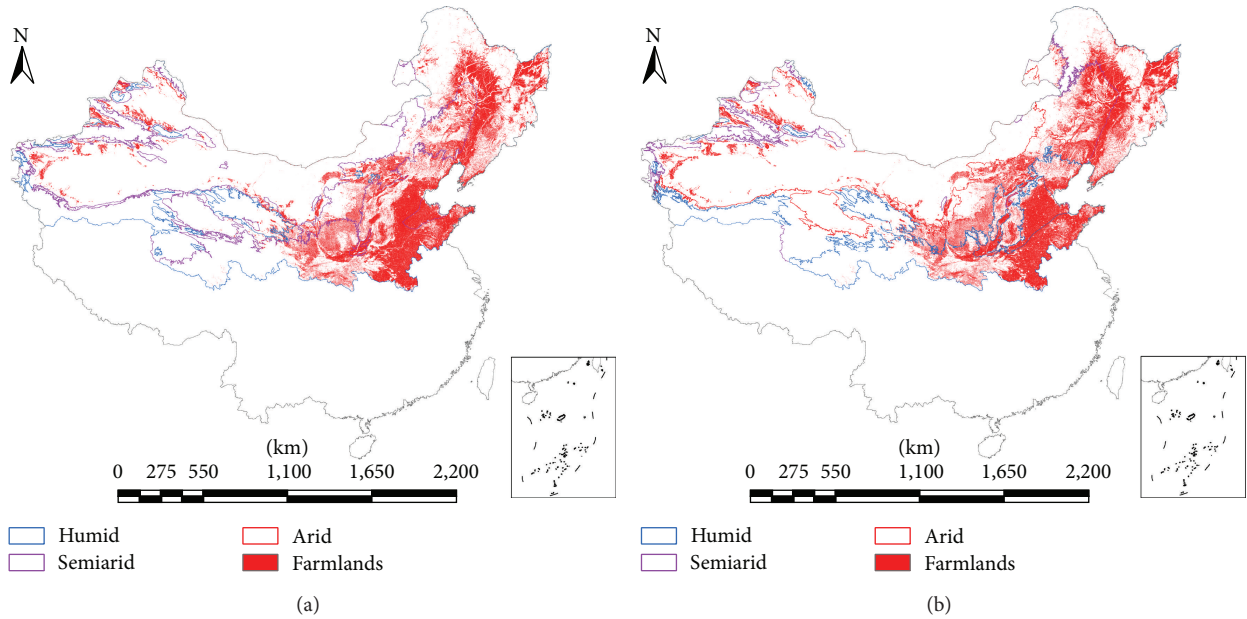

(a)

(b)

FIGURE 4: Farmland in northern China: (a) the late 1980s and (b) 2008.

TABLE 3: Conversion between farmland and other land-use categories from the late 1980s to 2008.

Humid region	Conversion from farmland to urban area		Conversion from farmland to other land		Conversion from other land uses to farmland	
	Area (ha)	Percent (%)	Area (ha)	Percent (%)	Area (ha)	Percent (%)
Humid	2,832,457	74.4	10,179,839	67.5	11,843,001	62.1
Semiarid	726,516	19.1	3,668,100	24.3	4,542,250	23.8
Arid	249,596	6.6	1,232,730	8.2	2,693,450	14.1
Total	3,808,569	100	15,080,669	100.0	19,078,701	100.0

(a)

Farmland → other land use

(b)

Farmland → urban areas
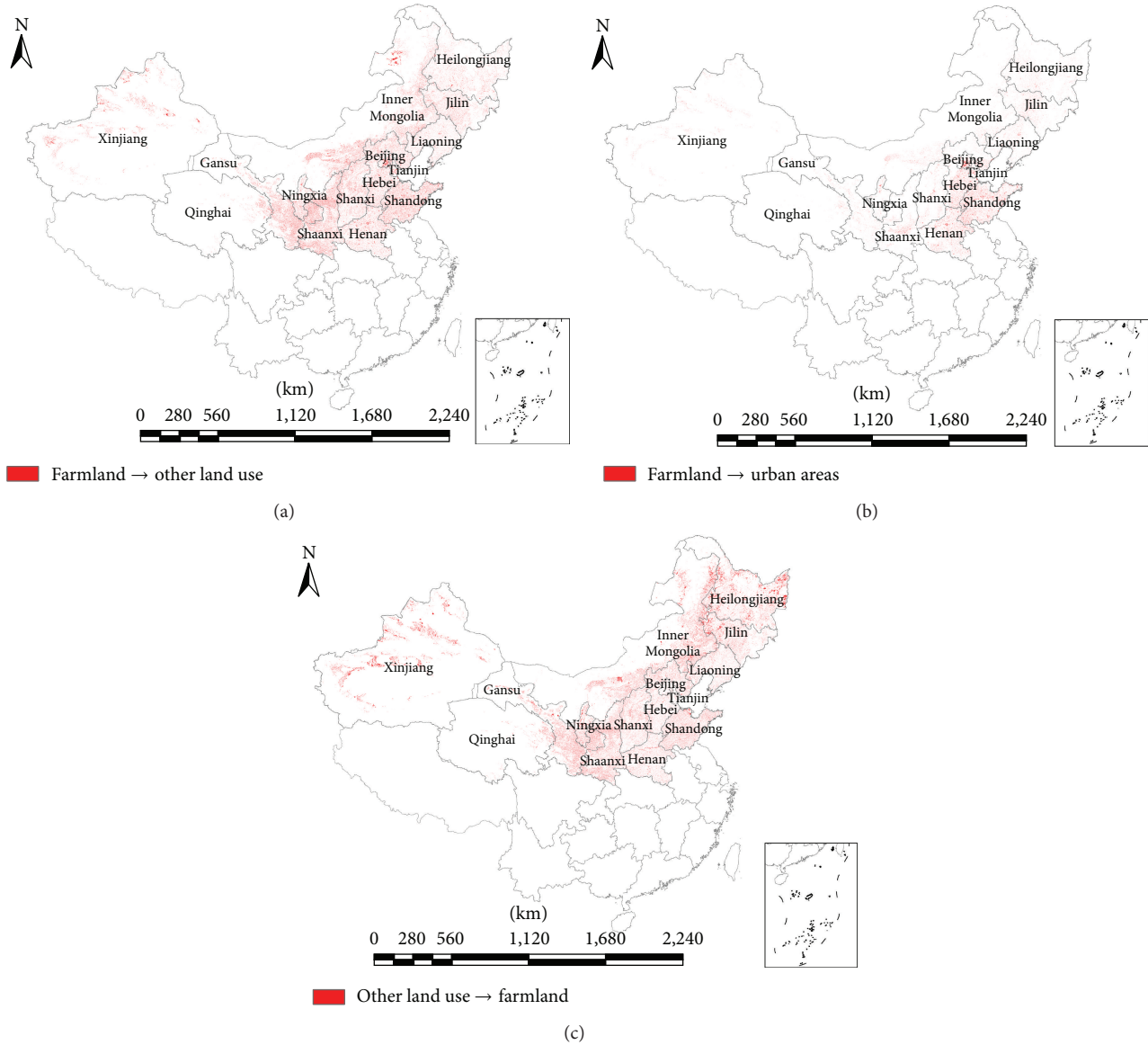

(c)

Other land use → farmland

FIGURE 5: Farmland dynamics from the late 1980s to 2008: (a) conversion from farmland to urban areas, (b) conversion from farmland to other land-use types, and (c) conversion from other land-use types to farmland.

still occurring at relatively low rates, and the government's priority was to maintain and improve grain production. The Chinese central government issued polices to ensure sufficient grain production to meet the increasing demand, causing farmland area to increase.

In contrast, the area of farmland that was converted to other land uses during this period was 15,080,669 ha, and most of this conversion took place from 1999 to 2008. The expansion of farmland before 1999 resulted in severe soil erosion, and the government launched the Grain-for-Green project in 1999 to promote conversion of eroded farmland to other land-use categories, such as forest or grassland.

Farmland area tended to increase from the late 1980s to 2008. The decreased humidity index indicated that semiarid and arid areas expanded in the middle and western parts of

northern China. The combined effects of decreased MI and changes in farmland area resulted in a lower percentage of cropland in humid areas and a higher percentage in semiarid and arid areas by 2008.

4.3. Grain Production. Grain production at the district level in the late 1980s and 2008 was calculated and analyzed with MI in ArcGIS (Table 4). Northern China produced 159,297,081 t in the late 1980s, and the percentage of grain production produced in humid areas was higher than that produced in semiarid and arid areas (Table 4).

Conversion of farmland to other land-use categories led to a loss in grain yield, which was estimated by average yield in 2008 at the district level (Table 5). Conversion of

TABLE 4: Grain production in the late 1980s and 2008.

Grain production	The late 1980s		2008		Percent increase (%) (late 1980s–2008)
	Tons	Percent (%)	Tons	Percent (%)	
Humid zone	122,799,081	77.1	188,532,597	58.9	53.5
Semiarid zone	28,875,900	18.1	115,976,814	36.2	301.6
Arid zone	7,622,100	2.4	15,490,026	4.8	103.2
Total	159,297,081	100	319,999,437	100	100.9

TABLE 5: Grain production changes from farmland conversion from the late 1980s to 2008.

Humid zone	Grain production change					
	Conversion of farmland to urban areas		Conversion of farmland to other land		Conversion of other land uses to farmland	
	Tons	Percent (%)	Tons	Percent (%)	Tons	Percent (%)
Humid	−14,593,629	−76.4	−38,795,588	−67.2	46,928,732	58.9
Semiarid	−3,305,860	−17.3	−12,558,400	−21.7	17,639,600	22.1
Arid	−1,205,870	−6.3	−6,411,010	−11.1	15,108,800	19.0
Total	−19,105,359	100	−57,764,998	100	79,677,132	100

farmland to urban areas caused grain production to decrease by 19,105,359 t, and conversion to other land-use categories caused grain production to decrease by 57,764,998 t (Table 5 and Figure 6). Urbanization corresponding to a 0.04% loss of farmland resulted in a 0.06% decrease in grain production across northern China (Figure 6), indicating higher unit grain production in agricultural areas. Conversion of other land-use categories to farmland led to increased grain production, by 79,677,132 t from 1989 to 2008. The net effect of these changes in land use was a slight increase in grain production in northern China.

Grain production in northern China increased from the late 1980s to 2008 (Table 4). Expanded farmland and improved management were the main factors causing the rapid increase in grain production in semiarid areas.

5. Discussion

5.1. Factors That Caused MI Changes. The moisture index tended to decrease in most of the study area and to increase in the southeastern and some western and middle parts of northern China from 1989 to 2008. Temperature and precipitation were the main factors causing these changes. The Juxian, Yuxian, and Kuerle weather observation stations were selected for analysis of the causes of increased MI in humid areas and of decreased MI in semiarid and arid areas (Figures 7–9).

Annual precipitation increased at Juxian station during the study period and decreased at the other stations. The slope of annual precipitation at Juxian station from 1989 to 2008 was 6.6696; annual precipitation in 1989 was 504 mm, increasing to 765.8 mm in 1999 and 841.5 mm in 2008. The slope of annual precipitation at Yuxian station was −3.026. Its annual precipitation was 382 mm in 1989, decreasing to 270.8 mm in 1999 and 289.5 mm in 2006. The slope of
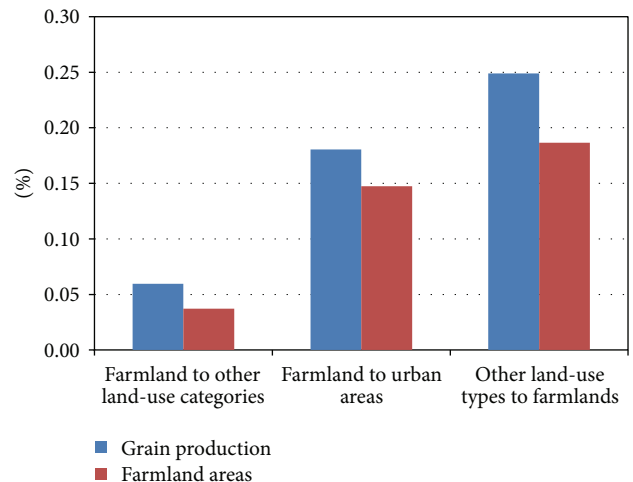

FIGURE 6: Relationship between percentage of farmland area and grain yield.

annual precipitation at Kuerle station was −0.877. Its annual precipitation was 84.4 mm in 1989, decreasing to 78.3 mm in 1996 and 69.5 mm in 2008.

The mean daily temperature showed an increasing trend at all of the weather stations (Figure 8). At Yuxian station, mean daily temperature was 7.3°C in 1989 and increased to 8.2°C in 2000 and 9.1°C in 2007. The mean daily temperature at Kuerle station in 1989, 1998, and 2008 was 12.0, 12.1, and 12.4°C, respectively, and the corresponding values at Juxian station were 12.3, 12.4, and 12.9°C.

The annual PET showed an increasing trend at all of the weather stations (Figure 10). At Yuxian station, annual PET was 630 mm in 1989 and increased to 679 mm in 1999 and 764 mm in 2007. The annual PET at Kuerle station in 1989,
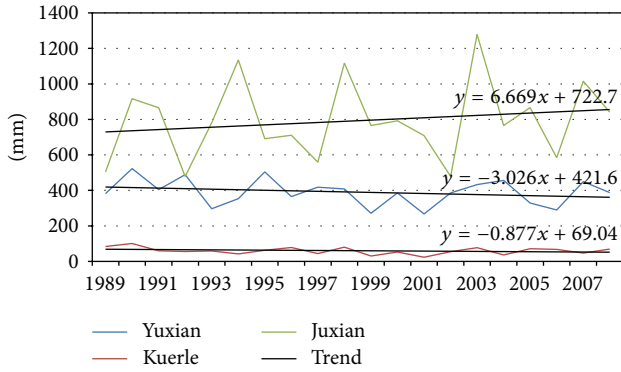
FIGURE 7: Precipitation recorded at the selected weather stations from 1989 to 2008.
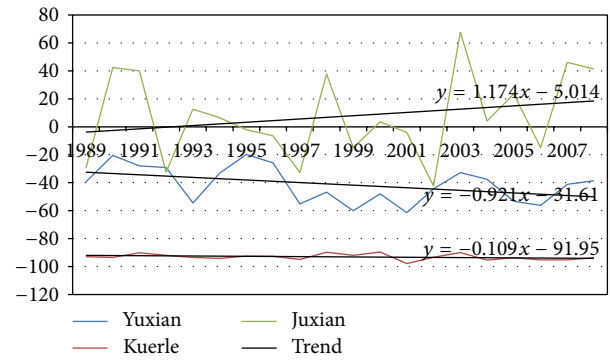

FIGURE 8: Temperature recorded at the selected weather stations from 1989 to 2008.

FIGURE 9: Moisture index at the selected weather stations from 1989 to 2008.

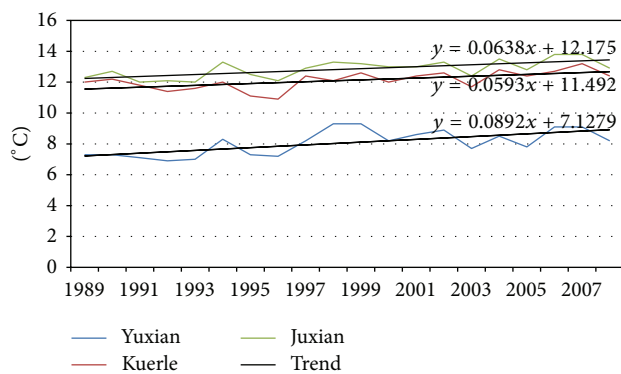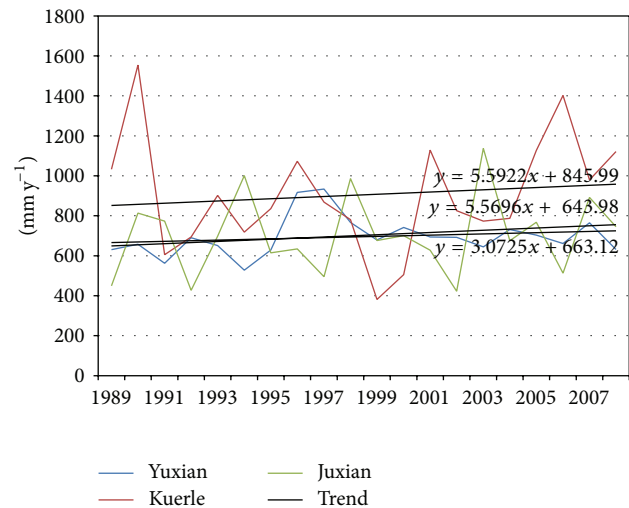FIGURE 10: PET at the selected weather stations from 1989 to 2008.

1996, and 2008 was 1033, 1072, and 1120 mm, respectively. The annual PET at Juxian station in 1989, 1999, and 2008 was 449, 676, and 745 mm, respectively.

The overall effect of the increased temperature, PET, and precipitation observed at Juxian weather station was an increase in the humidity index such that the annual MI was −29.7 in 1989 and increased to −14.9 in 1999 and 41.3 in 2008. These values indicate that increased annual precipitation was the main factor in the increased MI in the eastern and southern parts of northern China. However, the combined results of increased temperature, PET, and decreased precipitation caused a decrease in MI at the other two stations. At Yuxian, the annual MI was −39.4 in 1989 and decreased to −55.2 in 1997 and −56.2 in 2006; the annual MI at Kuerle was −92.9 in 1989, −94.9 in 1997, and −95.2 in 2007. In combination, the decreased annual precipitation and increased temperature led to decreased MI across most of northern China (Figure 9).

5.2. Grain Production Dynamics and Its Driving Forces. Grain production increased in all areas of northern China from 1989 to 2008. The reasons for this trend included increased farmland area (Table 2) and increased unit grain yield (Table 6). Unit grain yield is affected by many factors, including temperature, precipitation, chemical fertilizer, unit grain yield,

and grain planting area [21–24]. We further analyzed the main factors causing changes in unit grain yield in Yuxian and Juxian counties and determined that the cropping index and irrigated areas decreased in Juxian, indicating that the increased unit grain yield was mainly caused by chemical fertilizer application and increased machine power. In Yuxian County, the cropping index decreased, whereas unit grain yield and other factors increased. Thus, it can be concluded that the increased unit grain yield in semiarid areas was mainly caused by increased chemical fertilizer application, machine power, and percentage of irrigated farmland area.

6. Conclusions

The moisture index in northern China was calculated from daily weather observations at meteorological stations from 1988 to 2008. Farmland area during this time period was determined by visual interpretation of remote sensing images, and grain production at the district level was obtained from statistical data. Using spatial and statistical analyses, we determined that MI decreased across most of northern China and increased only in southeastern areas and some

TABLE 6: Factors that affect grain yield.

County	Year	Unit grain yield (kg/ha)	Cropping index	Chemical fertilizer applied (kg/ha)	Total power of agricultural machinery (W/ha)	Percentage of irrigated area (%)
Juxian	1989	4,635	1.22	304.3	2,648.2	53.9
	2008	6,382.6	0.78	1455.5	10,166.2	50.0
Yuxian	1989	809.8	0.75	65.1	688.3	25.4
	2008	911.0	0.73	106.9	3,453.0	35.0

parts of the middle of northern China during the study period. Decreased MI caused humid zones to decrease and semiarid and arid zones to increase. Loss of farmland due to urbanization mainly occurred in humid areas of eastern China. The combined effects of decreased MI and land-use changes led to a lower percentage of cropland in humid areas and a higher percentage of cropland in semiarid and arid areas by 2008. Unit grain yield increased in northern China. Increased unit grain yield in humid and semiarid areas was mainly caused by chemical fertilizer application and increased machine power; in semiarid areas, increased irrigation also contributed to the increase in unit grain yield. Expanded farmland and increased unit grain yield caused grain production to increase continuously and resulted in increased importance of grain production in semiarid areas.

Conflict of Interests

The authors declare that there is no conflict of interests in this paper.

Acknowledgments

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