气候变暖对中国西北地区农作物种植的影响

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摘要：采用对农作物生长有指标意义的≥10℃积温和 <0℃负积温与农作物适宜种植面积、生长发育速度及产量进行对比统计分析研究，指出气候变暖对中国西北地区农作物种植结构发生了较大改变，冬小麦种植区西伸北扩，棉花面积迅速扩大，多熟制向北和高海拔地区推移。农作物生长发育速度发生了明显变化，春播作物提早播种，喜温作物生育期延长，越冬作物推迟播种，生育期缩短。棉花气候产量明显增加。

关键词：西北地区；喜温及喜凉农作物；气候变暖；生育期

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The impact of climate warming on crop planting and production in northwestern China

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Abstract: One major challenge in agro-meteorological research is to accurately predict the impacts of global climate warming on future agricultural production. Towards this effort, the effects of climate warming over the past decades need to be assessed. In this study, we analyzed the effects of the climate warming on crop planting, structure and yield in five Northwestern provinces of China with a focus on Gansu utilizing accumulated temperature (≥10℃, AT), accumulated negative temperature (<0℃, ANT) and crop data collected from 1981 to 2003. The analysis led to the following conclusions: (1). Climate warming is the main driving force for the expansion of winter wheat toward North and West, for the rapid increase in cotton planting acreage, and for the expansion of annually multi-crops areas towards north and higher

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altitude. (2). Climate warming is the direct cause for early seeding of spring crops, and prolonged growth duration for thermophilic crops and shortened duration for overwinter crops. (3). Climate warming is largely attributable to the dramatic increase of cotton yield.

Key Words: Northwestern China; crops; climate warming; growth period

1 Introduction

Global warming is the most prominent change among all climate changes. As indicated in the fourth assessment report of the Intergovernmental Panel on Climate Changes (IPCC)[1], the global mean temperature was increased by (0.6 ±0.2)℃ in the 20th century. In fact, all of the 14 globally warm years of the century occurred after 1983, suggesting that the rate of climate warming is on a trend of acceleration. In China, it was reported that the annual mean temperature was increased by 0.4 — 0.5℃ in the 20th century[2-5], and 17 consecutive warm winters are observed after 1990. Climate warming displayed variations annually geologically, and seasonally as significant differences are reported in various regions. In China, larger increases were reported in the northern parts, particularly in the winter temperatures in Northwestern China (NWC). The annual mean temperature in NWC from 1987 to 2003 was 0.7℃ higher than that of period 1961 to 1986 due to a large change in the year of 1987. Seasonally, the mean temperature was increased by 0.33℃, 0.4℃, 0.73℃ and 1.37℃ for spring, summer, autumn and winter respectively during the same period. Noted is the dramatic increase in the winter temperature which is more than doubling of the global annual average increase in the 20th century (0.6℃). This climate warming resulted in increases of 112℃ in the annual average ≥0℃ accumulated temperature (AT), 107℃ in the annual average ≥10℃ AT, and a decrease of 137℃ in the accumulated negative temperatures (<0℃, ANT).

Since agricultural production is very sensitive to climate changes, assessing the impact of global warming on crop yields has attracted considerable attention. While many studies are attempting to predict the future impacts by using various models[6], the effects of the past changes on the production remain unclear. Contradicting results were reported in different studies and in different geographic regions. In Australia and Mexico, the increase in wheat yield was largely attributed to the climate warming[7,8], whereas in USA it was suggested that it caused a combined loss amounting to $5 billion annually for its negative effects on wheat, maize and barley production[9]. These intriguing results raised questions as to whether climate warming has different effects in different regions of the world.

China is the most populated country in the world and agricultural production is vital. Thus, understanding the consequences of climate warming on agriculture is the key to developing strategies in anticipation of future changes. As pointed out by Lin et al[10], the Chinese agriculture is facing three great challenges as a result of climate warming, (1) fluctuation in agricultural yields; (2) changes in the structure and management of agricultural production, along with the changes of the crop planting system; and (3) increasing costs. Previous investigations were conducted in the eastern regions of China[11-14]. Analysis in the NWC where comparatively larger increase in annual temperature occurred over the east is lacking. In this study, we analyzed the meteorological and agricultural data collected from 1961 — 2003 in the five northwestern provinces of China. We found that the climate warming resulted in a positive effect in the production of thermophilic crops, expansion of growing boundary of winter wheat, and different changes in the growth rate and periods of the planted crops.

2 Data and Methodology

The daily mean surface air temperature data were collected from 171 meteorological observation stations in the NWC provinces of Shaanxi, Gansu, Ningxia, Qinghai, and Xinjiang Autonomous Regions from January, 1961 to

December, 2003. The year to year AT and ANT at each station were calculated. The multi-year mean temperatures at each station for the two periods, 1961 — 1986 (pre-warming) and 1987 — 2003 (warming), were derived respectively, and their mean temperature differences were used as the climatic warming range at each station in the recent 40 years. Representative climatic-ecotype regions were selected as the following: Xifeng station representing the mild temperature/semi-humid climate; Tianshui, representing the warm/semi-humid climate; Wuwei, mildly cold/arid; and Dunhuang, mildly hot/arid.

In addition, agro-meteorological data for winter wheat (*Triticum* spp), spring wheat (*Triticum* spp), cotton (*Gosspium* spp), and corn (*Zea mays* L) at the above agro-meteorological stations were collected from 1984 to 2004. These data include acreage of each crop, planting time, timing of growth and developmental stages, yield along with the mortality of the overwintering winter wheat in Xifeng regions. The data of the planting acreage of each crop and the yield of winter wheat and cotton were retrieved from Gansu Province Statistic Bureau.

3 Climate Warming and Agricultural Planting Structure

3.1 Expansion of planting area for winter wheat

Early frosting and subfreezing temperatures were believed to be the major causes of winter wheat mortality. If this holds, climate warming may reduce the mortality. To find evidence, we analyzed the relationship between the ANT values and the winter wheat mortality in Xifeng region from 1981 to 2003. As indicated in Fig. 1, during the period of 1981 to 1986 , climate warming was not observed, and the mortality remained high.

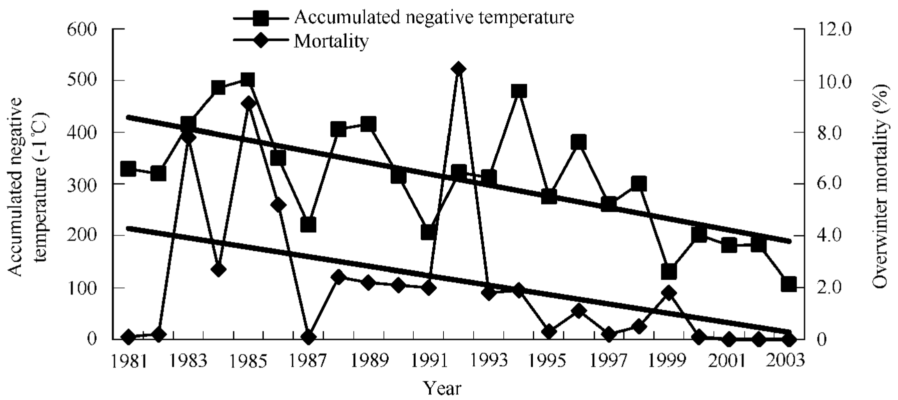

Fig. 1 Correlation relationship between the accumulated negative temperature (ANT) and overwinter mortality rate for winter wheat from 1981 —2003

With increasing climate warming after 1986 as indicated by the substantial increases in ANT, the mortality was decreased significantly and stayed lower than 2% in recent years (except the cold winter between 1991 and 1992, Fig. 1). Statistic analysis indicated that the ANT and mortality displayed a negative linkage relationship. The t-test yielded a strong correlation with a coefficient of −0.52 at the 0.01 confidence level.

Less cold winter climate favors the planting of winter wheat, whereas colder climate favors the planting of spring wheat. The unique geographical location and climate of Gansu province provide the conditions suitable for growing winter wheat in the East and spring wheat in the West. This feature practically resulted in a distinct boundary separating the two regions. An ANT value between −400℃ and −500℃ in overwinter period was reported as a reliable criterion for safe growing of winter wheat in NWC[15]. Based on the meteorological data, the north boundary of the planting area for winter wheat in east part of NWC in 1960's shifted from Yanan (with the ANT value of −483℃) via Qingcheng (−458℃) and Zhuanglang (−446℃) to Longxi (−448℃) boundary moved northwards about 50 — 100 km in 1990's, which shifted from Suide (−418℃) through Zhongning (−429℃) and Jingyuan

(−445℃) to Jingtai (−445℃ , Fig. 2).

To prove the expansion of winter wheat, we recorded the acreages of winter wheat and spring wheat along the boundary regions from 1987 to 2003. Since 1985, the average ANT values of these regions along the boundary were increased by 76℃ to 133℃ as the result of climate warming (Table 1). The winter wheat acreages were increased by 12.4% to 42.5% in these counties from 1990 to 2001; 12.8% for entire Gansu province; 42.5% in Lingtao; and 13% for Weiyuan. Notably, there was almost no winter wheat growing in the Weiyuan county before 1990 because of its high altitude (2111 m above sea level). By 1995, 8.9% of the lands were shifted to winter wheat. Thus, these data indicated that climate warming expanded the planting area of winter wheat towards north and west since the 1990's.

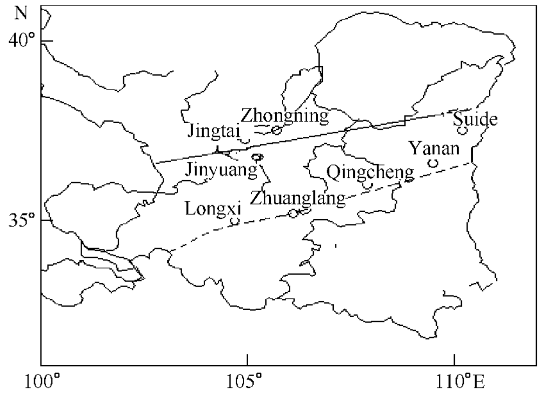

Fig. 2 Expansion in the North boundary of winter wheat planting area in eastern part of NWC. The dashed line marks the boundary in 1960's and the solid line in 1990's

Table 1 Percentages of winter wheat to all wheat planting acreage in Gansu Province in selected years

Year	Regions (Elevation(m))						
	Gnasu	Jinning (1658)	Tongwei (1768)	Longxi (1728)	Weiyuan (2111)	Lintao (1887)	Tanchang (1753)
1985	51.9	82.7	67.0	33.7	0.3	9.7	78.4
1990	49.9	78.8	63.5	37.3	0.0	0.2	57.3
1995	53.2	86.5	73.0	51.6	8.9	27.1	58.1
2000	60.8	95.5	84.8	60.5	13.1	39.4	71.2
2001	62.7	91.2	84.4	58.1	12.8	42.7	72.0
Increase from 1990 to 2001	12.8	12.4	20.9	20.8	12.8	42.5	14.7
$ANT_{(1987-2003)} - ANT_{(1961-1986)}$		132.8	107.5	83.1	102.0	102.8	76.1

3.2 Expansion of the planting area for thermophilic crops

AT values are frequently used as an important heat index measuring the growth of thermophilic crops in a place. Cotton is a thermophilic crop that is widely grown in tropical and subtropical regions. Hexi Corridor is the main cotton planting area in Gansu. Deng and Lin showed that the AT in Hexi Corridor in whole growth season for early-ripe cotton was about 3100 ~ 3200℃[16]. As seen from Table 2, the AT values was increased considerably in the 1990's. Interestingly, the year of 1986 was the turning point. The average AT values at various stations during 1987—2003 were 70℃ to 161℃ higher than the average of 1961—1986, with highest difference in Jintai and Mingqin. Even in Mingqin and Gaotai counties where altitude is 1332 and 1367 m a.s.l. respectively, cotton was planted. From 1991 to 2001, the planting area in both counties reached 7290 hm^2 and 2040 hm^2, respectively. The yields were above 1500 kg/hm^2. That indicates that the altitude of cotton planting area has increased by about 200m a.s.l. The

Table 2 Changes in cotton planting acreage yield and AT values in Gansu Hexi Corridor in four decades

Regions	Elevation (m)	Planting acreage in 2001 (hm^2)	Yield in 2001 (kg/hm^2)	AT values				Increased values from 1961 − 1986 to 1987 − 2003
				1960's	1970's	1980's	1990's	
Dunghuang	1139	14610	1500.4	3684.2	3599.3	3644.0	3746.4	132.8
Anxi	1171	12470	1624.4	3638.8	3581.8	3674.3	3674.3	69.5
Jingtai	1270	11500	1995.0	3375.8	3227.2	3446.2	3446.2	161.3
Gaotai	1332	2040	1950.0	3137.5	3019.4	3165.4	3165.4	107.4
Mingqin	1367	7290	1500.0	3245.5	3209.9	3431.1	3431.1	155.1

cotton planting acreage in Hexi Corridor has been increasing during the last two decades, particularly after 1990. For examples, there were no relatively dramatic changes in the cotton planting acreage in Dunhuang and Jingtai counties during the 1980′s. But since 1990, the planting acreage has been increasing quickly and stably (Fig. 3). By 2001, the total planting acreages in Gansu Hexi Corridor reached 56,900 hm^2, a 10-fold increase over the 1980′s.

3.3 Northward expansion of multi-crops planting area

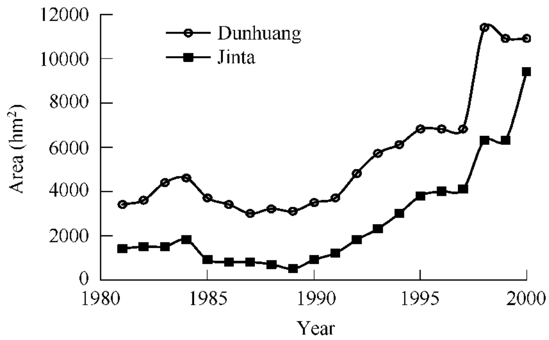

Fig. 3 Changes in the annual cotton planting area from 1981 to 2000

Climate warming causes early thawing in spring and delays the freezing in late autumn. As a result, the season suitable for crop growth was extended. the total heat energy in crop growing season was increased. the multi-crops acreage was enlarged. and multi-crops index was increased as well. Therefore the multi-crops practice area shifted toward north and higher altitudes as well in NWC. For instance, the averaged AT in various regions of Pingliang was 40 to 210℃ higher during 1987 − 2003 than that during 1961 − 1986. In the high altitude western and middle parts of Pingliang such as Jingning (1685m a. s. l), Zhuanglang (1615m a. s. l), Huating(1455m a. s. l) and Kongtong(1347m a. s. l), multi-crops practice did not exist historically[17]. However, these regions switched to multi-crops in recent years. In some regions, farmers planted the crops thrice a year in recent years. In the eastern parts like Jinchuan (1029m a. s. l), Chongxin (1148m a. s. l) and Lintai (996m a. s. l) where thermal resources were rich, farmers have developed and adopted new planting practices, such as alternating planting, interplanting and strip cultivation, two consecutive-croppings within a year, etc. The acreage of the multiple consecutive crops within a year in the whole city in 1990′s was increased by 4 ~ 5 times as compared with those in 1970′s or 1980′s.

The same change is true over the Hexi Corridor. Because the average AT in almost all counties was 70 − 202℃ higher over 1987 − 2003 than over 1961 − 1986, it made the oasis’ s multiple crops area expanded southwards and up in higher altitude. In regions about 1700 − 1800m a. s. l, multiple-crops practice was not adopted in 1980′s. Since 1990, the inter-planting and strip cultivation acreage was gradually enlarged year by year. So far, the strip cultivation acreage reached about 14,000 hm^2, and the yield reached about 11250 − 15000 kg/hm^2. The alternate- and inter-planting acreage in Gulang County (2072m a. s. l) in 2001 reached 17800 hm^2. The high yield transformed to increased profits for farmers. This implies that the altitude suitable for multiple crops area was increased by about 200 − 300m a. s. l. during this period.

4 Climatic Warming and Crop Growth

4.1 Thermophilic crops

Due to the warming in different growth seasons, the average sowing date of the thermophilic crops such as cotton in Dunghuang County was 7d earlier in 1990′s than 1980′s and the growth stop date was 3d earlier. As a result, the whole cotton growth duration was prolonged by about 4d (Table 3). Moreover, the impacts of the warming on different thermophilic crops in various areas are somewhat different. For example, the growth duration of corn in irrigated Wuwei areas was nearly the same as the cotton in Dunghuang. In the 1990′s, the half growth stages of corn (from sowing to jointing) were a little earlier than that in the 1980′s. However, the duration from shooting to maturity was prolonged by 4 days in the 1990′s. Therefore, the total growth duration of corn in this region was prolonged about 6d (Table 4).

Table 3　Timing of the growth and developmental stages for cotton in Dunghuang region in 1980′s and 1990′s (day/month)

Decades	Sowing	Emergence of seedling	Emergence of bud	flowering	Boll opening	Growth stop	Total growth duration (d)
1980′s	24/4	9/5	18/6	15/7	24/9	7/10	166
1990′s	17/4	30/4	10/6	7/7	11/9	4/10	170
1990′s minus 1980′s	−7*	−9	−8	−8	−13	−3	4*

* "−7" represents 7 days earlier in 1990′s than in 1980′s and "4" represents 4 days longer in duration in 1990′s

The growth and developmental processes of corn were also affected by moisture conditions. In the rainfed farming areas of Tianshui, the mean precipitation was a little more than normal in the 1980′s. But consecutive seven arid years occurred in 1990′s. Because of the shortage of water, all of the growth stages of corn were several days earlier in 1990′s than those in 1980′s. This resulted in a decrease of 6 days in the total growth duration (Table 4).

Table 4　Timing of the growth and developmental stages of corn in Wuwei and Tianshui regions in 1980′s and 1990′s(day/month)

Regions	Decades	Sowing	Emergence of seedling	Jointing	Shooting	Tasselling	Milky stage	Maturity	Total growth duration (d)
Wuwei	1980′s	12/4	4/5	1/7	25/7	1/8	23/8	22/9	163
(Irrigated	1990′s	10/4	2/5	29/6	29/7	2/8	29/8	26/9	169
area)	1990′s minus 1980′s	−2	−2	−2	4	1	6	4	6
Tianshui	1980′s	19/4	4/5	28/6	18/6	24/7	20/8	15/9	149
(Rain	1990′s	18/4	4/5	20/6	14/6	18/7	15/8	8/9	143
dependent area)	1990′s minus 1980′s	−1*	0	−8	−4	−6	−5	−7	−6*

* "−1" represents 1 days earlier in 1990′s than in 1980′s and "−6" represents 6 days shorter in duration in 1990′s

4.2　Cool temperature prone crops

Because of the warming autumns, the sowing date such as the winter wheat in Xifeng was about 4d later in 1990′s than in 1980′s, and the emergence of seedlings and the onset of overwinter stage were delayed as well. The climate warming is especially favorable for the overwinter crops. However, the frequent droughts in the 1990′s combined with warmer springs also caused the overwinter turn stage and maturity stage by 5 — 7d earlier. In this way, the whole growth period was shortened by 9 days (Table 5).

Table 5　Timing of the growth and developmental stages of winter and spring wheat at Xifengg and Wuwei in 1980′s and 1990′s(day/month)

Regions	Crops	Decade	Sowing	Emergence of seedling	Overwinter	Reviving	Jointing	Heading	Flowering	Milk	Maturity	Total growth period(d)
Xifeng	Winter	1980′s	16/9	25/9	22/12	15/3	28/4	20/5	28/5	15/6	5/7	292
(rainfed	wheat	1990′s	20/9	3/10	24/12	8/3	26/4	15/5	23/5	14/6	30/6	283
Area)		1990′s minus 1980′s	4*	8	2	−7	−2	−5	−5	−1	−5	−9*
Wuwei	Spring	1980′s	20/3	10/4			17/5	6/6	14/6	6/7	20/7	122
(Irrigation	wheat	1990′s	18/3	10/4			16/5	3/6	13/6	8/7	19/7	123
area)		1990′s minus 1980′s	2	0			−1	−3	−1	2	−1	1

* "4" represents 4 days later in 1990′s than in 1980′s and "−9" represents 9 days shorter in duration in 1990′s

5　Climate warming and crop yield

It is certain that both the heat and water conditions affect the agricultural crop yield. But in well irrigated areas, the heat condition may be the main factor influencing crop yield, particularly for the thermophilic crops. Fig. 4 showed the year-to-year changes between the AT and cotton yield in Dunhuang County.

Both factors in most of the years before 1992 were negative. They reversed indicating that the cotton yield was increased with the climatic warming after 1993. The same result was observed for the cotton yield and climate warming in Jinta County (Fig. 5). Possibly due to the fact that Jinta is situated far north, its yearly AT value is 300℃ which is less than that in Dunhuang. Thus, the AT value had a larger effect on the cotton yield in Dunhuang and both the curves were strongly linked to each other.

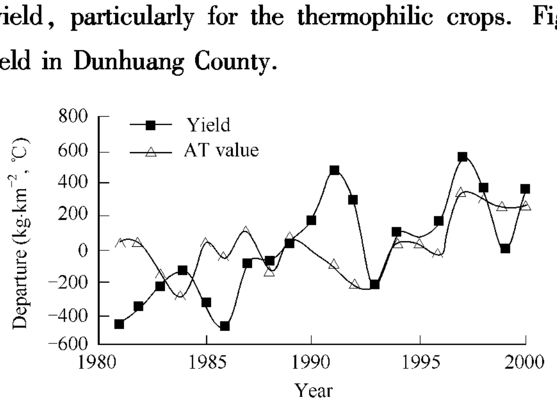

Fig. 4 Interannual changes of departure for cotton yield (kg/hm²) and AT value in Dunhuang region

Other factors like crop variety and planting techniques also contributed to the increase of the cotton yield. To distinguish the effects of these factors, the statistical method of orthogonal polynomial was employed[18]. This analysis removes the contribution from other factors and extracts the climatic yield. As shown in Fig. 6, the derived climatic yield of cotton in Hexi Corridor fluctuated in the last two decades, especially in 1990's. The difference between the maximum and minimum climatic yield is 575.1kg/hm² in 1990's. On average, the contribution of climate changes to the yield was about 29.0kg/hm² in 1990's and −52.5kg/hm² in 1980's. The climatic yield was increased by 81.5kg/hm² in 1990's compared with in 1980' s, which translated to a 54.3% increase. This yield increase is largely due to the increase in AT , i. e. the climate warming.

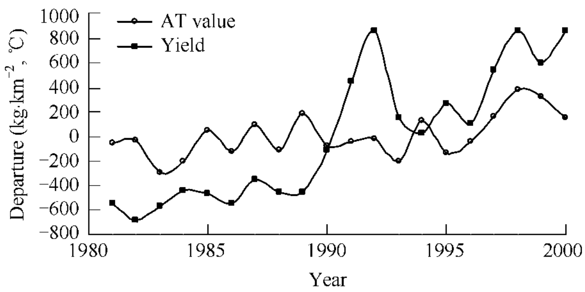

Fig. 5 Interannual changes of departure for cotton yield (kg/hm²) and AT value in Jinta region

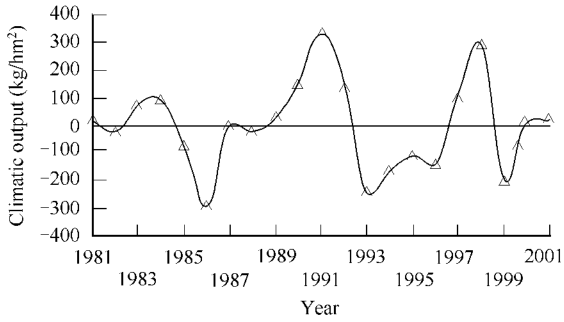

Fig. 6 Curve of the climatic yield of cotton from 1981 to 2001 in Gansu Hexi Corridor

6 Conclusions

(1) Global warming has significant impacts on the agricultural planting structure in NWC. Comparing the 1990' s and 1960's, climate warming caused the shift of the boundary of winter wheat planting area in northward direction by about 50 — 100km in eastern regions of Gansu and even more in westward direction in the western regions. It also increased the planting areas from 1800 — 1900m to 2000 — 2100m. As a result, in Gansu province, the planting acreage of winter wheat was increased by 10 —20% , cotton by 10 times, and multi-crops areas by 4 —5 times. The altitude of lands suitable for planting both cotton and multiple crops was raised by 200 — 300m.

(2) Climate warming significantly affects crop growth in NWC. It caused the earlier sowing in spring sowing crops; the increased growth rate of thermophilic and cool-prone crops; shortening in the duration of growth stages in the first half of crop growth; but prolonging the second half. These adaptive changes favor the crops to receive more sun light and heat energy for photosynthesis, thus favor the accumulation of dry material. Climate warming also

delayed the sowing time for winter wheat, delayed its growth in pre-winter, advanced its overwinter return stage and various stages in its second half of growth, and shortened the whole growth period. However, the growth of the cool-prone crops in irrigated areas such as spring wheat did not appear to affected by the climatic warming.

(3) Climate warming had a positive effect on the yield of thermophilic crop cotton in NWC. Comparing with the 1980's, cotton yield was increased by 81.5kg/hm^2 in 1990's, a 54.3% increase. This increase correlated strongly with the AT value.

This study analyzed the impacts of climate warming on crops focusing on Gansu province, one of the five provinces in NWC. However, the geographic features and the climatic conditions in different regions resembles many of the NWC regions. For example, Southern Xinjiang and the Tsaidam Basin are quite similar to the Gansu Hexi Corridor, whereas Mid- and Northern Shaanxi Province is quite comparable to Eastern Gansu. Therefore, we believe that the conclusions derived from this study can be applied to other regions of NWC.

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