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Source: Air, Soil and Water Research, 2(1)

Published By: SAGE Publishing

URL: https://doi.org/10.1177/ASWR.S2488

Air, Soil and Water Research

ORIGINAL RESEARCH

Effects of Temperature Increase on Pea Production in a Semiarid Region of China

Guoju Xiao[1,2], Qiang Zhang[2], Runyuan Wang[2], Yubi Yao[2], Hong Zhao[2], Huzhi Bai[2] and Youcai Xiong[3]

[1]Bioengineering Institute of Ningxia University, Yinchuan, Ningxia Hui Autonomous Region 750021, China. [2]Institute of Arid Meteorology, China Meteorological Administration, Gansu Key Laboratory of Arid Climate Changes and Disaster Reduction, Lanzhou, Gansu Province 730020, China. [3]State Key Laboratory of Arid Agroecology, Lanzhou University, Lanzhou, Gansu Province 73000, China. Email: xiaoguoju@hotmail.com

Abstract: In this study, a field experiment was used to evaluate a pea crop (*Pisum sativum L.*) at Tongwei Experimental Station (35°13′N, 105°14′E), which is in a semiarid region of China. In this experiment, the mean daily temperature was designed to increase by 0.6–2.2 °C throughout the complete growth stage of the pea crop. When the mean daily temperature increased by approximately 2.2 °C, the water use efficiency (WUE) of the pea crop decreased by 30.4%, the duration of the growth stage was shortened by approximately 17 days, the yields were decreased by 17.5%, the number of stems with root-rot sickness were increased by 50.6%, and the input-output ratio (In/Ou) of the pea crop was 1.20. When the mean daily temperature was increased by approximately 1.4 °C, the WUE decreased by 26.1%, the growth stage duration decreased by 10 days, the yields decreased by 11.1%, the number of stems with root-rot sickness increased by 23.3%, and the input-output ratio (In/Ou) was 1.11. In addition, supplementary irrigation was found to be beneficial to the pea yields when the temperature increased. Indeed, application of 60 mm of supplementary irrigation during the complete growth stages of crops that were subjected to an increase in mean daily temperature of 0.6–2.2 °C resulted in crop yields improving by 8.3%–12.8%. Consequently, in this region, supplementary irrigation may play an important role in maintaining pea yields that would otherwise be affected by climate warming. However, the results also show that application of 60 mm of supplementary irrigation does not decrease the number of stems with root-rot sickness and that the In/Ou ratio of pea crops subjected to the same temperature conditions will increase.

Keywords: pea, supplementary irrigation, climate change, water use efficiency

Air, Soil and Water Research 2009:2 31–39

This article is available from http://www.la-press.com.

Introduction

The global mean surface temperature increased by 0.56–0.92 °C between 1906 and 2005. In addition, it has been predicted that the global average surface temperature will increase by 0.6–2.5 °C over the next fifty years, and by 1.1–6.4 °C during the next century, although it is also predicted that there will be significant regional variation in these temperature changes.[1] In the last 100 years, the mean surface temperature in China has shown an increase of 0.4–0.6 °C,[2] and it is predicted that the average surface temperature in China will rise by 1.7 °C in the next thirty years and by 2.2 Cover the next fifty years.[3]

Increases in temperature could have many effects on crop growth and ecosystems. For example, increasing temperatures will result in increased evaporation, which is likely to cause a reduction in soil moisture in many regions. As a result, the growth stages of many crops will be shortened, albeit to different extents.[4–7] Indeed, there is now strong evidence that crop yields will decrease by 5%–10% in China by 2030 as a result of climate changes.[8,9]

Global warming will likely aggravate the effects of diseases and pests on agricultural production. Specifically, the occurrence of wheat rust, wheat sharp eyespot and powdery mildew, as well as armyworms, beet webworms, cotton bollworms, wheat aphids, green wheat mites and other diseases and pests are all expected to respond to climate change. Warm winters increase the winter survival rates of crop and forest diseases and pests, which can in turn aggravate crop production. Warmer conditions in the spring are also advantageous to the occurrence and reproduction of diseases and pests, while the aridity and infrequent rains in spring are extremely beneficial to the reproduction of wheat aphids, green wheat mites and other similar insect pests.[10]

The pea (*Pisum sativum L.*) is a major rotation crop in semiarid regions of China, and its sown area has reached approximately 20% of the total crop area. The pea is often incorporated in rotation sequences such as pea–spring wheat–potato, pea–winter wheat–potato, spring wheat–pea–spring wheat–potato, and winter wheat–pea–potato–millet. Crop rotation may be more effective than monoculture for minimizing soil erosion, improving water use efficiency and maintaining high yields.[11,12] In addition, crop rotation could affect the water availability for crop growth by changing infiltration and evaporation rates.[13] Although the benefits of crop rotation on the quantity and quality of soil organic matter are well documented,[14–16] it is possible that a wide range of adaptations to climate change exist in crop rotations. Such adaptation may enable farmers to maintain or increase crop yields under future climate change.[17] Consequently, farmers are able to respond to changes in environmental conditions by choosing the most favorable crops, cultivars, and cropping systems. Therefore, assessment studies should indicate which strategies have the best chance of success in the future and which specific climate conditions represent a threshold for adaptation.[18] However, in the last 20 years, climate change has already impacted the growth and development of the pea.[19] Therefore, it is vital for us to identify the most likely impacts of climate warming so that practical and effective counter-measures can be applied to ensure the continued efficiency of future crop production.

Here, we present the relationship between the growth stages and yields of pea crops and temperature increases as part of a long-term research effort aimed at development of sustainable agricultural practices. The results of this study indicate that it is necessary to identify the potential consequences of global warming and the methods best suited to maintaining pea production. The purpose of the present study was to evaluate the effects of temperature increases (0.6–2.2 °C) on pea yield and to predict the potential changes in crop yields that will occur in response to global warming.

Materials and Methods

Field site description

This study was conducted at Tongwei Experimental Station (35°13′ N, 105°14′ E), which is located in a semiarid region of China. The average annual rainfall at the station is approximately 422 mm and the average annual temperature was 6.8 °C between 1957 and 2005. During that period, the average annual temperature at the station increased by 1.0 °C and the average annual rainfall decreased by 86.4 mm. In this region, rain-fed farming is conducted with no irrigation and crops are planted only once a year. Major crops include spring wheat, potato, pea, and millet. Soils in the area are dominated by a Loess loam.

Experimental design and treatments

A field experiment on pea was conducted at Tongwei Experimental Station during 2007–2008. The experiment was subjected to four levels of temperature increase and two levels of supplementary irrigation, which resulted in eight different experimental treatments (Table 1). Each plot in all treatments was 6.0 m long and 2.4 m wide with 16 rows of pea. Each treatment was replicated in three randomized complete blocks. In this experimental field, available nitrogen (N) is 36.8 mg kg^{-1} and total N is 89.3 mg kg^{-1}. Available phosphorus (P) is 5.22 mg kg^{-1} and total P is 28.4 mg kg^{-1}. Organic matter content is about 10 g kg^{-1}.

The pea (*Pisum sativum L.*) is an annual plant that is sown in the middle ten days of March and harvested in the middle ten days of July every year in this region. In general, the growing period from seedling emergence to harvest is 110~120 days. The pea is a multi-flower and multi-pod plant, with each individual plant containing 8~10 pods and each pod containing 5~7 seeds.

Dingwan 2 is a typical variety of pea that was designed to be sown on March 15 in 2007 and 2008 at a density of 600,000 seeds ha^{-1}. After sowing, an electric wire was arranged on the soil surface between two rows of peas to induce a temperature increase of 0.6–2.2 °C, which was maintained from sowing to harvest. The increase in mean daily temperature was monitored continuously through a Computer-Temperature Control System. In addition, 60 mm of supplementary irrigation was applied during the sowing and flowering stages using a drip irrigation system. Furthermore, 1000 kg ha^{-1} of ammonium nitrate (NH_4NO_3) was applied during the sowing and flowering stages. Finally, soil samples were collected from individual plot using an auger (2.5 cm diameter and 20 cm deep) and then analyzed for the soil water content. The pea plots were harvested from July 11 to 28 in 2007 and 2008.

Table 1. The eight treatment combinations in the open-top chamber (OTC) pea experiment at Tongwei Experimental Station.

Treatments	Temperature increase above ambient (°C)	Supplementary irrigation (mm)		
		Sowing	Flowering	Total
T1	0	0	0	0
T2	0.6	0	0	0
T3	1.4	0	0	0
T4	2.2	0	0	0
T5	0	30	30	60
T6	0.6	30	30	60
T7	1.4	30	30	60
T8	2.2	30	30	60

Data collection

Rainfall and temperature data for 2007 and 2008 were recorded at Tongwei Meteorological Station. The soil water contents were measured weekly at depth increments of 10 cm to a maximum of 30 cm from sowing to harvest. The growing season, yield and number of stems with root-rot were recorded from sowing to harvest for all treatments. In addition, the water use efficiency (WUE) was calculated using a rain gauge, soil water and the drip irrigation data.

Statistical analyses were conducted using the GLM analysis of variance (ANOVA) from the SAS Institute[20] to determine the effects of temperature increase on the WUE and pea yields. Mean separations were accomplished by applying the Fisher protected LSD test at $p = 0.01$.

Results

Duration of the growth stage

The results of treatments T1–T4 revealed that an increase of 2.2 °C led to a decrease in the duration of the growth stage of the pea crop of approximately 17 days. In addition, an increase in the mean daily temperature of 1.4 °C led to duration of the growth stage of the crop being shortened by 10 days. Taken together, these findings indicate that a temperature increase will shorten the duration of the growth stage of pea crops (Table 2).

The results from treatments T5–T8, which receive 60 mm of supplementary irrigation, revealed that a 2.2 °C increase in temperature led to a 17 day reduction in the growth stage of the pea crop. In addition, an increase in the mean daily temperature of 1.4 °C combined with 60 mm of supplementary irrigation resulted in the duration of the growth stage of the crop being reduced by 11 days. Taken together, these findings show that application of 60 mm of

Table 2. Changes in the growth stage durations of peas in response to different temperature increases for all treatments (days).[a,A]

Growing period	No supplementary irrigation				Supplementary irrigation 60 mm			
	T1	T2	T3	T4	T5	T6	T7	T8
Sowing-Emergence	38a	38a	34b	31b	38A	39A	34B	32B
Emergence-Flowering	41a	40a	38a	35b	41A	41A	38A	34B
Flowering-Mature	44a	42a	41a	40a	45A	42A	41B	41B
Growth stages	123a	120a	113a	106b	124A	122A	113B	107B

[a,A]Means within rows followed by different letters are significantly different ($p < 0.01$).
"a" is significantly different from "b" and "A" is significantly different from "B".

supplementary irrigation will not change the duration of the growth stages of pea crops (Fig. 1).

Yields and their yield components

Grain outputs from the pea crops in T3 and T4 were 11.0% and 17.5% lower than those in T1, respectively ($p < 0.01$). When compared with T5, the yields in T7 and T8 were 11.1% and 14.1% lower, respectively ($p < 0.01$) (Table 3). These findings indicate that an increase in temperature will change the pea yield.

The pea yield in treatments T1–T4 was lower than that of treatments T5–T8. In addition, the results of this study indicate that the addition of 60 mm of supplementary irrigation combined with a 0.6–2.2 °C increase in mean daily temperature would result in an 8.3%–12.8% improvement in crop yields. These findings indicate that supplementary irrigation can play an important role in improving the pea yield when the temperature increases.

Taken together, the aforementioned results indicate that the pea yields are affected by both an increase in temperature and supplementary irrigation. To further evaluate these effects, we applied regression analysis to the relationship between temperature increase and yield decrease. The results of this analysis revealed that a non-linear negative relationship exists between the yield decrease (Y) and temperature increase (X) for treatments T1–T4 ($Y = 54.05e^{0.64X}$, $r = 0.98$). In addition, a non-linear negative relationship also exists between the yield decrease (Y) and temperature increase (X) for treatments T5–T8 ($Y = 83.45e^{0.38X}$, $r = 0.94$) (Fig. 2).

The number of stems with root-rot sickness

The ratio of Sr and Sn in T3 and T4 was 23.3% and 50.6% higher, respectively, than in T1 ($p < 0.01$). Additionally, The ratio of Sr and Sn in T7 and T8 was 24.4% and 51.7% higher, respectively, than the ratio of Sr and Sn on plants in T5 ($p < 0.01$) (Table 4).

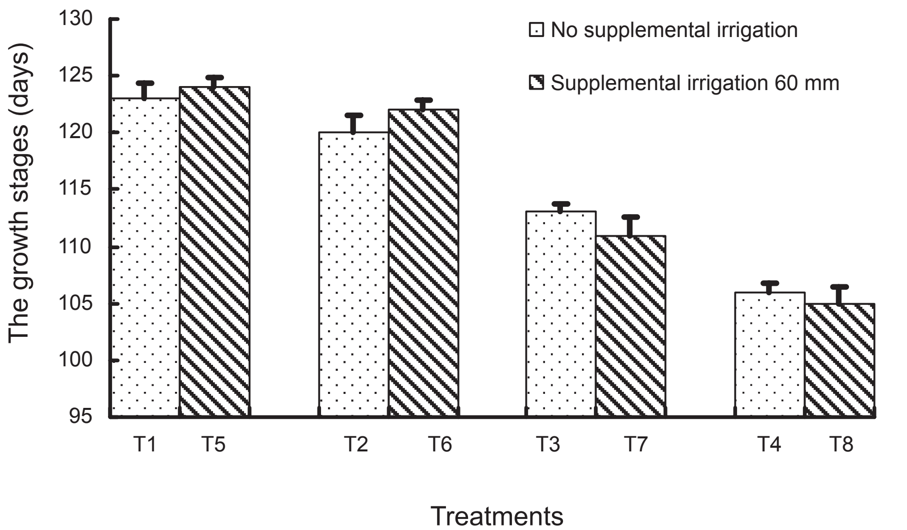

Figure 1. Changes in the growth stages of peas in response to different temperature increases in treatments T1–T4 and T5–T8.

Table 3. Pea yields and their yield components for all treatments.[a,A]

	Stem numbers in the harvest stage (10^4 ha^{-1})	Shale numbers per stem	Grain numbers per shale	Hundred-grain weight (g)	Yield (kg ha^{-1})	Decrease (%)
T1	58.8a	15a	7.6a	78.5a	1234a	0
T2	55.5a	14a	7.7a	80.5a	1156a	6.3
T3	47.7b	14a	7.5a	80.1a	1098b	11.0
T4	40.7c	12a	7.6a	80.6a	1018b	17.5
T5	59.8A	15A	8.3A	85.6A	1336A	0
T6	58.2A	14A	8.4A	88.7A	1235A	7.6
T7	55.7B	13A	8.2A	89.7A	1188B	11.1
T8	53.3C	13A	8.1A	88.6A	1148B	14.1

[a,A]Means within columns followed by different letters are significantly different ($p < 0.01$).
"a" is significantly different from "b" and "A" is significantly different from "B".

These results indicate that a temperature increase will lead to a significant increase in the number of stems with root-rot sickness.

The number of stems with root-rot sickness in treatments T1–T4 did not differ significantly from that of plants in treatments T5–T8. This result indicates that supplementary irrigation will not play an important role in improving the number of stems with root-rot sickness if the temperature increases. In addition, the results of this study also indicate that the number of stems with root-rot sickness is associated with an increase in temperature as well as supplementary irrigation. To further evaluate these effects, we applied regression analysis to the relationship between temperature increase and the number of stems with root-rot sickness. The results of this analysis revealed that a non-linear negative relationship exists between the number of stems with root-rot sickness (Y) and the increase in temperature (X) for treatments T1–T4 ($Y = 1.74e^{1.28X}$, r = 0.92). Furthermore, a non-linear negative relationship also exists between the number of stems with root-rot sickness (Y) and temperature increase (X) for treatments T5–T8 ($Y = 3.87X^2 + 0.30X–1.58$, r = 0.96) (Fig. 3).

Input–output analysis

The input-output ratios of T3 and T4 are 1.11 and 1.20, respectively, which is higher than that of T1. Furthermore, the results from treatments T1–T4 indicate that if the mean daily temperature increases by 0.6–2.2 °C, the In/Ou ratio of the pea group will be greater than 1.0. Taken together, these results show that an increase in temperature will change the In/Ou ratio of pea plants (Table 5).

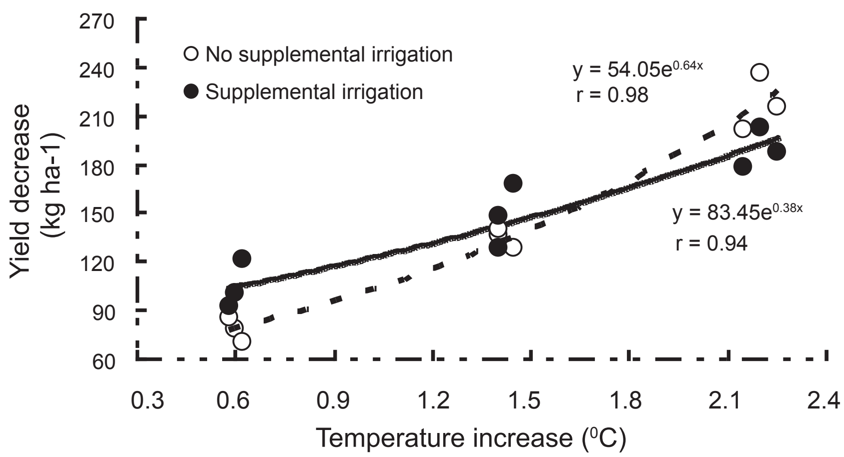

Figure 2. Relationship between yield decreases of peas and temperature increase in treatments T1–T4 and T5–T8.

Table 4. Number of stems with root-rot sickness for all treatments.[a,A]

	Stem numbers from emergence to mature stages (10^4 ha^{-1})	Number of stems with root-rot sickness (10^4 ha^{-1})	S_r/S_n (%)
T1	59.8a	1.6a	2.7a
T2	58.5a	4.4b	7.5a
T3	59.1a	13.8c	23.3b
T4	58.9a	29.8d	50.6c
T5	59.9A	1.4A	2.3A
T6	58.8A	4.2B	7.1A
T7	58.7A	14.3C	24.4B
T8	58.4A	30.2D	51.7C

[a,A]Means within columns followed by different letters are significantly different ($p < 0.01$).
"a" is significantly different from "b", "c", and "d" and "A" is significantly different from "B", "C", and "D".
S_r is the number of stems with root-rot sickness from emergence to mature stages; S_n is the number of stems from emergence to mature stages.

The input-output ratios of T7 and T8 are 1.08 and 1.12, respectively, which is higher than that of T5. These findings indicate that if the daily temperature increases by 0.6–2.2 °C and crops are irrigated with 60 mm of supplementary irrigation, the In/Ou ratio of pea plants will be greater than 1.0. Taken together, these results demonstrate that application of 60 mm of supplementary irrigation will not decrease the In/Ou ratio of pea plants that are being subjected to a 0.6–2.2 °C increase in temperature.

Water use efficiency

The results of this study revealed that a 0.6 °C increase in temperature resulted in a decrease in water use efficiency (WUE). However, the WUE of T3 and T4, which were subjected to a mean daily temperature increase of 1.4–2.2 °C, clearly decreased, and was significantly lower than that of T1 and T2. These results indicate that an increase in mean daily temperature could decrease the WUE of pea plants (Fig. 4).

Treatments T1–T4 revealed that a 2.2 °C increase in the mean daily temperature resulted in a decrease in the WUE of pea plants of 2.1 kg ha^{-1} mm^{-1}. However, application of 60 mm of irrigation in conjunction with a 2.2 °C increase in temperature resulted in a 1.7 kg ha^{-1} mm^{-1} decrease in the WUE of the crop. These results show that supplementary irrigation may be beneficial to the improvement of WUE in response to an increase in temperature.

Discussion

EPIC (The erosion/productivity impact calculator) and DSSAT (The decision support system for agro-technology transfer) model projections suggest that, although increased temperature and decreased soil moisture will act to reduce global crop yields by 2050, the direct fertilization effect of rising CO_2 will offset these losses.[21] However, the CO_2 fertilization factors used in models to project future yields were derived from enclosure studies conducted approximately 20 years ago. In addition, most information regarding crop responses to elevated CO_2 and temperature has been obtained from studies conducted in greenhouses,

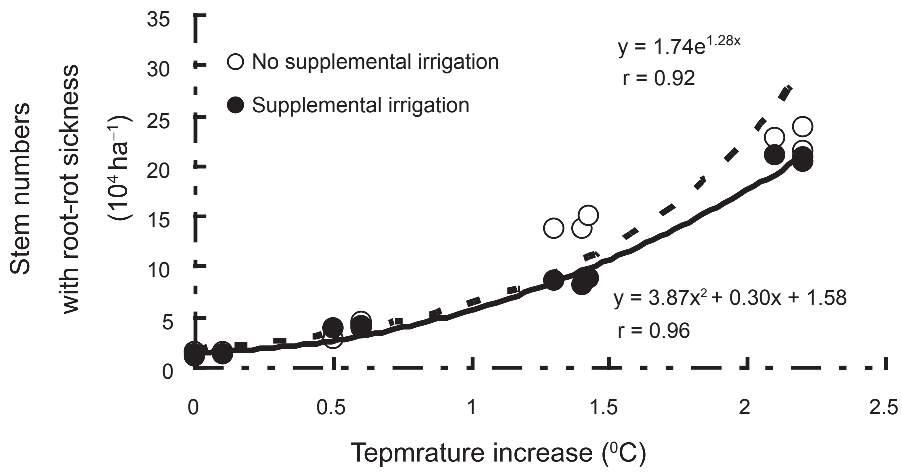

Figure 3. Relationship between the number of stems with root-rot sickness and temperature increase in treatments T1–T4 and T5–T8.

Table 5. Input–output analysis of pea production with different temperature increases for all treatments.[a,A]

	Input (RMB ha^{-1})*						Output (RMB ha^{-1})	In/Qu
	Sowing	Chemical fertilizer	Seeds	Irrigation	Management	Total		
T1	525	1275	675	0	450	2925	2961a	0.99a
T2	525	1275	675	0	450	2925	2774b	1.05a
T3	525	1275	675	0	450	2925	2635b	1.11b
T4	525	1275	675	0	450	2925	2443c	1.20b
T5	525	1275	675	150	450	3075	3206A	0.96A
T6	525	1275	675	150	450	3075	2964B	1.04A
T7	525	1275	675	150	450	3075	2851B	1.08B
T8	525	1275	675	150	450	3075	2755C	1.12B

[a,A]Means within columns followed by different letters are significantly different ($p < 0.01$).
"a" is significantly different from "b" and "A" is significantly different from "B".
*Conversion rate of US dollars to Renminbi (RMB) was approximately US$ 1 = 7.9 RMB at the time this study was conducted.
O_u is the output value; In is the input cost.

laboratory controlled-environmental chambers, and transparent field chambers, where CO_2 concentrations and temperature may be easily controlled. Free-air concentration enrichment (FACE) technology has now facilitated large-scale trials conducted to evaluate major grain crops subjected to elevated CO_2 levels under fully open-air field conditions.[22] Open-top chamber (OTC) facilities are less costly than FACE experiments and have been used to evaluate plant responses to ozone and other air pollutants.[23] More recently, OTCs were also used in multi-site experiments to evaluate the combined effects of elevated CO_2 and ozone concentrations and/or changes in water supply related to changes in weather on wheat.[24] However, OTCs modify growing conditions, primarily by increasing the air temperature and reducing the incident solar radiation.[25,26] In this study, the field experiment was used to evaluate the effects of increases in air temperature on water use and the yields of pea plants.

The effects of temperature increase on the growth and yields of crops have become a major research theme that has led to some significant breakthroughs and advances in the wider field of global climate change.[27–30] Indeed, many studies have reported decreased dry matter production and decreased yields of annual crops in response to only an increase in temperature.[31,32] According to the results of these studies, a constant

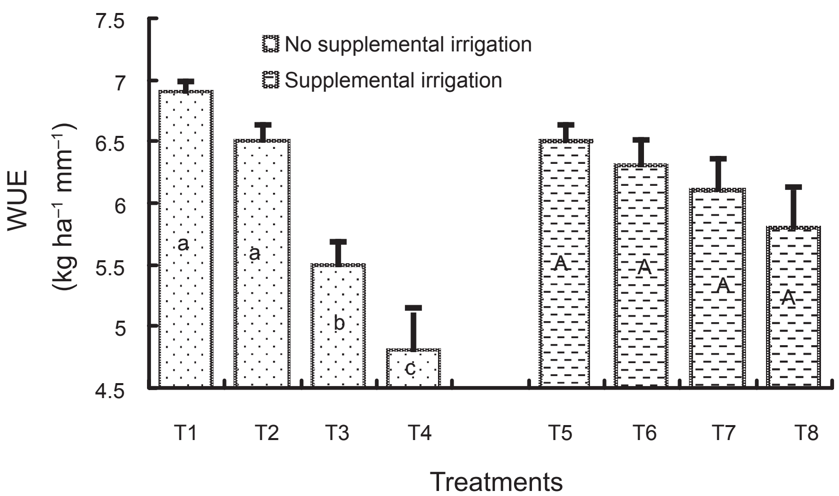

Figure 4. Water use efficiency of pea plants in treatments T1–T4 and T5–T8. WUE is the water use efficiency. [a,A]Means within columns followed by different letters are significantly different ($p < 0.01$). "a" is significantly different from "b" and "'A" is significantly different from "B".

16% and/or 49% decrease in crop yield occurs due to an average temperature increase of 1.4 °C and/or 4.2 °C. In addition, the growth stage of rain-fed spring wheat is known to decrease by 8–10 days in response to an average increase of 1.0 °C in temperature. Warming generally reduces wheat yield, probably due to a shorter grain filling period caused by more rapid development.[33] The aforementioned studies were conducted to evaluate the growth and yields of crops as a monoculture over the course of a year. However, the effects of global warming on the growth and yields of the pea over several years have not yet been reported.

In conditions where high temperature is accompanied by staggered drought, the population and regeneration rate of diseases and pests is showing an increasing trend, which often results in the mass occurrence of diseases and pests. Due to climate warming, the period during which diseases and pests occur and reproduce is prolonged, which results in the growth and development rates of eggs and ova being accelerated. Therefore, the duration required for one generation to reproduce is shortened, resulting in an increased generation rate.[34] In this study, when the mean daily temperature increased by 1.4 °C or 2.0 °C, the number of stems with root-rot sickness increased significantly, by 23.3%, or 50.6%, respectively. These results indicate that a temperature increase will significantly increase the number of stems on pea plants with root-rot sickness. This combination of an increase in root-rot and a decrease in yield will provide a new challenge for future pea production and crop rotation systems in the semiarid regions of China.

The response of agricultural systems to future climate change also depends on management practices, such as variations in the types and levels of water and nutrients being applied.[35] The annual mean rainfall decreased by approximately 60 mm from the 1950s to the 1990s in semiarid regions of China, during which time the evaporation also increased by 35–45 mm due to an increase in temperature.[36] Additionally, rainfall and available soil moisture during the complete growing stage of crops were reduced by approximately 100 mm in the 1990s when compared with the 1950s. Therefore, the study of soil moisture is an important theme in agriculture that addresses the effects and responses to temperature increase. However, it may be necessary to study the effects of micro-irrigation systems on crop yield under global climate change to find a practical and effective way for improving future crop production.[37] This study has shown that supplementary irrigation using micro-irrigation technology can improve pea yields when temperatures increase. Specifically, supplementary irrigation with 60 mm of water applied over the entire growth stage of the crop was found to improve crop yields by 8.3%–12.8% when coupled with an increase of 0.6–2.2 °C in mean daily temperature.

Conclusions

In this study, the mean daily temperature was increased by 0.6–2.2 °C over the entire growth stage of the pea. When the mean daily temperature was increased by approximately 2.2 °C, the water use efficiency (WUE) of the pea decreased by 30.4%, the duration of the growth stage was shortened by approximately 17 days, the crop yield was decreased by 17.5%, and the number of stems with root-rot sickness increased by 50.6%. When the mean daily temperature was increased by about 1.4 °C, the WUE decreased by 26.1%, the duration of the growth stage of the crop was shortened by 10 days, crop yields were decreased by 11.1%, and the number of stems with root-rot sickness increased by 23.3%. In addition, supplementary irrigation was beneficial to the improvement of pea yields when accompanied by a temperature increase. Specifically, application of 60 mm of supplementary irrigation during the complete growth stages of the crop along with an increase of 0.6–2.2 °C in mean daily temperature resulted in an increase in crop yields of 8.3%–12.8%. However, the results also revealed that application of 60 mm of supplementary irrigation will not decrease the number of stems with root-rot sickness.

Acknowledgements

This study was supported by the Public Welfare (Weather) Special Research Project of the China Meteorological Administration (GYHY200806021-05), The China Key Science Foundation (40830957), the Ningxia Science Foundation (NZ0733), and the Postdoctoral Science Foundation (20060390100).

Disclosure

The authors report no conflicts of interest.

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