Analysis of Climatic Potential Productivity and Wheat Production in Different Producing Areas of the Northern Hemisphere

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Abstract. Cultivation patterns under water saving management are closely related to climate change and crop productivity. Survey data for wheat production in China, Canada, and the USA from 1965 to 2014 was analyzed through classification statistics, comparative analysis and weighting methods. The results showed that China, Canada and the USA wheat grain production accounts for 26.49% to 34.68% of global wheat production. Of these three countries, both the highest total yield and the highest average yield per area sown were in China post 1985. Since 2000, China has accounted for 10.70% to 11.12% of global wheat planted area, producing 15.73% to 17.45% of global wheat output. Achieving high wheat yield in China was mainly based on consuming more irrigation water. The per capita arable land in China, Canada and the USA was 0.10 ha, 1.31 ha and 0.70 ha, respectively. The per capita arable land in Hebei, China, Saskatchewan, Canada and Oklahoma, USA was 0.09 ha, 16.11 ha and 3.48 ha, respectively. Hengshui, China (HS) produces two crops a year. Outlook, Saskatchewan, Canada (OK) and Woodward, Oklahoma, USA (WW) produce one crop a year. Mean precipitation averages 109 mm, 210 mm and 291 mm during the wheat growing season, respectively. Due to less per capita arable land in China, achieving high yield means higher water consumption, which creates a sharp contradiction between water scarcity and demand for grain in China. Consequently, high water use efficiency technologies in agriculture are more needed in China than in the other two countries. High demand for water at post 1985 yield levels cannot be met by rain-fed production in HS. Grain yields of 5975.6 kg/ha to 7031.2 kg/ha can be achieved with irrigation. Economic benefits mainly
determine wheat production in the USA and Canada, whereas in China production is driven by food security and sustainable production goals. The conclusions of this paper could provide a reference for wheat production in different regions.

1. Introduction
Due to the wheat crop’s adaptation to drought and cool climatic conditions, the wheat belt is distributed from temperate to subtropical regions, making it the most abundant food crop in the world (Leff et al, 2004). Compared with rice and maize, wheat is more drought-resistant, allowing for high yield under rain-fed conditions (Cutforth and McConkey, 1997). Beyond a certain level of yield, higher yields require greater water consumption (Caiyun et al, 2016). In order to achieve high yield, wheat has become the main crop under irrigated conditions in some regions (Dang et al, 2010; Cao et al, 2016). Climate change induced extreme weather events are a challenge to production, especially for winter wheat due to its extended growth period (Trnka et al, 2014). To research water-saving and high-yielding cultivation technologies of wheat, Junguo et al (2007) estimated the irrigation depth by comparing simulated and statistical yield data. Kröbel et al. (2014) determined how cropping frequency, inclusion of a legume green manure, and the type of spring wheat influence water use efficiency (WUE). From the perspective of the water balance, Hongyong et al (2006) explored the relationship between irrigation, yield and water use efficiency. Weiwei et al (2015) evaluated the effects of supplemental irrigation on water use characteristics and grain yield of several wheat cultivars. Xue, et al (2013) indicated that stem dry weight at anthesis might be an important trait for high yield under water limited conditions. In the extremely dry areas, Xie et al (2017) evaluated the suitability of an ecological compensation standard for a winter wheat-fallow cropping system. All the above research would help to achieve highly efficient crop water use and adaptation to climate change in wheat production. There is a lack of systematic comparative study about planting regimes and water-saving technology for wheat production in regions with different potential productivity. China, Canada and USA are important producers of wheat. Canada and USA are major exporters, while China, the world's largest wheat producer, is also the world's largest wheat importer (Curtis, 2002). China imports wheat mainly from the USA and Canada (Dong and Han, 2011). This paper compares water-saving production in typical wheat producing regions of China, Canada and the USA, to illustrate different water-saving planting regimes and corresponding yield levels under different climatic and production conditions. This could provide a technical reference for improving water use efficiency in wheat production to help guide agricultural and food policy decisions.

2. Materials and Methods
2.1. General Situation of Wheat Producing Countries and Regions
Wheat accounts for a large proportion of cereal production in China, Canada and the USA. Hebei, Saskatchewan and Oklahoma are important wheat production regions in China, Canada and the USA. The climate, economic conditions, and wheat yield potential are different between regions. These locations
have been chosen to represent the general climatic conditions, production practices and levels of production for different wheat producing regions.

**Table 1.** Basic situation of agriculture indifferent wheat producing countries and regions, 2014.

|                      | World | China | Canada | USA |
|----------------------|-------|-------|--------|-----|
|                      | Total | Hebei | Total  | Saskatchewan | Total | Oklahoma |
| Agriculture area (×10^4 ha) | 493387.64 | 12621.52 | 649.37 | 2928.08 | 1412.4 | 15243.83 | 436.31 |
| Wheat crop area (×10^4 ha) | 22041.77 | 2407.16 | 237.41 | 975.33 | 345.05 | 1877.16 | 214.49 |
| Agriculture area per person (ha) | 0.23 | 0.10 | 0.09 | 1.31 | 16.11 | 0.70 | 3.48 |

The Dry-land Farming Institute of Hebei Academy of Agricultural and Forestry Sciences research station (115.72°E, 37.90°N; altitude 21.0 m), is located on the Hebei Plain, part of the Haihe River Basin wheat growing region, with characteristics typical of the northern China semi-arid agricultural production area. The basic rotation is winter wheat-summer maize with two crops a year. Annual sunshine hours average 2509, the frost-free period is 188 d, annual evaporation is 1785 mm, average precipitation is 510 mm and average temperature is 12.8 °C (Feng et al, 2015). The soil is loam with a field holding capacity of 442.89 mm, 80 cm depth. Wilting coefficient was 143.50 mm.

The winter wheat and summer maize residues are crushed to the field after harvest. Diammonium phosphate as 525 kg·hm⁻² and Potassium chloride at 150 kg·hm⁻² are applied pre-plant. Urea is top-dressed at the jointing stage at 375 kg·hm⁻². The fertilizer applied is equivalent to 267 kg N·hm⁻², 241.5 kg P₂O₅·hm⁻², and 90 kg K₂O·hm⁻². Seed rate was 420.0×10³·hm⁻², resulting in an average spike number of 665.0×10³·hm⁻². Wheat was seeded after summer maize harvest on 13 October 2012. Anthesis occurred on May 10 2013, and harvest was taken June 10 2013.

The Canada-Saskatchewan Irrigation Diversification Centre (CSIDC, 107.06°W, 51.49°N, Altitude 540.0 m), is located on the banks of the South Saskatchewan River, near Lake Diefenbaker, in the Canadian Prairies wheat growing region. Summer average temperature changes from 8°C to 22°C, and winter average temperature changes from -8°C to -18°C. Annual sunshine hours are 3300. Sandy loam soil textures predominate. Spring wheat was sown under no tillage and 25cm rows spacing on canola stubble. Nitrogen (46-0-0) was applied at rate of 120kg N/ha and phosphorus (12-51-0) at 35 kg P₂O₅/ha. All fertilizer was side-banded at the time of seeding. Seed rate was 280.04×10⁴·hm⁻², producing an average spike number of 680×10³·hm⁻². Spring wheat was seeded on 20 May 2015, headed on 11 July, and was harvested 1 September.

The Southern Plains Range Research Station (36.43 N, 99.40 W, elevation 615 m), is in northwestern Oklahoma on loamy upland soils. Long-term average annual precipitation in the area is 651mm. About 70% of the precipitation is normally received during the frost-free period from mid-April to mid-October. The mean annual temperature is about 15°C with an expected yearly range of -18 to 40°C. Soils are loam textures with a water holding capacity of 580.0 mm, to 80 cm depth. Wilting coefficient was 220.0 mm. The N fertilizer treatments were applied all at once prior to planting or midseason just prior to first hollow stem at a rate of 45 kg N/ha⁻¹ or 90 kg N/ha⁻¹ as urea (46-0-0). The P
fertilizer treatments were applied prior to planting at a rate of 20 kg P/ha⁻¹ as triple super phosphate (0-20-0). The K fertilizer treatments were also applied prior to planting at a rate 37 kg K/ha⁻¹ as muriate of potash (0-0-50) (Trmka M et al, 2014). Wheat is grown in rotation with other crops. Seed rate was 193.75×10⁴ to 236.81×10⁴/hm² on a 20 cm row spacing. Spike number ranges from 645.83×10⁴ to 753.47×10³/hm² (Patignani et al, 2014). Spring wheat was seeded on 22 September to 12 October, heading occurred on 11 May, and harvest was 15 June (Nass U. 1997).

### Table 2. Long term annual precipitation (mm).

|           | Jan | Feb | Mar | April | May | June | July | Aug | Sep | Oct | Nov | Dec | Total |
|-----------|-----|-----|-----|-------|-----|------|------|-----|-----|-----|-----|-----|-------|
| Outlook   | 15.2| 10.3| 14.7| 20    | 45  | 65   | 54   | 44  | 33  | 16.7| 13.3| 15.9| 347.1 |
| Hengshui  | 2.4 | 5.8 | 9.3 | 12.9  | 33.4| 60.3 | 160.2| 129.2| 47.9| 24.7| 12.3| 3.1  | 501.5 |
| Woodward  | 18  | 23  | 54.4| 56.6  | 19.7| 87.1 | 65.3 | 64  | 54.6| 54.6| 38  | 25.9 | 651.0 |

2.2. Data sources

Production data from the World bank, Statistics Canada, the United States Department of Agriculture National Agricultural Statistics Service Oklahoma Agricultural Statistics, and on-line resources (https://www.factfish.com/zh, https://zh.wikipedia.org) were used. Meteorological data for Hengshui City and Outlook, Saskatchewan were provided by the Hengshui Meteorological Bureau and by Environment Canada and Climate Change respectively.

Experiment of irrigation regional arranged in test station of Dry-land Farming Institute. Data analysis Mainly used from 2012 to 2013 during wheat growth season. Experiments were split-plot designs, irrigation levels as main plot and wheat varieties as sub-plot treatments. Every time amount of irrigation water was 75 mm. W0 (no irrigation), W1 (jointing / April 16), W2 (jointing / April 16 + early filling/ May 15), W3 (double ridge/ April 6 + anthesis/ May 15 + filling / May 31), W4 (double ridge / March 26 + jointing / April 16 + anthesis / May 15 + filling / May 31). Other field managements were similar to local high yield farmland. Moisture data were monitored by soil drilling and soil moisture data was used to calculate evapotranspiration.

ET was calculated using the soil water balance equation for the growing season and for individual growth periods as follows:

\[
ET = SWD + P + I + D + Wg - R
\]

(1)

Where ET is evapotranspiration(mm), SWD is the soil water depletion in the measured soil depth during the growing stage, P is rainfall (mm), I is irrigation applications (mm), D is soil water drainage (mm), R is surface run off (mm), Wg is water used by crop through capillary rise from groundwater (mm). When the groundwater table is lower than 10 m below the ground surface, Wg is negligible(Sun, et al. 2006). There usually is no runoff in the area, so R was also ignored.

2.3. Statistical Analysis

Analysis of standard deviation was performed using Microsoft Excel 2010 software. Analysis of variance was using Data Processing System software.

3. Results
3.1. Changes in Cultivated Land Area

[Bar charts showing changes in cultivated land area for World, China, and Canada over different years.]
Figure 1. Cultivated, Irrigated and Wheat Crop Area for Selected Countries, 1965-2014.

Global cultivated area gradually increased from 1965 to 1995, and has been stable since (Figure 1). The global irrigated area has also increased. Global wheat seeding area peaked from 1980-1984. Total irrigated area accounted for less than 7% of the global cultivated area.

Total cultivated area in China peaked from 2000-2004. Irrigation area has also increased. The wheat seeded area changed proportionally to the cultivated area, peaking in 1995. Irrigation area accounts for more than 50% of the cultivated area in China.

There are large annual differences in both cultivated area and wheat seeded area in Canada. Irrigation area showed a stable increase. The total irrigated area of Canada accounts for less than 5% of the cultivated area.

Cultivated area, irrigated area and wheat seeded area remained stable in the USA. The total irrigated area accounts for approximately 20% of the cultivated area.

Table 3. The Ratio of Wheat Crop Area to Total Cultivated Area (%).

| Year      | World Wheat seeding area | China Wheat seeding area | Canada Wheat seeding area | USA Wheat seeding area | 3 countries Proportion of global wheat seeding area | China Proportion of global wheat seeding area | Canada Proportion of global wheat seeding area | USA Proportion of global wheat seeding area |
|-----------|--------------------------|--------------------------|--------------------------|-----------------------|--------------------------------------------------|---------------------------------------------|---------------------------------------------|---------------------------------------------|
| 2010-2014 | 4.45±0.03                | 20.11±0.78               | 32.89±3.10               | 12.34±0.26            | 23.93±0.80                                       | 11.05±0.11                                 | 4.23±0.39                                    | 8.66±0.30                                    |
| 2005-2009 | 4.46±0.13                | 21.67±1.00               | 37.77±3.19               | 12.71±0.79            | 24.37±0.96                                       | 10.70±0.26                                 | 4.32±0.23                                    | 9.35±0.47                                    |
| 2000-2004 | 4.33±0.06                | 25.69±1.31               | 45.81±7.03               | 11.75±0.76            | 25.28±2.01                                       | 11.12±0.91                                 | 4.66±0.04                                   | 9.49±0.67                                    |
| 1995-1999 | 4.47±0.12                | 26.37±1.52               | 43.10±3.30               | 13.60±0.75            | 29.42±0.89                                       | 13.36±0.18                                 | 5.07±0.25                                    | 10.99±0.47                                   |
| 1990-1994 | 4.84±0.48                | 30.24±1.56               | 45.39±1.29               | 13.82±0.87            | 30.82±1.34                                       | 13.58±0.01                                 | 5.84±0.54                                    | 11.40±0.62                                   |
| 1985-1989 | 5.36±0.14                | 33.40±0.52               | 58.10±13.71              | 12.87±0.97            | 29.76±0.94                                       | 13.02±0.19                                 | 6.06±0.13                                    | 10.68±0.62                                   |
| 1980-1984 | 5.75±0.13                | 42.09±8.03               | 53.78±6.20               | 15.40±1.67            | 29.92±2.11                                       | 12.25±0.48                                 | 5.36±0.47                                    | 12.31±1.15                                   |
| 1975-1979 | 5.67±0.08                | 57.30±8.00               | 53.07±5.35               | 14.09±1.34            | 28.44±1.57                                       | 12.42±0.33                                 | 4.52±0.23                                    | 11.50±1.01                                   |
| 1970-1974 | 5.37±0.11                | 75.98±7.71               | 59.29±4.91               | 11.14±1.90            | 25.52±2.25                                       | 12.14±0.13                                 | 3.71±0.75                                    | 9.67±1.37                                    |
| 1965-1969 | 5.54±0.08                | 92.56±3.31               | 63.26±8.14               | 11.72±1.14            | 26.14±1.25                                       | 11.29±0.23                                 | 5.27±0.34                                    | 9.58±0.68                                    |

Wheat seeding area accounts for about 5% of global cultivated area (Table 3). The proportion of wheat seeding area peaked in 1985. The range was from 4.33% to 5.75%. Wheat seeding area in China...
was nearly 90% of total cultivated area before 1970, and gradually decreased to 20% by 2010. Wheat seeding area changes were similar in Canada. Wheat seeding area in the USA was similar to the global trend, increasing to 1985, and decreasing thereafter. The range was from 11.14% to 15.40% of the cultivated area.

The proportion of wheat seeded area in these three countries accounted for 23.93% to 30.82% of the global area. Chinese production varied from 10.70% to 13.58% of global production, followed by USA at 8.66% to 12.31%, and Canada at 3.71% to 6.06%.

3.2. Changes in Wheat Yield

Table 4. Wheat Production in Selected Countries and Regions, 1965-2014 (x 10^7 t).

|          | 1965-69 | 1970-74 | 1975-79 | 1980-84 | 1985-89 | 1990-94 | 1995-99 | 2000-04 | 2005-09 | 2010-14 |
|----------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| Global   | 299.4±23.25 | 345.9±22.16 | 405.0±35.32 | 473.7±29.39 | 514.4±17.80 | 558.9±24.35 | 583.7±25.75 | 588.4±26.71 | 643.6±42.18 | 690.4±34.01 |
| China    | 26.2±1.44 | 34.8±4.32 | 50.7±8.31 | 70.5±13.91 | 87.6±2.60 | 100.3±3.97 | 111.9±7.65 | 92.5±4.85 | 108.6±6.75 | 120.4±3.54 |
| Canada   | 18.5±2.40 | 13.5±2.69 | 19.8±2.75 | 23.7±3.30 | 24.5±5.55 | 28.8±3.84 | 26.0±2.40 | 22.5±1.11 | 25.3±1.20 | 28.5±5.50 |
| USA      | 38.80±7.91 | 43.6±4.52 | 55.7±4.26 | 70.5±12.12 | 57.0±5.96 | 64.7±7.37 | 64.2±4.12 | 56.0±7.90 | 58.1±6.86 | 57.9±3.11 |

Global wheat yield has gradually increased (Table 4). Wheat yield in the USA was higher than China before 1985-1989, and wheat yield was higher in China after 1980-1984. Both country’s wheat yields were higher than Canada.

Table 5. Wheat Production for Selected Countries Relative to Total Global Output.

|          | Three Country Total | China | Canada | USA |
|----------|---------------------|-------|--------|-----|
| 2010-2014 | 29.98±1.32 | 17.45±0.51 | 4.12±0.68 | 8.41±0.81 | 9.6 |
| 2005-2009 | 29.84±0.77 | 16.90±1.09 | 3.93±0.38 | 9.01±0.60 | 6.61 |
| 2000-2004 | 29.03±2.45 | 15.73±0.88 | 3.77±0.68 | 9.53±1.46 | 15.35 |
| 1995-1999 | 34.62±0.42 | 19.17±0.64 | 4.47±0.49 | 10.99±0.38 | 3.47 |
| 1990-1994 | 34.68±0.88 | 17.97±0.96 | 5.15±0.57 | 11.57±1.04 | 8.96 |
| 1985-1989 | 32.87±1.98 | 17.03±0.11 | 4.74±1.01 | 11.10±1.31 | 11.77 |
| 1980-1984 | 34.72±1.74 | 14.79±2.03 | 5.01±0.69 | 14.92±1.41 | 9.47 |
| 1975-1979 | 31.25±2.30 | 12.49±1.50 | 4.89±0.58 | 13.88±1.95 | 14.03 |
| 1970-1974 | 26.49±1.61 | 10.04±0.89 | 3.87±0.60 | 12.58±0.62 | 4.92 |
| 1965-1969 | 28.13±1.29 | 8.97±0.64 | 6.19±0.86 | 12.98±0.87 | 6.69 |

The proportion of total wheat production in these three countries accounted for 26.49% to 34.68% of global production. China’s share of the global wheat production increased year by year before 2000, and has since stabilized. USA wheat production was basically stable before 1995, and tends to decline afterward. In contrast, Canadian wheat production as share of the global total was basically stable, but changed abruptly within 5 years. The largest fluctuation appeared from 1985 to 1995. Of these three countries, USA produced the greater share of global production prior to 1980-1984. China’s share was highest after 1995-1999.

Table 6. Wheat Yield Trends in different countries (kg/ha).
A trend long term pattern for rainfall is greatest from May to August, accounting for 40%. The range is from 338.6 mm to 596.0 mm in Hengshui. The timing of precipitation does not coincide with ET$_0$ demands. Precipitation is mainly concentrated in July and August, accounting for 40% to 50% of the annual total. Precipitation varies by month from year to year with more pronounced differences occurring between June and September. There was no obvious trend long term pattern for rainfall in this region.

### Table 7. Monthly and Annual ET$_0$, Hebei, China, 1974 – 2013 (mm).

| Year Range | 1974-1978 | 1979-1983 | 1984-1988 | 1989-1993 | 1994-1998 | 1999-2003 | 2004-2008 | 2009-2013 |
|------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Yield (CV%) | 3.37 (6.6) | 2.89 (7.1) | 2.21 (7.3) | 1.88 (7.3) | 1.55 (7.3) | 1.29 (7.3) | 1.10 (7.3) | 0.90 (7.3) |
| Yield (CV%) | 3.37 (6.6) | 2.89 (7.1) | 2.21 (7.3) | 1.88 (7.3) | 1.55 (7.3) | 1.29 (7.3) | 1.10 (7.3) | 0.90 (7.3) |
| Yield (CV%) | 3.37 (6.6) | 2.89 (7.1) | 2.21 (7.3) | 1.88 (7.3) | 1.55 (7.3) | 1.29 (7.3) | 1.10 (7.3) | 0.90 (7.3) |
| Yield (CV%) | 3.37 (6.6) | 2.89 (7.1) | 2.21 (7.3) | 1.88 (7.3) | 1.55 (7.3) | 1.29 (7.3) | 1.10 (7.3) | 0.90 (7.3) |
| Yield (CV%) | 3.37 (6.6) | 2.89 (7.1) | 2.21 (7.3) | 1.88 (7.3) | 1.55 (7.3) | 1.29 (7.3) | 1.10 (7.3) | 0.90 (7.3) |
| Yield (CV%) | 3.37 (6.6) | 2.89 (7.1) | 2.21 (7.3) | 1.88 (7.3) | 1.55 (7.3) | 1.29 (7.3) | 1.10 (7.3) | 0.90 (7.3) |
| Yield (CV%) | 3.37 (6.6) | 2.89 (7.1) | 2.21 (7.3) | 1.88 (7.3) | 1.55 (7.3) | 1.29 (7.3) | 1.10 (7.3) | 0.90 (7.3) |
Effects of Irrigation Regime on Water Consumption and Yield

The effects of irrigation regime on water consumption and wheat yield was performed at the Dryland Farming Institute of Hebei Academy of Agricultural and Forestry Sciences. This station is located on the Hebei Plain (part of the Haihe River Basin wheat growing region) with conditions typical of the northern semi-arid agricultural production area of China. The typical cropping pattern is a winter wheat-summer maize rotation with two crops a year.

Annual sunshine averages 2509 hours, frost-free period is 188 days, evaporative demand averages 1785 mm, mean precipitation is 510 mm and average annual temperature is 12.8°C for the region (Feng et al., 2015). The soil is of loam texture with a water holding capacity of 442.89 mm to 80 cm depth. Wilt coefficient is 143.50 mm.

### Table 8. Monthly and Annual precipitation, Hebei, China, 1974 – 2013 (mm).

|          | 1974-78 | 1979-83 | 1984-88 | 1989-93 | 1994-98 | 1999-2003 | 2004-08 | 2009-13 |
|----------|---------|---------|---------|---------|---------|-----------|---------|---------|
| Total    | 596.0±168.44 | 499.1±89.08 | 509.7±100.65 | 476.3±165.21 | 483.9±212.53 | 440.9±92.69 | 480.6±113.86 | 506.2±51.04 |
| Jan      | 1.0±1.20 | 1.8±2.38 | 1.1±0.94 | 3.5±4.37 | 0.8±0.82 | 5.3±6.25 | 0.5±0.58 | 0.8±1.49 |
| Feb      | 8.1±9.84 | 8.7±9.15 | 2.3±2.24 | 7.1±15.59 | 7.6±9.10 | 3.5±4.88 | 5.1±7.03 | 7.7±4.08 |
| Mar      | 3.2±4.58 | 13.3±6.12 | 8.2±5.76 | 21.4±18.72 | 12.7±13.18 | 3.2±3.51 | 9.1±16.67 | 6.5±5.52 |
| Apr      | 10.9±6.82 | 32.6±24.87 | 7.18±10.37 | 28.8±24.81 | 24.5±17.68 | 29.0±21.83 | 16.0±15.71 | 17.8±9.70 |
| May      | 54.1±71.40 | 24.1±17.27 | 33.8±10.59 | 32.7±24.00 | 37.9±23.64 | 35.1±40.74 | 52.6±11.89 | 24.9±14.54 |
| Jun      | 71.3±59.85 | 71.6±46.32 | 37.5±18.15 | 70.7±24.44 | 43.8±29.82 | 48.9±39.62 | 79.9±45.66 | 68.0±13.99 |
| Jul      | 236.7±177.32 | 152.9±112.41 | 114.7±80.71 | 149.6±50.72 | 176.4±159.72 | 140.5±29.48 | 127.8±62.43 | 158.4±81.99 |
| Aug      | 96.6±50.42 | 134.8±82.77 | 21.0±106.18 | 87.5±45.12 | 120.9±73.71 | 69.4±16.80 | 102.1±63.21 | 130.5±76.60 |
| Sep      | 65.2±62.12 | 31.7±27.74 | 61.3±77.77 | 32.2±16.47 | 27.5±23.32 | 29.3±14.55 | 66.4±57.03 | 61.8±33.47 |
| Oct      | 31.4±18.47 | 19.8±19.96 | 19.5±12.46 | 18.3±12.12 | 20.0±8.05 | 59.6±59.66 | 14.6±17.20 | 8.6±5.50 |
| Nov      | 9.3±7.13 | 5.7±5.42 | 9.5±14.06 | 22.0±21.04 | 8.3±9.82 | 13.9±14.14 | 2.5±4.82 | 18.4±13.81 |
| Dec      | 8.4±7.12 | 2.9±7.24 | 4.3±3.91 | 2.6±3.36 | 3.5±4.66 | 3.3±5.08 | 3.8±4.75 | 2.8±5.55 |

3.3.2. Effects of Irrigation Regime on Water Consumption and Yield

The effects of irrigation regime on water consumption and wheat yield was performed at the Dryland Farming Institute of Hebei Academy of Agricultural and Forestry Sciences. This station is located on the Hebei Plain (part of the Haihe River Basin wheat growing region) with conditions typical of the northern semi-arid agricultural production area of China. The typical cropping pattern is a winter wheat-summer maize rotation with two crops a year.

Annual sunshine averages 2509 hours, frost-free period is 188 days, evaporative demand averages 1785 mm, mean precipitation is 510 mm and average annual temperature is 12.8°C for the region (Feng et al., 2015). The soil is of loam texture with a water holding capacity of 442.89 mm to 80 cm depth. Wilt coefficient is 143.50 mm.
The experiment was conducted in the 2012/13 wheat growth season. Experiments were split-plot designs, with irrigation levels as main plot and wheat varieties as sub-plot treatments. Crop residues of winter wheat and summer maize were crushed to the field after harvest. Diammonium phosphate at a rate of 241.5 kg P₂O₅ ·hm⁻², and potassium chloride at 90 kg K₂O ·hm⁻² were applied prior to seeding. Urea was top-dressed at the jointing stage at a rate of 267 kg N·hm⁻². Seed rate was 420.0×10⁴·hm⁻². Wheat was seeded after the summer maize harvest on 13 October 2012. Anthesis occurred on May 10 and the crop was harvested on June 10, 2013.

Irrigation was applied in 75 mm applications in the following treatments:

- **W0**: Unirrigated
- **W1**: Jointing stage (April 16)
- **W2**: Jointing stage (April 16); early grain fill (May 15)
- **W3**: Double ridge stage (April 6); anthesis (May 15); grain filling (May 31)
- **W4**: Double ridge stage (March 26); jointing (April 16); anthesis (May 15); grain filling (May 31)

![Figure 2](image.png)

**Figure 2.** Effect of Irrigation Regime on Water Consumption Components of Winter Wheat.

The water consumption components under different irrigation regimes are shown in Figure 2. Water consumption changes with increased irrigation frequency amount. Total water consumption increased with irrigation along with a concomitant decrease in consumption of stored soil water. Soil water supplied more than 50% of consumption under treatments W0 and W1. Irrigation water consumption accounts for the largest share of crop water use under treatments W2, W3 and W4.
Figure 3. Effect of Irrigation Regimes on Grain Yield of Winter Wheat.

Compared to the control treatment yields (4926.2-5901.5 kg/ha), wheat yield was significantly increased under the W1 treatment to 5975.2 to 6432.4 kg/ha. The W2 irrigation regime increased yields to 6347.2 to 7031.2 kg/ha. The W3 treatment could achieve high, but more variable, yields ranging from 5938.6 to 7216.4 kg/ha) The yield of treatment W4 was decreased in comparison to the W2 and W3 irrigation regimes and was similar to treatments W1 and W2. Response of individual cultivars to irrigation was different, but the yield curves are basically the same. The cultivar Heng4399 produced high and stable yield under different water supply conditions.

4 Discussion
4.1. Effect of Climatic Characteristics and Improvement of Irrigation Conditions on Wheat Yield

There was no obvious trend to changing precipitation amounts over the study period, but ET$_0$ trended toward lower values during the study. This result was also noted by Zhang et al (2011). Due to rapid growth in the already large irrigated area in China, the consumption of irrigation water relative to the renewable supply has become increasingly important (Yan et al, 2015). The cities of Beijing and Tianjin are located in Hebei province, therefore agriculture is tasked with ensuring the security of both the regional water and food resources (Tang et al, 2016). To date social development has had a greater impact on wheat production than has climate change in Hebei.

Arable land is 0.09 ha, 16.11 ha and 3.48 ha per capita in Hebei, Saskatchewan and Oklahoma, respectively. Per capita arable land is relatively low in Hebei, therefore to meet food demand crop yields
must be high. In consideration of the components of water consumption as measured in this study, sufficient soil water reserve or stable irrigation water supply is required to achieve high and stable yield. In the two crops per year system, summer precipitation is adequate but is always consumed by maize. Precipitation is low during the wheat growing season. Natural precipitation cannot meet the demand for water needed to produce high wheat grain yield (Sun et al, 2006). Based on the climatic characteristics and social conditions, using scarce water resources to irrigate wheat in Hebei province is of national importance to China (Tang et al, 2016). Due to priority being given to meeting urban water and reservoir re-stocking needs and due to losses to surface runoff, there is no usable surface water for irrigation in the Hebei plains. Irrigation of the wheat crop is reliant on groundwater. Groundwater withdrawals for irrigation in this region represent the world's largest area of groundwater depletion. Therefore there is a need not only to research water-saving technology, but also to seek new agricultural water sources in Hebei. Construction of the South-to-North Water Diversion Project, utilization of shallow saline water, efficient storage and use of pond water, etc., will, to a certain extent, ease the deficit between water supply and demand.

Long term average precipitation during the wheat growing season in Woodward, USA is 290 mm, much higher than Hengshui. Soil water and precipitation can meet the annual wheat crop’s demand for water. Given the drought resistance in wheat, it is produced under rain fed conditions. Wheat is also predominantly grown under rain fed production in Canada. Therefore improved water use efficiency in Canada and the USA can be realized through breeding high yield wheat varieties for dryland and by making efficient use of precipitation (Cutforth and McConkey, 1997; Xue, et al. 2013; Patrignani et al. 2014).

4.2. Impact and Adaptation of Cropping Structure Adjustment on Wheat Cultivation

While wheat seeding area was stable, total production of wheat had steadily increased in all three countries. Statistics show that increased irrigation area was not used primarily to produce wheat (Mohammad, 2014). Increased wheat production will mainly depend on comprehensive water saving technology (Sun et al, 2006). When the yield of wheat increasing with technology advanced does not meet people's demand for food, they have to try planting structural adjustment. Wheat production in China will vary within the climatic, economic, and policy constraints. With the economic development of Chinese society came a demand for an expanded and improved diet. China launched a potato staple strategy so that the crop could become the county's fourth staple food, diversifying the basic diet.

China started planting potatoes by 2015, indicating that the staple food was gradually diversified. Lessening the dependence on wheat eased production pressure on Hebei province, and reduced over-exploitation of groundwater for wheat production and ameliorated damage to the ecological environment. In this context, reducing wheat acreage reduced ecological stress and helped to realize sustainable agricultural development in Hebei.
Unlike China, wheat production Canada and USA is primarily for export markets. Economic benefits mainly determine wheat production. Based on the climatic characteristics, Canada produces one wheat crop per year in rotation with other crops. Wheat is mainly produced under rain fed cropping. Similar to Canada, the US multiple cropping index is low, with generally one crop per year. Wheat is mainly produced in rain fed areas (Bushong et al. 2014).

4.3. Developing Water-Saving Technology in Accordance with Local Conditions

Under the predicted effects of climate change of increased risk of extreme drought or severe precipitation events, conditions not conductive to plant growth may become more common (James, 2016). Irrigation could effectively reduce the negative impact of climate change on crops. Irrigation area continues to increase, thus exacerbating deficits between consumption and renewable water supply (Yan et al, 2015). The challenge is whether water availability for irrigation will be sufficient to meet growing food demand and improve global food security (Tollefson et al, 2014). Therefore, there is a global need to improve crop water use efficiency to cope with climate and social change.

Field boundaries under the household responsibility system in China are denoted by using ridges to distinguish boundaries of different farmland in Hebei. This is a natural consequence of conveniently using flood irrigation on the level fields and small land holdings prevalent in Hebei. However, in western China (such as Xinjiang), under conditions of high evapotranspiration, drip irrigation under mulch technology is more suitable for local production (Mingxian et al, 2012). Flood irrigation of large fields tends to waste water and therefore irrigation by center pivot is widely adopted elsewhere (Bjornlund, 2007). Therefore, production practices are different between regions and the water saving technical problems which need to be solved are also different. The decision to adopt water-saving irrigation technology is in response to local production conditions. Developing technologies to improve water use efficiency under both irrigated and dryland production in accordance with local conditions are the future challenges.

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