PHENOLOGICAL LITERACY

UNDERSTANDING THROUGH SCIENCE & STEWARDSHIP

Module 9
Socio-phenology:
How might phenological shifts influence human populations?

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Goals For Student Learning

This seminar module was created to help students:

- Describe and understand peer-reviewed studies evaluating the effects of phenological shifts on human society
- Synthesize knowledge garnered from previous modules to discuss the implications of phenological shifts for human well-being.

Phenology And Society

Many phenological processes are intricately linked to the immediate health and well-being of the human population. Many studies of phenology and global climate change focus on phenological responses in populations of wild plant and non-human animal species. Yet numerous research endeavors focus on assessing how climate change may influence phenological processes that directly affect the human population. In fact, more and more such "socio-phenological" studies are being published each year! For this seminar activity, pairs of students will search for and select peer-reviewed articles that address phenological processes that influence the human population.

Before the Seminar:

Students divide into pairs and use *Web of Science* or *Google Scholar* to find their own peer-reviewed research papers to share with the group. Potential topics include:

- Crop phenology and impacts on agricultural yields
- How a reduction in winter chill may affect orchard or tree crops that require vernalization for flowering (e.g., walnut trees, apple trees)
- Whether a warming climate may affect maple syrup yields
- Mismatches between wild pollinators and the crops that depend on them
- Phenology of insect emergence of crop pests
- Insect pest outbreaks that damage agricultural or wild species due to mismatches with the pests' natural enemies
- Phenology of algal blooms
- Phenology and fisheries (especially migratory fish, such as salmon)
- Range expansion of invasive species
- Phenology and pollen: implications for the timing of the allergy season

- Changes in ecosystem services that are influenced by phenological schedules (e.g., ecotourism)
- Wildflower displays and climate change
- Autumn leaf color displays and climate change

Articles To Read

- As described above, seminar participants will search for and select the articles for discussion.

- The articles listed below may also provide a good starting point for in-class discussions:

    - Ziska, L., K. Knowlton, C. Rogers, D. Dalan, N. Tierney, M. A. Elder, W. Filley, J. Shropshire, L. B. Ford, C. Hedberg, P. Fleetwood, K. T. Hovanky, T. Kavanaugh, G. Fulford, R. F. Vrtis, J. A. Patz, J. Portnoy, F. Coates, L. Bielory, and D. Frenz. 2011. Recent warming by latitude associated with increased length of ragweed pollen season in central North America. Proceedings of the National Academy of Sciences of the United States of America 108:4248-4251.

    - Tao, F., M. Yokozawa, Y. Xu, Y. Hayashi, and Z. Zhang. 2006. Climate changes and trends in phenology and yields of field crops in China, 1981-2000. Agricultural and Forest Meteorology 138:82-92.

Suggested Activity

Synthesize the literature. In class, each pair of students will present their article and describe their study's:

- Overall focus and its relevance to human society
- General objectives
- Experimental methodology
- Research findings
- The study authors' conclusions
- Any caveats of the study that might limit the ability of the data collected to support the study authors' conclusions

Presentations can be given using Powerpoint, or a white board. This may also extend into multiple class periods, depending on class size and the length of student presentations.

Post-presentation Discussion Questions

1. How many different phenological processes that relate to human populations did the class find?

2. How many of the articles brought to class reported a statistically significant relationship between climate variables and a phenological process that directly affects the human population?

3. How many of the articles brought to class did NOT report a statistically significant relationship between climate variables and a phenological process that directly affects the human population? How, if at all, was climate change addressed in these articles?

4. Based on the papers found today, which socio-phenological topic has the greatest *economic effect* on our society?

5. Based on the papers found today, which socio-phenological topic has the greatest *cultural relevance* our society?

6. Based on the papers found today, which socio-phenological process may influence the most people worldwide?

7. Which area of socio-phenological research is the most intensively studied at this time?

8. Which area of socio-phenological research is still in its early stages?

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Climate changes and trends in phenology and yields of field crops in China, 1981–2000

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Abstract

A warming trend has become pronounced since the 1980s in China and is projected to accelerate in the future. Concerns about the vulnerability of agricultural production to climate change are increasing. The impact of future climate change on crop production has been widely predicted by using crop models and climate change scenarios, but little evidence of the observed impacts of climate change on crop production has been reported. In this study, we synthesized crop and climate data from representative stations across China during 1981–2000 to investigate whether there were significant trends in changes of climate variables in different regions, and whether theses changes have had significant impact on the development and production of the staple crops (i.e. rice, wheat, and maize). Our results showed that significant warming trends were observed at most of the investigated stations, and the changes in temperature have shifted crop phenology and affected crop yields during the two decades. The observed climate change patterns, as well their impacts on crop phenology and yields are spatially diverse across China. Our study also highlights the need for further investigations of the combined impacts of temperature and CO_2 concentration on physiological processes and mechanisms governing crop growth and production.

Keywords: Agricultural production; Crop; Food security; Observed impacts; Warming trend

1. Introduction

A warming trend has been well documented at most locations around the world during the last several decades, and this trend is projected to accelerate in the future. The potential impacts of climate change on natural and managed ecosystems are of concern and have been extensively evaluated by various simulation models (e.g. Tao et al., 2000; Cramer et al., 2001; Parry et al., 2004), but few studies have examined how rising temperatures have actually affected crop development and production in the field. Such observed evidence or ''fingerprints'' of climate change can provide more accurate and valuable information for examining the mechanisms and processes of vegetation response. Such diagnostic studies can also be very helpful in improving models, and, consequently, have important implications for predicting the impacts of future climate change.

Recent documentation of systematic change across a broad range of species spread over many continents

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provides convincing evidence that 20th century climate trends have impacted natural systems (Easterling et al., 2000; Wuethrich, 2000). The responses of natural vegetation to climate change have been investigated by analysing satellite data, including changes in vegetation greenness (Zhou et al., 2003), phenology (Zhang et al., 2004), and net primary production (NPP) (Nemani et al., 2003). The phenological seasons of natural vegetation have also been shown to change spatially and temporally in response to trends in climate change by using the observed data from phenological networks (e.g. Menzel et al., 2001; Zheng et al., 2002). However, most studies focus on changes in the natural vegetation; only a few deal with trends in agricultural and horticultural varieties despite their potential economic importance (Chmielewski et al., 2004). In Germany, a shift in phenology of fruit trees and field crops due to increased temperature from 1961 to 2000 has been observed, but the changes in plant development are still moderate so no strong impacts on yield formation processes have been observed so far (Chmielewski et al., 2004). Gradual temperature changes from 1982 to 1998 have caused a measurable impact on the yields of corn and soybeans in the United States (Lobell and Asner, 2003). Also, in the Philippines, rice grain yield was found to decline by 10% for each 1 °C increase in growing-season minimum temperature in the dry season (January–April) from 1992 to 2003 (Peng et al., 2004). Obviously, ongoing warming trend has had measurable impacts on the development and production of field crops, but the size and extent of the impacts have differed spatially and temporally. There is a clear and present need to synthesize crop yield and climate data from different areas to provide critically needed observational constraints on projections of the impacts of both climate change and management practices on future food production (Lobell and Asner, 2003).

In China, mean temperature has increased in the last several decades, especially since the 1980s (Tao et al., 2003). During 1951–1990, annual mean minimum temperature generally tended to increase all over China, with the largest increase in the north and smaller increases in the south. Annual mean minimum temperature increased significantly by 0.175 °C/decade for all of China. The largest trend was found in winter, with a warming rate of 0.417 °C/decade. The annual mean maximum temperature showed a slight, but not statistically significant, increase (Zhai et al., 1999). The explicit spatial and temporal changes in temperature, characterized by a marked asymmetry between maxima and minima, are presumed to have caused significant changes in crop development and production in China. Studies on the responses of field crops to such gradual climate changes on a decadal scale are scarce, however, although the impacts of seasonal and interannual climate variability on crop production have been investigated (Tao et al., 2004).

In this study, we examined the relation between climate variation, crop phenology, and crop production by compiling and analysing data on maximum temperature, minimum temperature, precipitation, and the phenology and yields of staple crops (rice, wheat, and maize) from agricultural experiment stations for the period 1981–2000. Our objective was to show whether there were significant time trends in changes of the climate variables at different locations across China, and whether these changes have had significant impacts on the development and production of the staple crops.

2. Data and methods

2.1. Crop and weather data

The data on crop (rice, wheat, and maize) phenology, yields and yield components, and management practices from 1981 to 2000 are from local agricultural meteorological experiment stations, which are maintained by the Chinese Meteorological Agency. In this study, we selected two stations for each crop that (1) were located in the crop's primary production region, (2) represented the typical cropping system in China for that crop, (3) were geographically and climatologically different, (4) had good records of weather parameters, and (5) had good records of crop data for the period 1981–2000. For rice, we selected Hefei station in Anhui Province, eastern China, and Changsha station in Hunan Province, southern China. For wheat, we selected Zhengzhou station in Henan Province, central China, and Tianshui station in Gansu Province, northwestern China. For maize, we selected Zhengzhou station in Henan Province, central China, and Harbin station in Heilongjiang Province, northeastern China (Fig. 1). General information on the crops and stations selected for the study is shown in Table 1. Crop management practices in the experiment stations were generally same as or better than the local traditional practices. The traditional management practices did not change much during the studied period, although the cultivars were frequently changed. Irrigation was not conducted every year, but fertilizer was used several times every year. In addition, pesticides were also used frequently to control pests and diseases.

The daily weather data for the climate parameters used, i.e. maximum temperature, minimum temperature,

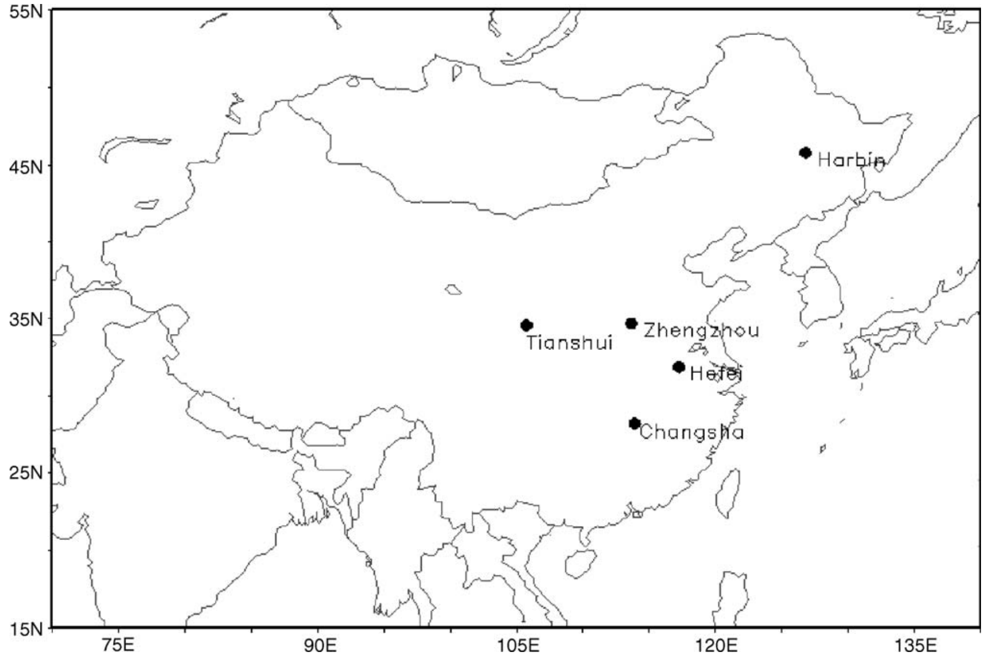

Fig. 1. Locations of the stations used in the study.

solar radiation, and precipitation, from 1980 to 2000 for the agricultural meteorological stations are from the Chinese Meteorological Agency.

After 1980, the climate observations and crop records at experiment stations were not disturbed any more by political events, such as 'Cultural revolution'. Also the fact that crops were quite well managed by irrigating, fertilizing, and using pesticides, etc., depending on weather variability and crop growth status (e.g. insects, diseases) makes the crop records reliable for trend analysis to much extent.

2.2. Analysis

We analysed the time trends of changes in climate parameters, crop phenology, and yields by regression and Kendall-tau statistic (see also Lobell and Asner, 2003; Chmielewski et al., 2004). The relationships among crop phenology, yield, and climate parameters were evaluated by using Pearson correlation analyses. Statistical significance was tested using the two-tailed *t*-test.

3. Results

3.1. Climate change and trends in China during the period 1981–2000

As showed in Table 2, during the period 1981–2000, significant warming trends, especially for minimum temperatures, were observed at all stations except Changsha in southern China. In contrast, precipitation changed significantly ($p < 0.01$) only at Changsha station. At Changsha station, during the early rice-growing period (May–July), maximum temperature decreased slightly ($p > 0.05$), and minimum temperature increased slightly ($p > 0.05$). Over the late rice-growing period (July–September), both maximum temperature and minimum temperature decreased not significantly ($p > 0.05$) (Table 2). Precipitation increased significantly over both the early rice-growing period ($p < 0.05$) and the late rice-growing period ($p < 0.01$).

At Hefei station, the mean maximum and minimum temperatures in summer (June–August) increased by 0.37 ($p > 0.05$) and 0.63 °C/decade ($p < 0.05$), respectively. Precipitation had a general decrease trend ($p > 0.05$). At Zhengzhou station, the maximum and minimum temperatures in winter (December–February) increased significantly by 0.95 °C/decade ($p < 0.05$) and 0.92 °C/decade ($p < 0.01$), respectively (Fig. 5A). In spring (March–May), minimum temperature also increased by 0.74 °C/decade ($p > 0.05$), and the maximum temperature increased not significantly. In summer, minimum temperature increased significantly by 0.51 °C/decade ($p < 0.05$), and maximum temperature increased by 0.39 °C/decade ($p > 0.05$). At Tianshui station, minimum temperatures increased significantly in winter by 0.72 °C/decade ($p < 0.05$)

Table 1
General information on the crops and stations selected for the study

	Rice		Wheat		Maize	
Stations	Changsha	Hefei	Zhengzhou	Tianshui	Zhengzhou	Harbin
Latitude, longitude	28°13′N, 112°55′E (1987–2000); 28°12′N, 113°05′E (1981–1986)	31°52′N, 117°14′E	34°43′N, 113°39′E	34°35′N, 105°45′E	34°43′N, 113°39′E	45°45′N, 126°46′E
Typical planting dates	Early rice: 29 March–10 April, late rice: 20 June–30 June	20 April–10 May	10 October–25 October	6 October–16 October	5 June–15 June	26 April–6 May
Typical anthesis dates	Early rice: 15 June–30 June, late rice: 12 September –22 September	20 July–25 August	25 April–4 May	10 May–20 May	28 July–4 August	20 July–30 July
Typical maturity dates	Early rice: 15 July–25 July, late rice: 20 October–30 October	20 August–25 September	28 May–6 June	20 June–30 June	5 September–20 September	16 September–30 September
Typical cropping system	Double rice	Rotation between winter wheat and rice	Rotation between winter wheat and maize	Single wheat	Rotation between winter wheat and maize	Single maize or rice
Annual mean temperature (°C)	17.2	16.4	14.4	11.2	14.4	4.6
Annual total precipitation (mm)	1498	982	623	494	623	555
Period of crop data	1981–2000	1981–2000	1981–2000	1981–2000	1981–2000	1984–2000
Period of weather data	1981–2000	1981–2000	1980–2000	1980–2000	1981–2000	1981–2000
Years with irrigation	Early rice: 1985, late rice: 1982; 1984; 1985	1997; 1998	Every year except 1984	Every year except 1982–1983; 1985–1987; 1989–1990	1981–1988; 1991; 1997; 1999	

Table 2
Trends in seasonal climate at 5 stations across China during the period 1981–2000

Station	Season	Maximum temperature		Minimum temperature		Precipitation	
		Trend (°C/decade)	R^2	Trend (°C/decade)	R^2	Trend (mm/decade)	R^2
Changsha	May–June–July	−0.4	0.10	0.2	0.03	55.0*	0.35
	July–August–September	−0.8	0.24	−0.1	0.03	62.9**	0.41
Hefei	Summer	0.4	0.04	0.6*	0.22	−27.7	0.007
Zhengzhou	Winter	0.9*	0.22	0.9**	0.44	1.5	0.007
	Spring	0.2	0.006	0.7	0.31	−1.8	0.002
	Summer	0.4	0.11	0.5*	0.23	−2.1	0.001
Tianshui	Winter	1.0	0.16	0.7*	0.27	0.1	0.00
	Spring	1.0	0.24	1.1**	0.65	7.1	0.11
Harbin	Summer	0.7	0.15	1.0*	0.37	15.6	0.08
	Spring	0.1	0.003	0.80	0.14	1.7	0.02

* Trends are significant with $p < 0.05$.
** Trends are significant with $p < 0.01$.

and in spring by 1.09 °C/decade ($p < 0.01$). Maximum temperature increased not significantly in spring and winter, by 0.98 °C/decade ($p > 0.05$). At Harbin station, in summer minimum temperature increased significantly by 0.99 °C/decade ($p < 0.01$), and maximum temperature increased not significantly by 0.70 °C/decade ($p > 0.05$). Both maximum temperature and minimum temperature increased not significantly in spring.

3.2. Climate change and trends in phenology and yields of field crops

The trends in climate may have had impacts on the trends in phenology and yields of field crops. Therefore we further investigate the trends in phenology and yields of staple crops in China (i.e. rice, wheat, and maize) during the period 1981–2000, as well their relationships with trends in climate.

3.2.1. Climate change and trends in rice phenology and yields

At Changsha station, the planting date ($p < 0.01$), the anthesis date ($p < 0.01$) and maturity date ($p < 0.05$) of early rice became significantly earlier by 5.7, 6.2 and 3.6 days/decade, respectively (Fig. 2, Table 3). The planting dates were related to the minimum temperature in March ($p < 0.05$). The anthesis date and maturity date were related to the maximum and minimum temperature, as well as precipitation during the growing period (May–July) (Table 4). Early rice yields increased not significantly during the period studied. The slight changes in maximum and minimum temperatures did not significantly affect rice yields (Table 4). Extreme precipitation during several years, however, reduced rice yields sharply. Over the late rice-growing period (July–September), the anthesis and maturity days became slightly earlier ($p > 0.05$) (Table 3). The trend in anthesis dates was significantly related to minimum temperature in August ($p < 0.05$) (Table 4). Rice yields increased significantly during the studied period ($p < 0.01$) (Table 3) and were significantly ($p < 0.01$) related to precipitation during the growing-season (Table 4). Maximum and minimum temperatures were negatively related to rice yields (Table 4), suggesting that the cooling trend at this station was favourable for rice production, but the relationships were not significant ($p > 0.05$).

At Hefei station, rice planting ($p < 0.01$), anthesis ($p > 0.05$) and maturity dates ($p < 0.05$) were delayed during the two decades. Nevertheless rice anthesis and

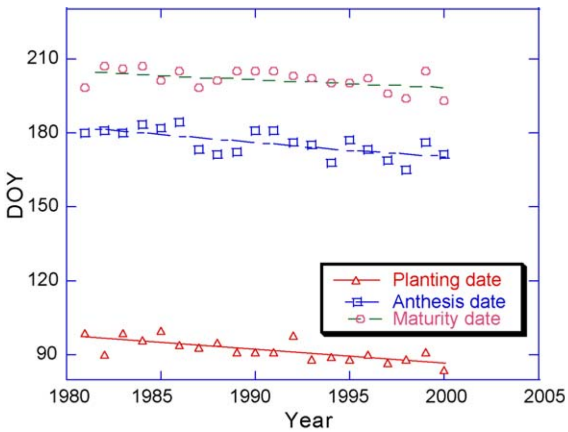

Fig. 2. Trends in early rice phenology at Changsha station during the period 1981–2000.

Table 3
Trends in phenology and yields of field crops at 5 stations across China during the period 1981–2000

Crop	Station	Planting date		Anthesis date		Maturity date		Yield	
		Trend (days/decade)	R^2	Trend (days/decade)	R^2	Trend (days/decade)	R^2	Trend (kg/ha/yr)	R^2
Early rice	Changsha	−5.7**	0.56	−6.2**	0.45	−3.6*	0.25	14.2	0.018
Late rice	Changsha	0.6	0.01	−1.0	0.02	−1.0	0.01	81.6**	0.28
Rice	Hefei	16.2**	0.56	17.0	0.36	21.3*	0.39	−20.2	0.03
Wheat	Zhengzhou	−3.4	0.09	−3.0	0.21	−0.0	0.00	−112.8	0.15
Wheat	Tianshui	−2.9	0.18	−2.7	0.11	−3.3*	0.28	−7.1	0.007
Maize	Zhengzhou	1.7	0.05	3.0	0.13	5.5	0.24	−168.8	0.17
Maize	Harbin	−5.3	0.29	−0.6	0.003	7.3	0.09	271.1**	0.47

* Trends are significant with $p < 0.05$.
** Trends are significant with $p < 0.01$.

Table 4
Pearson correlation coefficients between trends in seasonal climate and in phenology and yields of field crops

Crop	Station	Climate variable	Planting date	Anthesis date	Maturity date	Yield
Early rice	Changsha	T_{max} in May–July	0.22	0.17	−0.15	−0.13
		T_{min} in May–July	−0.19	−0.17	−0.24	0.15
		T_{min} in March	−0.45*	−0.10	−0.38	−0.15
		Precipitation in May–July	−0.57**	−0.61**	−0.33	−0.21
Late rice	Changsha	T_{max} in July–September	−0.05	0.04	0.05	−0.44
		T_{min} in July–September	−0.39	−0.18	−0.44	−0.19
		T_{min} in August	−0.35	−0.50*	−0.28	−0.28
		Precipitation in July–September	0.03	−0.09	−0.23	0.60**
Rice	Hefei	T_{max} in summer	0.20	−0.04	−0.01	−0.39
		T_{min} in summer	0.32	0.12	0.11	−0.52*
		T_{max} during 20 days before and after anthesis	−0.27	−0.53*	−0.54*	−0.30
		T_{min} during 20 days before and after anthesis	−0.42	−0.66**	−0.65**	−0.22
		Precipitation in summer	0.03	0.36	0.30	0.04
Wheat	Zhengzhou	T_{max} in winter	0.03	−0.37	−0.13	−0.38
		T_{min} in winter	−0.26	−0.68**	−0.24	−0.21
		T_{max} in spring	0.05	−0.33	−0.56*	−0.28
		T_{min} in spring	0.09	−0.58**	−0.33	−0.43
		Precipitation in winter	−0.32	−0.17	−0.09	0.44*
		Precipitation in spring	0.21	−0.10	0.33	0.34
Wheat	Tianshui	T_{max} in winter	−0.19	−0.14	−0.17	−0.26
		T_{min} in winter	−0.32	−0.11	−0.36	−0.07
		Precipitation in winter	−0.30	0.22	0.10	0.32
		T_{max} in spring	−0.17	−0.70**	−0.69**	−0.45*
		T_{min} in spring	−0.34	−0.66**	−0.70**	−0.29
		Precipitation in spring	0.25	0.45*	0.50*	0.02
Maize	Zhengzhou	T_{max} in summer	0.28	0.10	0.12	0.02
		T_{min} in summer	−0.15	−0.01	−0.14	−0.44
		Precipitation in summer	−0.26	0.16	−0.05	−0.51*
Maize	Harbin	T_{max} in spring	−0.63**	−0.11	0.14	0.15
		T_{min} in spring	−0.63**	−0.20	0.06	0.36
		Precipitation in spring	0.11	−0.05	−0.20	0.33
		T_{max} in summer	−0.10	−0.23	0.13	0.16
		T_{min} in summer	−0.16	−0.62**	−0.23	0.33
		Precipitation in summer	0.29	−0.51*	−0.69**	−0.03

T_{max}, mean maximum temperature; T_{min}, mean minimum temperature.
* Correlations are significant with $p < 0.05$.
** Correlations are significant with $p < 0.01$.

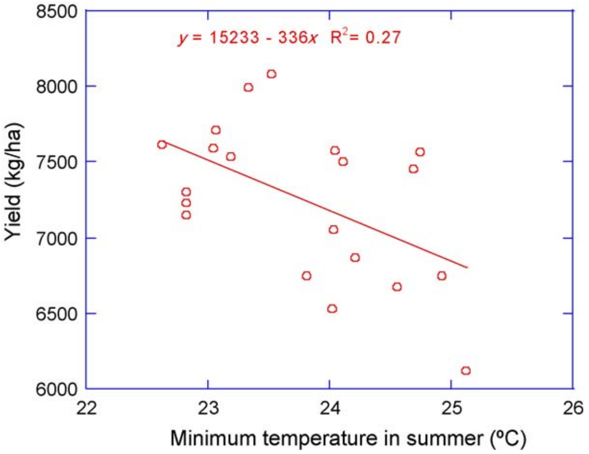

Fig. 3. Relationship between rice-yield and mean minimum temperature in summer at Hefei station.

maturity dates were significantly related to the minimum ($p < 0.01$) and maximum temperatures ($p < 0.05$) during the 20 days before and after anthesis (Table 4). Rice yield decreased not significantly during the two decades (Table 2). There was a significantly negative relationship between grain yield and minimum temperature ($p < 0.05$) (Fig. 3). About 26.85% of the rice grain yield trend can be explained by temperature, similar to the results of Lobell and Asner (2003). Grain yield decreased by about 4.63% for each 1 °C increase in minimum temperature, which is less than the 10% decrease in yield observed in the Philippines (Peng et al., 2004). The increase in minimum temperature (T_{min}) was about 1.69 times the increase in maximum temperature (T_{max}) at the station. According to the relationship between mean temperature (T_{mean}), and minimum and maximum temperature (i.e. $T_{mean} = 0.5(T_{max} + T_{min})$), if the mean temperature increased by 1 °C, minimum temperature would increase by 0.8 °C. Therefore, we conclude that grain yield declined by about 3.7% for each 1 °C increase in the mean growing-season temperature. Maximum temperature was negatively but not significantly related to grain yield. Precipitation was positively related to grain yield generally ($p > 0.05$).

3.2.2. Climate change and trends in wheat phenology and yields

At Zhengzhou station, wheat planting, anthesis and maturity dates became not significantly earlier (Table 2). Minimum temperature in winter ($p < 0.01$) and spring ($p < 0.01$) were significantly related to the anthesis date. Maximum temperature in spring was significantly related to the maturity date ($p < 0.05$) (Table 4). Wheat yields decreased not significantly at this station during the study period (Table 3). Maximum and minimum temperatures in winter and spring were negatively related to wheat yields ($p > 0.05$). Precipitation during winter ($p < 0.05$) and spring ($p > 0.05$) increased wheat yields (Table 4).

At Tianshui station, wheat planting, anthesis and maturity dates became earlier during the study period, by 2.95 ($p > 0.05$), 2.86 ($p > 0.05$), and 3.30 days/decade ($p < 0.05$), respectively (Table 3). The anthesis and maturity dates were significantly ($p < 0.01$) related to maximum and minimum temperature in spring. They became earlier significantly by 2.98 and 2.15 days, respectively, for each 1 °C rise in maximum temperature in spring (Fig. 4), equivalent to 3.15 and 2.27 days, respectively, for each 1 °C rise in mean temperature in spring. Wheat yields showed a slightly decreasing trend during the period (Table 3). Maximum temperature in spring was significantly negatively related to wheat yields ($p < 0.05$) (Table 4). Wheat yields would decrease by 9.68% for each 1 °C rise in maximum

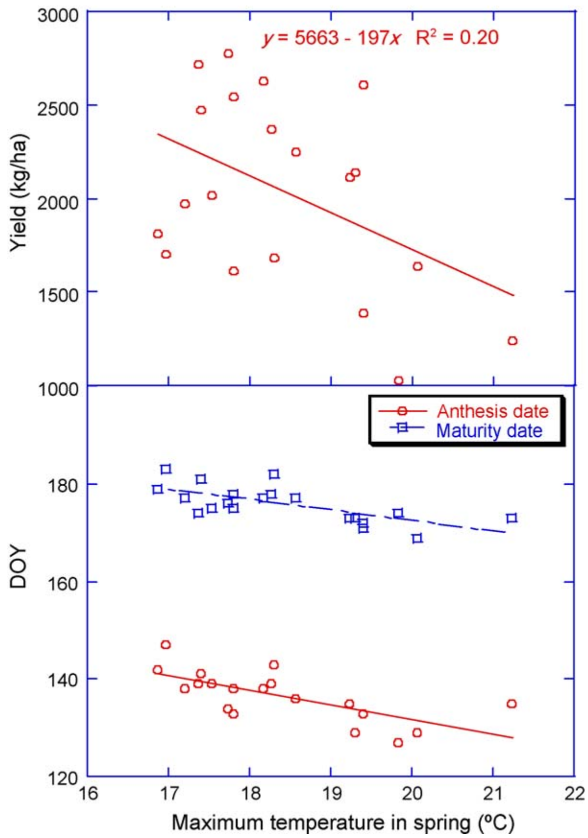

Fig. 4. Relationship between wheat yield, phenology and mean maximum temperature in spring at Tianshui station.

temperature in spring ($p < 0.05$) (Fig. 4), equivalent to 10.22% for each 1 °C rise in mean temperature in spring. In addition, maximum and minimum temperatures in winter, and minimum temperature in spring, were also negatively, but not significantly, related to wheat yields. Precipitation in winter was favourable for wheat production ($p > 0.05$) (Table 4).

3.2.3. Climate change and trends in maize phenology and yields

At Zhengzhou station, maize planting, anthesis and maturity dates were delayed slightly. Maize yields showed a decreasing trend during the two decades (Table 3), which were negatively related to precipitation ($p < 0.05$) and minimum temperature in summer ($p > 0.05$) (Table 4).

At Harbin station, during the two decades, maize planting began earlier ($p > 0.05$) by 2.12 days for each 1 °C increase in maximum temperature ($p < 0.01$), or by 2.28 days for each 1 °C increase in minimum temperature in spring ($p < 0.01$). The maize anthesis date also became earlier by 4.23 days for each 1 °C increase in minimum temperature in summer ($p < 0.01$). Maize yields increased significantly during the period ($p < 0.01$) (Table 3). The increasing trends in minimum and maximum summer temperatures were favourable for maize production during the two decades ($p > 0.05$) (Table 4).

4. Discussion

4.1. Climate change pattern and crop responses

Our sample stations are located in various geographical and climate zones and consequently showed diverse climate change patterns. A warming trend was significant during 1981–2000 at all stations except Changsha station. Moreover, the magnitude of the temperature increase was far greater than the mean for 1951–1990 across China (Zhai et al., 1999). At all stations minimum and maximum temperatures showed different rates of change. The increase in minimum temperature was less than twice that in the corresponding maximum temperature during 1981–2000, in contrast to an increase in the minimum temperature of approximately three times the corresponding maximum temperature during 1951–1990 over much of the Earth's surface (Karl et al., 1991).

Our sample stations also cover all the major cropping systems and primary crop production regions of China: single maize in northeastern China, single wheat in northwestern China, rotation between winter wheat and maize in central China, rotation between winter wheat and rice in eastern China, and double rice cropping in southern China. The observed changes in climate parameters affected the phenology and yields of the crops differently at different stations. Nevertheless, in general, the changes in temperature significantly affected crop phenology. Temperature was negatively correlated with crop yield at all stations except Harbin in northeastern China (Table 4), suggesting that the present temperatures are above the optimal range for crop production in most parts of China other than northeastern China. The observed warming trends significantly reduced rice yields at Hefei station by 3.7%, wheat yields at Tianshui station by 10.2% for each 1 °C increase in growing-season temperature during the study period. In contrast, crop production at Harbin station benefited from the observed warming trend. Rice production at Changsha, on the other hand, apparently benefited from a cooling trend during the last two decades of the 20th century.

When the diverse climate change patterns and management practices are taken into account, the magnitude of yield reduction is generally consistent with the results of previous simulations. For example, the simulated yield reduction corresponding to a 3 °C rise in mean daily temperature was about 16% for maize, wheat, sorghum, and soybeans in the central United States (Brown and Rosenberg, 1997). The simulated rice yield in the major rice-growing regions of Asia, with the present atmospheric CO_2 concentration, decreased by 7% for every 1 °C rise above current mean temperature (Matthews et al., 1997). For each 1 °C increase in the average seasonal temperature, rice yields were predicted to decrease by 9% (Kropff et al., 1993). The magnitude of yield reduction from an increase in mean daily temperature was about 15% (Peng et al., 2004) and 17% (Lobell and Asner, 2003) in previous studies using historical observed data. These differences could be ascribed to cultivar sensitivity, different management practices (for example, irrigation, fertilization and pesticides), or local climate (change) conditions. For example, under optimal irrigation management at the International Rice Research Institute (IRRI) farm, about 77% of yield variation could be explained by minimum temperature (Peng et al., 2004), in contrast to the about 26.85% explained by minimum temperature in an experiment without irrigation conducted at Hefei station. In the latter experiment, about 20% ($p > 0.05$) of yield variation was explained by precipitation during the growing-season.

It is very difficult to account thoroughly for the effects of technology and management, as well as weather variability, insects, disease, etc., occurring over the two decades of observations. To some extent, the effects could disturb the trend analysis. For example, crop yields may have increased because of the increasing use of modern cultivars and technology during the study period. If so, the estimated the decreases (increases) in crop productivity may actually be larger (smaller) than we estimated.

4.2. Potential physiological mechanisms

Although the physiological mechanisms by which extreme high temperatures affect yields of crops such as rice are well understood (Horie, 1988; Horie et al., 2000), the effects of small increases in temperature associated with global warming are poorly understood. Physiological mechanisms that caused the observed decreases in field crop yields should be related to both of them.

High temperatures, during anthesis prevent anther dehiscence and pollen shedding, reduce pollination and grain numbers, and increase sterility (Mackill et al., 1982; Matsui and Horie, 1992). Our analysis showed that rice spikelets were subjected to high temperatures during anthesis. For example, at Hefei station, spikelet sterility was related to the maximum temperatures ($p < 0.01$) during the 20 days before and after anthesis (Fig. 5).

The large diurnal change in temperature during the growing-season, which has warm days and cool nights, is beneficial for plant growth because warm days increase the photosynthetic rate and cool nights reduce the respiration rate (Leopold and Kriedemann, 1975).

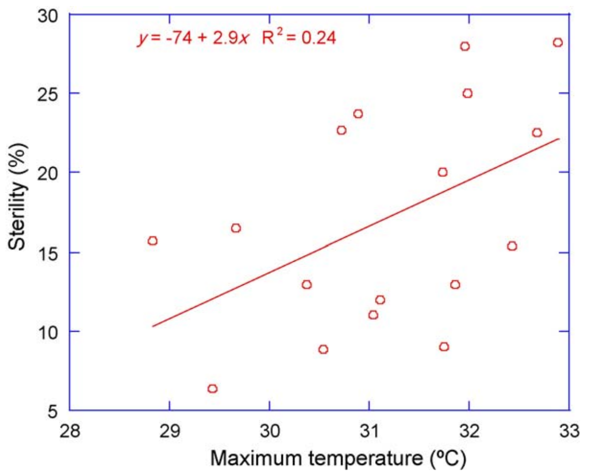

Fig. 5. Relationship between rice spikelet sterility and the mean maximum temperature during the 20 days before and after anthesis at Hefei station.

However, because temperature minima rose more than maxima, the diurnal temperature range showed a decreasing trend during the two decades. The different temperature changes could reduce maize growth and yield at Zhengzhou ($p < 0.05$) (Fig. 6), by causing an increase in nighttime maintenance respiration rates (Ryan, 1991) and consequently biomass consumption.

Despite the observed negative effects of high temperature on leaf photosynthesis, the optimum temperature for net photosynthesis is likely to increase with elevated levels of atmospheric CO_2. Several studies have concluded that CO_2-induced increases in crop yields are much more probable in warm than in cool environments. Thus, global warming may not greatly affect net photosynthesis overall (Egeh et al., 1994). Temperature affects grain weight directly rather than assimilate availability (Bremner and Rawson, 1978). Furthermore, respiration effects do not appear to be a direct cause of decreased grain size in heat-stressed wheat (Wardlaw, 1974). Reported yield reductions in maize, wheat, and soybeans with increased nighttime temperatures cannot be explained fully by the effects on respiration (Peters et al., 1971). Reduction of grain weight by heat stress may be explained mostly by the effects of temperature on rate and duration of grain growth. Our results indicate that changes in temperature shifted crop phenology during the period studied, but mechanisms in addition to reduced grain weight may have contributed to the observed yield reduction, such as reduced numbers of grains formed or inhibition of sucrose assimilation by grains (Hawker and Jenner, 1993). Further investigations of the effects of temperature on the physiological processes governing crop development and yield are necessary to improve crop yield models and crop production predictions.

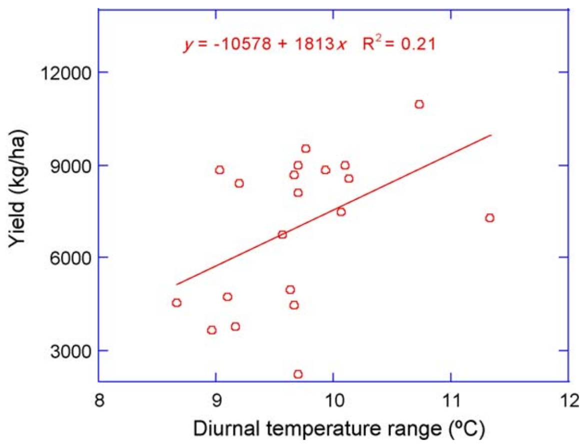

Fig. 6. Relationship between maize-yield and mean diurnal temperature in summer at Zhengzhou station.

The rise in atmospheric CO_2 concentration from about 280 μmol/mol before the industrial revolution to about 377 μmol/mol currently is well documented (e.g. Keeling et al., 1995; Keeling and Whorf, 2005). The fertilization effects of elevated atmospheric CO_2 on plants have been reported and are considered in crop models (see Kimball, 1983; Allen, 1990; Allen and Amthor, 1995; Tubiello and Ewert, 2002). However, the beneficial effects of increasing CO_2 on crop yields were not obviously detected from our data. Amthor (1998) also found the relative insignificance of increasing atmospheric CO_2 concentration to crop yield using long-term records of yield. CO_2 effects are likely to change with temperature increase (Long, 1991; Morison and Lawlor, 1999), water or nitrogen availability (Kimball et al., 2002). Yield should be most responsive to CO_2 when temperatures approximate the optimum for crop growth. Elevating CO_2 can ameliorate negative effects of above-optimal temperatures, but temperatures near the upper limit for crops will depress yields irrespective of CO_2 concentration (Polley, 2002). Therefore the long-term and large-scale effects of elevated CO_2 are still open to question (Levy et al., 2004), although process-based models have been used to estimate climate and CO_2 effects on potential yield (e.g. Tubiello and Ewert, 2002) and more recently also for water (Asseng et al., 2004) and nitrogen (Jamieson et al., 2000) limited conditions. Understanding of the combined effects of climate and CO_2 concentration on crop growth and yield, especially under limited conditions, is still necessary (Ewert, 2004).

5. Conclusions

Trends in temperature, as well their impacts on crop development and production, have become significant in some locations of China. The observed climate change patterns and their impacts were diverse both spatially and temporally. The sensitivity of crop responses to temperature change is also influenced by other factors such as changes in other climate parameters (e.g. precipitation), and management practices, suggesting a potential role of management for adaptation. This study also highlights the need for further investigations of the combined impacts of temperature and CO_2 concentration on physiological processes and mechanisms governing crop growth and yield.

The globally averaged surface temperature is projected to increase by 1.4–5.8 °C over the period 1990–2100, approximately representing global warming rates of between 0.1 and 0.5 °C/decade. This compares to an observed global warming rate of 0.15 °C/decade since 1970s. Therefore, the responses of crop development and production to the accelerated warming become of concern.

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Recent warming by latitude associated with increased length of ragweed pollen season in central North America

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A fundamental aspect of climate change is the potential shifts in flowering phenology and pollen initiation associated with milder winters and warmer seasonal air temperature. Earlier floral anthesis has been suggested, in turn, to have a role in human disease by increasing time of exposure to pollen that causes allergic rhinitis and related asthma. However, earlier floral initiation does not necessarily alter the temporal duration of the pollen season, and, to date, no consistent continental trend in pollen season length has been demonstrated. Here we report that duration of the ragweed (*Ambrosia* spp.) pollen season has been increasing in recent decades as a function of latitude in North America. Latitudinal effects on increasing season length were associated primarily with a delay in first frost of the fall season and lengthening of the frost free period. Overall, these data indicate a significant increase in the length of the ragweed pollen season by as much as 13–27 d at latitudes above ∼44°N since 1995. This is consistent with recent Intergovernmental Panel on Climate Change projections regarding enhanced warming as a function of latitude. If similar warming trends accompany long-term climate change, greater exposure times to seasonal allergens may occur with subsequent effects on public health.

aerobiology | allergies | global warming

Allergic disorders represent an important group of chronic diseases in the United States, with estimated costs at approximately $21 billion per year (1). Aeroallergen exposure is associated with two principal allergic diseases: allergic rhinitis (hayfever) and asthma. For much of geographic North America, there are three distinct plant-based aeroallergen seasons; tree pollen in the spring; grass pollen in the early summer, and, weed pollen, including ragweed (*Ambrosia* spp.) in the summer and fall. Pollen from the genus *Ambrosia* which includes *A. artemisiifolia* (short or common ragweed), *A. trifida* (giant ragweed), *A. psilostachya* (western ragweed), and *A. bidentata* (lanceleaf ragweed) has long been acknowledged to be a significant cause of allergic disease (2). An extensive skin test survey demonstrated that at least 10% of the US population is ragweed sensitive; the prevalence of ragweed sensitivity among atopic individuals was 27% in two large case series (3, 4). It has been reported that *Ambrosia* may cause more seasonal allergic rhinitis than all other plants combined (5).

Although there is unequivocal evidence that the prevalence of allergic disease has increased in the United States and elsewhere during the last 30 y (6), the reasons for this increase are uncertain. One possibility is an overall increase in exposure to significant aeroallergens such as ragweed pollen. An increase in ragweed pollen exposure, in turn, may be due to a number of factors including anthropogenic land use and climate change, although the connection between aeroallergens and climate change remains elusive.

There are several potential mechanisms by which climate change might affect allergic disease. First, longer pollen seasons may increase the duration of human exposure to aeroallergens and may thus increase allergic sensitization. Second, longer pollen seasons may increase the duration of allergy symptoms in individuals with allergic disease. Finally, higher atmospheric pollen counts may increase the severity of allergic symptoms (6).

To evaluate actual exposure to ragweed over time, a series of temporal measurements of ragweed pollen production is being determined by members of the National Allergy Bureau of the American Academy of Allergy, Asthma and Immunology. Although at present almost all US counting stations associated with this monitoring network (7) use Burkard Samplers, other volumetric devices (e.g., Rotorod Sampler) and gravimetric methods (e.g., Durham Sampler) have been used in recent decades. Unfortunately, quantitative comparisons between these various sampling methods are not possible (8). This confounds some analyses involving climate change, pollen counts, and allergy epidemiology.

Longer pollen seasons have been suggested (9) based on previous reconstructions of phenology networks and analysis of anthropogenic warming. However, other long-term temporal studies investigating possible anthropogenic changes in aeroallergen load or seasonality have been inconclusive, with several studies indicating no consistent change in duration of a pollen season for a given location (10–13).

Prior struggles relating aeroallergen season length to climatic warming may reflect geographical variation. The Intergovernmental Panel on Climate Change (IPCC) assessments have emphasized that the current and projected increases in global warming are not uniform, and enhanced land-surface temperatures (relative to the global average) are more probable with

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poleward and altitudinal increases (14, 15). If this is true, then longer aeroallergen seasons associated with anthropogenic warming could reflect elevational or latitudinal changes and may not be indicative of a given location per se.

Results

For this study, we apply this hypothesis regarding the differential rise in global surface temperatures to ragweed pollen data obtained by the National Allergy Bureau in the United States and Aerobiology Research Laboratories in Canada. By evaluating locations across central North America, a region of high spatial and altitudinal coherence, we could test the effects of latitude on season length of aeroallergen production for ragweed in response to climate warming as projected by the IPCC.

The National Allergy Bureau has eight locations with at least 15 y of ragweed data ranging from a latitude of 30.63°N (Austin, TX) to 46.88°N (Fargo, ND) (Table 1). A software program developed by Texas A&M University (16) was used to locate the nearest US weather station to obtain daily temperatures that corresponded to the pollen record. Ragweed data from two additional sites in Canada (Winnipeg, 50.1°N; Saskatoon, 52.1°N) were obtained from Aerobiology Research Laboratories. Corresponding weather data for these latter sites was obtained from Environment Canada, National Climate Data and Information Archive (17).

Pollen counting stations along this south–north latitudinal transect from east Texas to Saskatoon extended ~2,200 km (Table 1). Although the number of years of collection data varied, comparisons were made for a common temporal period (from 1995 through 2009) for each location. Simple regressions (± 95% confidence intervals) were used to determine changes in the start and end dates of the ragweed season over this period for each location. There was a highly significant correlation between latitude and increase in the length (days) of the ragweed pollen season over the period from 1995 to 2009 ($r^2 = 0.95$).

Seasonal changes in temperature, particularly the number of frost-free days and delays in the onset of the first fall frost were plotted for each location and compared with the duration of the ragweed pollen season for each location (Fig. 1). There was a clear increase in frost-free days and a temporal shift in the delay of fall frosts that were associated with an increase in the ragweed season length during the last two decades (Fig. 1). Other weather phenomena, most notably annual seasonal precipitation, did not change in any systematic fashion as a function of latitude, and no correlation was observed with pollen season length for this same time period (Fig S1).

For each pollen collection location, latitude was compared with both the number of frost-free days and changes in the length of the ragweed pollen season (Fig. 2). These data demonstrate a clear correlation between frost-free days and ragweed pollen season as a function of latitude. This finding is consistent with both IPCC projections regarding climate impacts (14), and with greater shifts in the plant hardiness zones for the upper midwestern United States (18).

Discussion

A number of studies have made compelling arguments that plant phenology is shifting in response to global environmental change (19). These shifts in timing of plant activity provide valuable confirmation that species as well as ecosystems are being affected by global change. However, a clear association between such shifts and aeroallergen exposure times has been unavailable.

Perhaps the most studied plant species in the context of earlier temperature shifts has been birch (*Betula* spp.), a known aeroallergen and cause of allergic disease in both North America and Europe. Emberlin (12, 20) observed earlier start dates for *Betula* by 6 d, but ranging up to 30 d. Yli-Panula et al. (21) demonstrated that warming temperatures contributed to early phenological development and greater pollen concentrations over a 31-y period for *Betula* in Turku, Finland, however no change in season length was reported. Research with *Betula* is complicated by differential responses among birch species to low winter temperatures (22), and often difficulties in distinguishing birch pollen from pollen of similar species (23). Although trees release aeroallergens during the spring, warmer winters may result in earlier flowering, or delays in flowering and floral numbers, depending on the tree species' specific need for vernalization.

Multiyear pollen season analysis has also been determined in a few cases for other known aeroallergen species (10, 24, 25). Over a 21-y period, an analysis of 11 different plant taxa demonstrated that 71% of the taxa flowered earlier each year (10); however, no pollen type demonstrated any increase in season length. A recent Italian study (26) did report increased seasonal floral durations and pollen counts for *Parietaria* (prob. *judaica*) as well as olive and cypress, but only for western Liguria (approximately) 47°N. It is unclear whether this increase is a result of greater relative impact of warming at this latitude or of urbanization per se (27).

PLANT BIOLOGY

Table 1. Change in length (day of year, days) of ragweed pollen season as a function of latitude for National Allergy Bureau and Aerobiology Research Laboratories sites along a south–north latitudinal gradient

Location	Latitude	Years of data	Start 1995	End 1995	Start 2009	End 2009	Change
Georgetown, TX	30.63°N	17	198 ± 7	320 ± 7	195 ± 7	313 ± 7	−4 d
Oklahoma City, OK	35.47°N	19	212 ± 7	300 ± 10	227 ± 9	316 ± 15	+1 d
Rogers, AR	36.33°N	15	231 ± 7	295 ± 8	227 ± 6	296 ± 8	−3 d
Papillion, NE	41.15°N	21	212 ± 3	281 ± 6	208 ± 4	288 ± 10	+11 d
Madison, WI	43.00°N	27	208 ± 2	272 ± 4	205 ± 3	281 ± 6	+12 d
LaCrosse, WI	43.80°N	22	213 ± 3	271 ± 3	205 ± 5	276 ± 5	+13 d*
Minneapolis, MN	45.00°N	19	208 ± 5	270 ± 6	206 ± 7	284 ± 7	+16 d*
Fargo, ND	46.88°N	15	216 ± 4	252 ± 8	217 ± 4	269 ± 8	+16 d*
Winnipeg, MB, Canada	50.07°N	16	207 ± 7	264 ± 6	197 ± 7	279 ± 7	+25 d*
Saskatoon, SK, Canada	52.07°N	16	206 ± 12	250 ± 6	197 ± 13	268 ± 7	+27 d*

Years represent the number of years for which pollen data were available. Regression analysis was used to determine the "best-fit" line for all years for a given location. This analysis was then used to determine the start and end day of each year (±95% confidence interval) for the duration of the ragweed pollen season in 1995 and again in 2009.

*Significant increase in the length (days) of the ragweed pollen season.

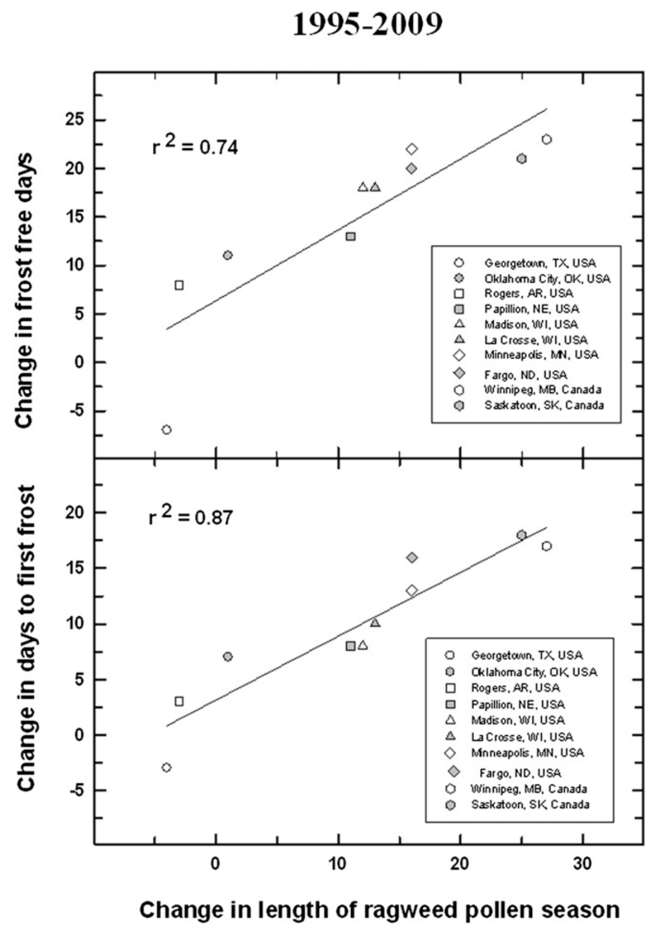

Fig. 1. Change in the length (days) of ragweed pollen season from 1995 to 2009 as a function of frost-free days, and delays in the time of first frost during the fall, for 10 central North American locations (eight in the United States and two in Canada) as a function of latitude. Data were determined as a function of simple regression for each location. Additional details are provided in text.

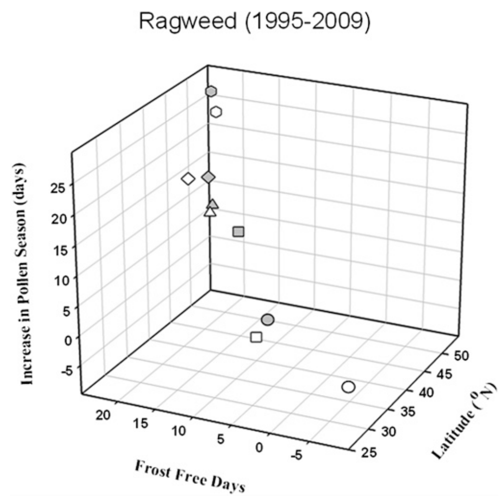

Fig. 2. Change in the length (days) of ragweed pollen season as a function of frost-free days with latitude for the period 1995–2009. Data were determined as a function of simple regression for each location. Additional details are provided in text. Legend is the same as in Fig. 1.

Outside of anthropogenic changes related to land use, for example, the importation or destruction of tree species due to changing architectural and landscape preferences (28), it has been thought that aeroallergen exposure times have remained consistent in relation to human activity (6). Because of its well-recognized association with allergic disease, a number of studies have demonstrated a probable role between climate change (i.e., rising CO_2 and temperature), phenology, and pollen production of common ragweed (29–31). However, these links were established at the laboratory level (30) and as a function of urbanization (27). The current study illustrates, on a continental scale, a clear association between recent warming, and an increase in the duration of ragweed pollen season, a major aeroallergen. Furthermore, this finding regarding surface temperatures and allergy season length is consistent with the IPCC projections of disproportionate warming at higher latitudes (14).

To more accurately assess the intensity and duration of the pollen season in response to anthropogenic warming, standardized local pollen collection should be expanded. Pollen data, relevant meteorological variables, carbon dioxide concentrations, and local land use variables as well as clinical data could address this need, particularly in regard to health-relevant outcomes (32, 33). In this way, it will be possible to better determine the contribution of climate change on aeroallergen concentrations in the United States and the resultant public health impacts, and to derive appropriate scientific and policy solutions.

Materials and Methods

The American Academy of Allergy, Asthma and Immunology (AAAAI) administers the National Allergy Bureau (NAB; http://www.aaaai.org/nab/index.cfm), a network for monitoring clinically relevant outdoor aeroallergens in the United States. Composed primarily of physician's offices, volunteer members meet various quality standards for pollen sampling and counting proficiency. For the Aerobiology Research Laboratory sites in Canada, postgraduates are trained in pollen and spore identification using optical microscopes and a standardized, computer-aided counting methodology (http://www.aerobiology.ca/company/profile.php). All data used to determine pollen season length for ragweed was obtained by certified pollen counters at the stations listed in this study.

Counting stations were selected based on two criteria: geographic position along a South-North transect, and at least 15 y of ragweed pollen data. A search of pollen records among the NAB collection sites in the central United States indicated eight locations with 15+ y of data collection on site. These data were obtained directly for the location, or if available, supplemented from the American Academy of Allergy and Immunology, Aeroallergen Monitoring Network Pollen and Spore Reports that were published from 1965 through 1993 by the AAAAI. With the exception of Minneapolis, care was chosen to consider counting stations that were not near major metropolitan (i.e., +500,000) centers. Collection data were met, in part, by combining previously published reports by the American Academy of Allergy and Immunology, Aeroallergen Monitoring Network for Ambrosia pollen start and end dates (if available) as well as post 1993 data obtained from the same counting locations.

Two additional criteria were applied to ragweed pollen records based on plant physiological parameters: First, ragweed is a short-day plant, meaning that it will not flower before June 21st; as such, if pollen was recorded on or before this date, it was not considered; Second, any pollen reported for ragweed after average daily minimum temperatures fell at or below 0 °C were not recorded. This is because ragweed is frost sensitive and does not survive below this temperature (34). Pollen counts outside this range generally did not occur over the time period examined. Within these parameters, start and end dates of the pollen season were defined as the days of year when 1% and 99% of the cumulative season ragweed pollen total were reached.

A stepwise regression program (Statview; SAS Institute) was used to determine the best-fit regression line for each location with respect to pollen season, year, frost-free days, and day of year for first fall frost. Regressions of frost-free days, pollen season, and latitude were significant using a 3D mesh curve with Sigmaplot (version 10.0; SAS Institute). In this analysis predictive intervals were used to determine a 95% confidence limit for the start and end of ragweed pollen season for each location for a 15-y period from 1995 through 2009.

Weather data, including precipitation, was downloaded from the nearest available station that matched all years of pollen data collection as described here. Data were then examined to determine first and last days of the year when average daily minimum temperatures fell to 0 °C or below, and this interval was recorded as frost-free days. In addition, the day of year for the initial fall frost was documented. Precipitation indicated no consistent effect on pollen season with latitude (Fig. S1 and Dataset S1).

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