Impacts of Recent Climate Change on Dry-Land Crop Water Consumption in the Northern Agro-Pastoral Transitional Zone of China

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ABSTRACT

Climate change has substantially impacted crop growth and development in the northern agro-pastoral transitional zone. Examination of the response of crop water consumption to climate change may provide a guide for adapting local agricultural production and ecological construction to new realities. The water consumption of three local crops (wheat, naked oats, and potatoes) is examined for Wuchuan County in the northern agro-pastoral transitional zone of China using meteorological data from 1960 to 2007 and soil moisture data from 1983 to 2007. The relationships between climate change and the crop water consumption are discussed. The results show that Wuchuan experienced both a warming trend and a reduction of precipitation between 1960 and 2007. The annual mean surface air temperature increased at a rate of 0.04℃ yr^{-1} and the annual precipitation decreased at a rate of 0.7 mm yr^{-1}. Both trends are particularly pronounced between 1983 and 2007, with an increase in annual mean temperature of 0.09℃ yr^{-1} and a decrease in annual mean precipitation of 2.1 mm yr^{-1}. Crop water consumption decreased between 1983 and 2007 for wheat (1.65 mm yr^{-1}), naked oats (2.04 mm yr^{-1}), and potatoes (3.85 mm yr^{-1}). Potatoes and naked oats consume more water than wheat. Climate change has significantly impacted crop water consumption. Water consumption and rainfall during the growing season are positively correlated, while water consumption and active accumulated temperature are negatively correlated. Compared to precipitation, accumulated temperature has little impact on crop water consumption. Recent climate change has been detrimental for crop production in Wuchuan County. Adaptation to climate change should include efforts to breed drought-resistant crops and to develop drought-resistant cultivation techniques.

Key words: climate change, impact, dry-land crop water consumption, northern agro-pastoral transitional zone of China

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1. Introduction

The northern agro-pastoral transitional zone of China encompasses the shift in land use between an agricultural area to the east and a grassy area to the west. This transitional zone is located in a semi-arid climate and is very sensitive to climate change (Zhang Shengjun et al., 2006; Qi et al., 2012). The temperature of this region has increased in recent decades, while the precipitation has decreased (IPCC, 2007).

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These climate changes have exerted visible impacts on the ecological system (Crane et al., 2011) as well as crop growth and development (Lobell et al., 2011).

Water is a key factor affecting the growth and development of crops in the northern agro-pastoral transitional zone (Pan et al., 2010; Xia et al., 2010). Crop water consumption refers to evaporation and transpiration by agricultural plants during growth and development. The water supply in the northern agro-pastoral transitional zone is always inadequate, so actual crop water consumption is typically lower than water demand (Shi et al., 2007). Currently, several methods (Ma et al., 2005; Zhang Hexi et al., 2006) can be used to calculate crop water demand and consumption, including water balance, lysimeter measurements, the FAO (Food and Agriculture Organization of the United Nations) Penman-Monteith method (Allen et al., 1998), energy balance, and remote sensing. Lysimeter measurements are the most accurate of these methods, but the instruments are expensive and data coverage is limited due to an insufficient number of available instruments (Zhang et al., 2001). The precision achieved by the Bowen Ratio-equilibrium Energy Method is relatively low (Prueger et al., 1997). The Penman-Monteith formula is the standard method for estimating evapotranspiration and is applied worldwide, but calculation of this formula is complicated due to large number of parameters required (Allen et al., 1998). By contrast, the water balance method is based on clear and sensible principles and is easy to calculate, with universal applicability (Zhang et al., 2001; Si et al., 2005; Liu and Liu, 2006; Lie and Tang, 2007).

A large number of previous studies have analyzed crop water consumption, but few have characterized crop water consumption under the background of climate change. Understanding how climatic change influences crop water consumption will help to guide local agricultural production and ecological development. Here, the response of crop water consumption to recent climate change is explored in Wuchuan County of Inner Mongolia in the northern agro-pastoral transitional zone of China. The analysis is based on meteorological data from 1960 to 2007 and soil moisture data from 1983 to 2007. The characteristics of climate change are analyzed along with water consumption by three local crops (wheat, naked oats, and potatoes) during their respective growth periods. The relationships between climate change and crop water consumption are discussed.

2. Methods

2.1 Study area

Wuchuan County (41°08.344′N, 111°17.580′E) is located in the middle of the northern agro-pastoral transitional zone and has the continental monsoon climate typical of the area. The average annual air temperature is approximately 3.0℃ and the average annual precipitation is approximately 250–400 mm, mainly occurring during summertime. The frost-free period lasts approximately 90–120 days. The annual mean wind speed is 4.5 m s^{-1}. The strongest winds occur in May, when the monthly mean wind speed increases to 6 m s^{-1}. The soil is chestnut, with a bulk soil density of 1.2–1.7 g cm^{-3} at 0–50 cm. The cropping system is focused on one harvest per year.

2.2 Data source

The Weather Service of Wuchuan County has provided the data used for the analysis. This dataset includes meteorological data from 1960 to 2007, soil moisture data from 1983 to 2007 (reported separately for wheat, naked oat, and potato fields), and crop yields of wheat, naked oats, and potatoes from 1983 to 2007.

2.3 Research methods

The mass water content is calculated in the 0–50-cm soil layer for each type of crop field between 1983 and 2007. The water consumption by each crop during the growth period is then calculated using the water balance method.

Natural rainfall represents the main source of agricultural water in the study area. Crops mainly consume water from soil moisture prior to planting and precipitation during the growth period. Crop water consumption includes both crop transpiration and soil evaporation (i.e., evapotranspiration or ET). The water balance equation is

$$\Delta W = P + I + G - \mathrm{ET} - R_{\mathrm{n}} - D, \qquad (1)$$

where ΔW is the variation of the soil moisture over a period of time, P is the precipitation during the same period, I is irrigation, ET is farmland evapotranspiration, $R_{\rm n}$ is runoff, D is leakage, and G is capillary-lifted water. All terms in Eq. (1) are expressed in units of mm. The underground water level in Wuchuan County is below 7 m and the plough sole is typically between 15 and 23 cm. The leakage D and capillary water G are therefore largely negligible. The study area is a rain-fed area where the irrigation I is zero. Typically, the small magnitude of rainfall ensures that the runoff $R_{\rm n}$ is also negligible. The water balance equation for the study area can therefore be approximated as

$$\mathrm{ET} = P \pm \Delta W. \tag{2}$$

ΔW can be calculated using the change in soil water storage in the 0–50-cm layer between the beginning and the end of the period.

The soil water mass content can be transformed into soil water storage using the formula

$$V = R \times H \times W, \tag{3}$$

where V is the soil moisture storage capacity (mm), R is the soil bulk density (g cm^{-3}), H is the depth of the soil layer (cm), and W is the soil water mass content (%). Representative values of soil bulk density are listed in Table 1.

3. Results and discussion

3.1 Characteristics of climate change

We use the meteorological data from 1960 to 2007 in Wuchuan to analyze the characteristics of climate and climate change in this region. The climatological mean annual precipitation in Wuchuan County is 342.4 mm, with 306.6 mm between April and September. The annual mean air temperature is 3.0℃. The rainfall has decreased since 1960 at a rate of 0.7 mm yr^{-1}, while the annual mean temperature has significantly increased at a rate of 0.04℃ yr^{-1}. These trends are even more pronounced over the period 1983–2007 (which matches the availability of the soil data), with a drying trend of 2.1 mm yr^{-1} and a warming trend of 0.09℃ yr^{-1} (Fig. 1).

Table 1. Soil bulk density for different layers of soil in Wuchuan County

Soil layer (cm)	0–10	10–20	20–30	30–40	40–50
Soil bulk density (g cm^{-3})	1.643	1.483	1.332	1.470	1.434

3.2 Characteristics and trends of crop water consumption

The water consumption by wheat, naked oats, and potatoes in Wuchuan County declined from 1983 to 2007 (Fig. 2a). The water consumption by wheat, naked oats, and potatoes declined at rates of 1.65, 2.04, and 3.85 mm yr^{-1}, respectively. The decrease in crop water consumption was even more pronounced between 1991 and 2007 (Fig. 2b), particularly for wheat (7.41 mm yr^{-1}) and naked oats (4.87 mm yr^{-1}). The trend for potatoes was relatively stable, with a

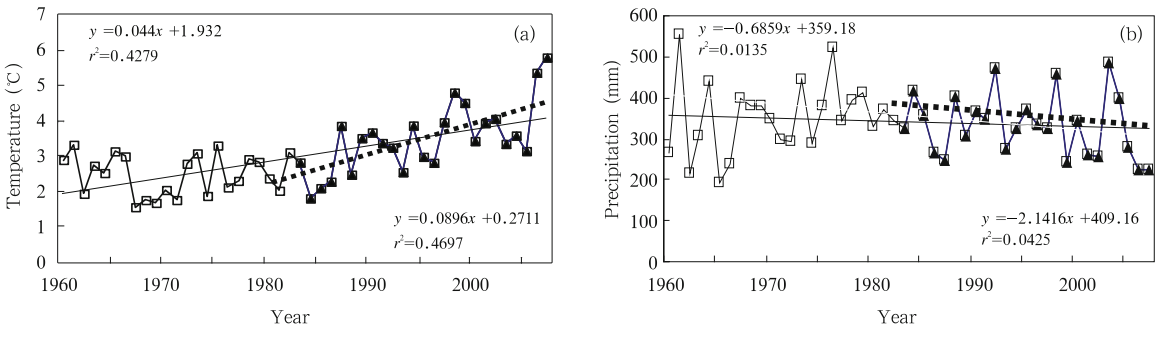

Fig. 1. Changes in the (a) temperature and (b) precipitation of Wuchuan County from 1960 to 2007.

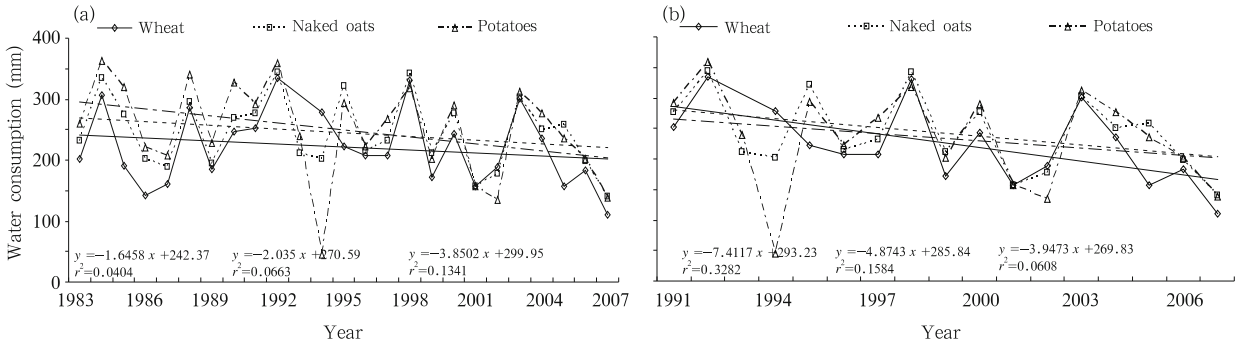

Fig. 2. Changes in water consumption for different crops over the period (a) 1983–2007 and (b) 1991–2007.

decrease of 3.95 mm yr^{-1} between 1990 and 2007. This difference is primarily dependent on the degree of temporal coincidence between local rainfall and the critical period of water requirements for each crop type.

3.3 Effects of climate change on crop water consumption

Crop water consumption is affected by meteoro-

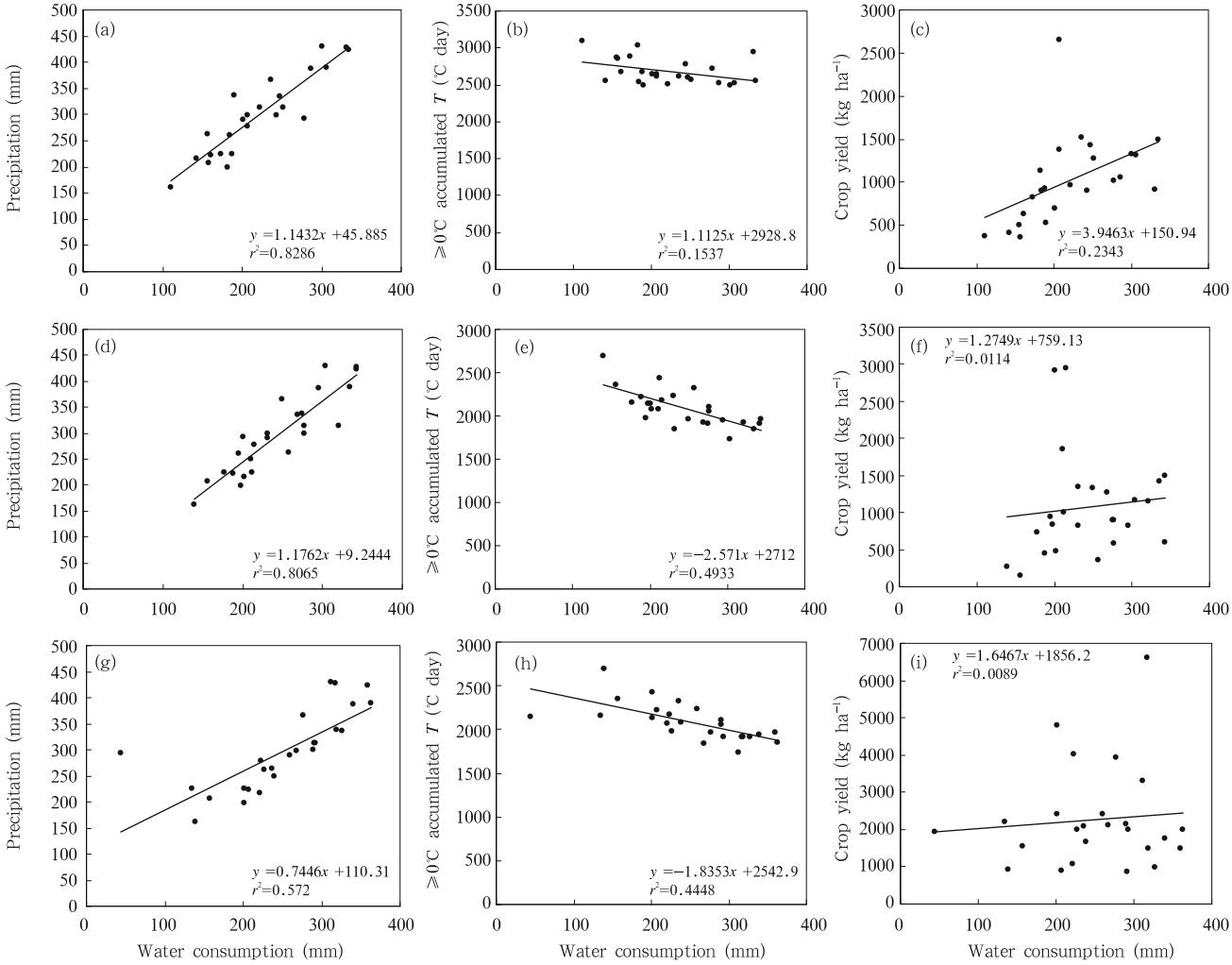

Fig. 3. Relationships between water consumption for (a–c) wheat, (d–f) naked oats, and (g–i) potatoes; (a, d, g) annual rainfall, (b, e, h) accumulated temperature, and (c, f, i) crop yield.

logical factors such as rainfall and temperature. We therefore analyze the correlations between water consumption and annual rainfall, accumulated temperature (above 0℃ for wheat; above 10℃ for naked oats and potatoes) (Zheng and Sun, 2010), and crop yields. The results are shown in Fig. 3.

Water consumption for each crop is positively correlated with rainfall (Figs. 3a, 3d, and 3g). The correlation coefficients between water consumption and rainfall are very high and statistically significant at the $p < 0.01$ level. As rainfall decreases, water consumption by these crops also decreases. This relationship is the weakest for potatoes (0.74 mm yr^{-1}). Water consumption and active accumulated temperature are negatively correlated (Figs. 3b, 3e, and 3h). The recent warming trend therefore led to significant decreases in crop water consumption in this region ($p < 0.01$ for naked oats and potatoes; $p < 0.05$ for wheat). Water consumption and crop yields are positively correlated (Figs. 3c, 3f, and 3i). These correlations are statistically significant for wheat ($p < 0.01$) and naked oats ($p < 0.05$), but not for potatoes.

We next perform a multiple regression analysis of water consumption during the growth periods of wheat, naked oats, and potatoes with accumulated temperature and precipitation. The results are presented in Table 2.

The results of the multiple regression analysis suggest that changes in precipitation affect crop water consumption much more than changes in accumulated temperature. Accumulated temperature and water consumption are negatively correlated for all three types of crops, while precipitation and water consumption are positively correlated. Recent climate change has been detrimental to agricultural productivity in the northern agro-pastoral transitional zone. Adaptation to climate change in this region should focus on the development of drought-resistant crop varietals and cultivation measures.

Table 2. Effects of climate change on crop water consumption

Crop	The regression equation	Regression effect
Wheat	$Y = -0.047X_1 + 0.782X_2 - 139.832$	Remarkable*
Naked oats	$Y = -0.007X_1 + 0.672X_2 + 58.668$	Remarkable*
Potatoes	$Y = -0.075X_1 + 0.606X_2 + 226.423$	Remarkable*

Note: Y refers to water consumption during the growth period, X_1 denotes accumulated temperature, and X_2 denotes precipitation. The asterisk (*) indicates statistical significance at the $p < 0.05$ level.

4. Conclusions and discussion

We have examined the characteristics of climate change in the northern agro-pastoral transitional zone (Wuchuan County) and related these characteristics to changes in water consumption by wheat, naked oats, and potatoes during their respective growth periods. Our conclusions are as follows.

(1) Temperatures have warmed and precipitation has decreased in Wuchuan County since 1960. Annual mean rainfall has decreased at a rate of 0.7 mm yr^{-1}, while annual mean temperature has increased at a rate of 0.04℃ yr^{-1}. These trends were particularly pronounced between 1983 and 2007, with a warming trend of 0.09℃ yr^{-1} and a drying trend of 2.1 mm yr^{-1}.

(2) Crop water consumption has decreased under the backdrop of this climate change. Water consumption by wheat, naked oats, and potatoes decreased at rates of 1.65, 2.04, and 3.85 mm yr^{-1}, respectively.

(3) Water consumption and rainfall during the growth season are positively correlated, while water consumption and active accumulated temperature are negatively correlated. Compared to precipitation, accumulated temperature has only a small impact on crop water consumption. The relationships between water consumption, rainfall, and accumulated temperature are different for different types of crops.

Climate change has a significant impact on water consumption by crops. Recent climate change has been detrimental to crop productions in the northern agro-pastoral transitional zone, with decreases in precipitation playing the largest role. These results suggest that local agriculture could most effectively

adapt to climate change by transitioning to drought-resistant crop varietals and cultivation techniques.

Few previous studies have examined the relationships between climate change and crop water consumption in dry-land regions. This paper has addressed this gap. The results represent a guide for adapting local agricultural production and ecological construction to climate change. However, this study has only obtained these relationships for one site, i.e., Wuchuan County, typical of the northern agro-pastoral transitional zone of China. The results may be dependent on soil properties or other local factors. Further studies of this type should be conducted in other areas to extend the results and evaluate their robustness.

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REFERENCES

Allen, R. G., L. S. Pereira, D. Raes, et al., 1998: Crop Evapotranspiration: Guidelines For Computing Crop Requirements. Irrigation and Drainage Paper No. 56, FAO, Rome, Italy, 15 pp.

Crane, T. A., C. Roncoli, and G. Hoogenboomet, 2011: Adaptation to climate change and climate variability: The importance of understanding agriculture as performance. *NJAS–Wagen J. Life Sci.*, **57**(3–4), 179–185.

IPCC, 2007: *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, United Kingdom and New York, NK, USA, 30–31.

Lie Zhengping and Tang Bo, 2007: The measuring and estimating methods of the crop evapotranspiration. *Anhui Agri. Sci. Bull.*, **13**(2), 54–56. (in Chinese)

Liu Jingtao and Liu Shiring, 2006: Advances and perspectives in evapotranspiration studies. *Scientia Silvae Sinicae*, **42**(6), 108–114. (in Chinese)

Lobell, D. B., W. Schlenker, and J. Costa-Roberts, 2011: Climate trends and global crop production since 1980. *Science*, **333**(6042), 616–620.

Ma Lingling, Zhan Chesheng, Tang Lingli, et al., 2005: Review and prospect on the study progress in crop water requirements. *Arid Land Geography*, **8**(4), 531–534. (in Chinese)

Pan Zhihua, Zhang Luyang, Chen Dongdong et al., 2010: Research progress and thoughts about proper exploitation of field water potential productivity in farming-pastoral ecotone of northern China. *Journal of Agricultural Science and Technology*, **12**(1), 40–45. (in Chinese)

Prueger, J. H., J. L. Hatfield, J. K. Aase, et al., 1997: Bowen-ratio comparisons with lysimeter evapotranspiration. *Agronomy Journal*, **89**(1), 730–736.

Qi Yangbin, Chang Qingru, Jia Kelin, et al., 2012: Temporal-spatial variability of desertification in an agro-pastoral transitional zone of northern Shaanxi Province, China. *Catena*, **88**(1), 37–45.

Shi Yafeng, Shen Yongping, Kang Ersi, et al., 2007: Recent and future climate change in Northwest China. *Climatic Change*, **80**(2007), 379–393.

Si Jianhua, Feng Qi, Zhang Xiaoyou, et al., 2005: Research progress on surveying and calculation of evapotranspiration of plants and its prospects. *Adv. Water Sci.*, **16**(3), 450–459. (in Chinese)

Xia Zhechao, Pan Zhihua, Zhang Luyang, et al., 2010: Examining mechanisms of vegetation ecosystems degradation based on water in northern farming-pastoral zone: A case study in Wuchuan Country. *Resources Science*, **32**(2), 317–322. (in Chinese)

Zhang Hexi, Chi Daocai, Liu Zuoxin, et al., 2006: The progress in crop water requirements and consumption. *Modern Agricultural Science and Technology*, **3**, 52–54. (in Chinese)

Zhang Jinsong, Meng Ping, Yin Changjun, et al., 2001: Review on methods of estimating evapotranspiration of plants. *World Forestry Research*, **14**(2), 23–28. (in Chinese)

Zhang Shengjun, Yang Gaihe, and Liu Helin, 2006: Some problems about water resources and ecological environment in north ecotone and their cause. *J. Anhui Agri. Sci.*, **34**(9), 1945–1947. (in Chinese)

Zheng Dawei and Sun Zhongfu, 2010: Discussion on scientificalness problem of accumulated temperature and its unit. *Chinese J. Agrometeor.*, **31**(2), 165–169. (in Chinese)