PLOS ONE

RESEARCH ARTICLE

Assessing the Impact of Air Pollution on Grain Yield of Winter Wheat - A Case Study in the North China Plain

Xiuwei Liu[1,2☯], Hongyong Sun[1☯], Til Feike[3☯], Xiying Zhang[1]*, Liwei Shao[1], Suying Chen[1]

1 Key Laboratory of Agricultural Water Resources, The Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology, The Chinese Academy of Sciences, Shijiazhuang, China, **2** Texas A&M AgriLife Research and Extension Center, Uvalde, Texas, United States of America, **3** Julius Kühn-Institut (JKI) | Federal Research Centre for Cultivated Plants, Institute for Strategies and Technology Assessment, Kleinmachnow, Germany

☯ These authors contributed equally to this work.
* xyzhang@sjziam.ac.cn

Citation: Liu X, Sun H, Feike T, Zhang X, Shao L, Chen S (2016) Assessing the Impact of Air Pollution on Grain Yield of Winter Wheat - A Case Study in the North China Plain. PLoS ONE 11(9): e0162655. doi:10.1371/journal.pone.0162655

Editor: Dafeng Hui, Tennessee State University, UNITED STATES

Received: January 30, 2016

Accepted: August 28, 2016

Published: September 9, 2016

Data Availability Statement: Air pollution data are available at http://datacenter.mep.gov.cn. Daily data on top-of-atmosphere insulation at the research site extracted from the NASA POWER Agroclimatology webpage (http://power.larc.nasa.gov/cgi-bin/cgiwrap/solar/agro.cgi). Other relevant data are within the paper.

Funding: This study was supported by the Special Fund for Agro-scientific Research in China (201203077 and 201303133) and Hebei S&T Project (14227007D).

Abstract

The major wheat production region of China the North China Plain (NCP) is seriously affected by air pollution. In this study, yield of winter wheat (*Triticum aestivum* L.) was analyzed with respect to the potential impact of air pollution index under conditions of optimal crop management in the NCP from 2001 to 2012. Results showed that air pollution was especially serious at the early phase of winter wheat growth significantly influencing various weather factors. However, no significant correlations were found between final grain yield and the weather factors during the early growth phase. In contrast, significant correlations were found between grain yield and total solar radiation gap, sunshine hour gap, diurnal temperature range and relative humidity during the late growing phase. To disentangle the confounding effects of various weather factors, and test the isolated effect of air pollution induced changes in incoming global solar radiation on yield under ceteris paribus conditions, crop model based scenario-analysis was conducted. The simulation results of the calibrated Agricultural Production Systems Simulator (APSIM) model indicated that a reduction in radiation by 10% might cause a yield reduction by more than 10%. Increasing incident radiation by 10% would lead to yield increases of (only) 7%, with the effects being much stronger during the late growing phase compared to the early growing phase. However, there is evidence that APSIM overestimates the effect of air pollution induced changes on radiation, as it does not consider the changes in radiative properties of solar insulation, i.e. the relative increase of diffuse over direct radiation, which may partly alleviate the negative effects of reduced total radiation by air pollution. Concluding, the present study could not detect a significantly negative effect of air pollution on wheat yields in the NCP.

Competing Interests: The authors have declared that no competing interests exist.

Introduction

Incoming solar radiation, the driver of plant photosynthesis, has continuously declined on the world's land surface over the last decades [1]. This phenomenon is known as total dimming and is driven mainly by changes in cloud cover and aerosols [2, 3]. Aerosols as the most common form of air pollution reflect, absorb, and scatter solar radiation [4], causing a decrease in direct radiation and an increase in diffuse radiation, generally resulting in a reduction of total solar radiation. With the rapid economic development and expansion of industrial activities in many parts of the world, a strong increase in the concentration of anthropogenic particles in the lower atmosphere needs to be recognized [5, 6].

A global hotspot of air pollution are the densely populated coastal regions of China, which experience high levels of air pollution resulting from gas or dust emissions from transport, fossil-fuel power generation and construction activities [7, 8]. These densely populated regions are at the same time the major crop production regions of China. As such, our study region the North China Plain (NCP) produces the majority of Chinese wheat (*Triticum aestivum* L.), which is mainly cultivated as winter wheat [9]. Wheat is globally the third largest crop and an essential contributor to food security in China and the world [10].

Previous studies indicate that climate trends negatively influence wheat yields in the NCP [9, 11]. A significant increase in average temperature (primarily daily minimum temperature), a decrease in the number of sunshine hours and radiation, and a consecutive reduction in the length of the growing season are considered the respective major causative factors acting negatively on wheat yields [12, 13]. These climate trends tend to reduce the length of the growing season for winter wheat [13]. A previous study identified a reduction in incoming solar radiation of up to 5–30% in some of China's most productive agricultural regions under hazy conditions and high aerosol concentrations [14]. For maintaining high levels of wheat productivity and its resource efficient production, it is crucial to examine how high levels of air pollution and consecutive reduction in incoming solar radiation affect winter wheat, which is cultivated during the most polluted period of the year in the NCP.

For describing air pollution the air pollution index (API) was introduced as a generalized measure, which is capable of identifying those variables that significantly affect air pollution [15]. In China, data on API is collected by the Ministry of Environmental Protection of the People's Republic of China. In several previous studies Chinese API data was implemented to analyze the effects of air pollution on different meteorological variables such as radiation or sunshine hours [16–18]. Thus, the officially released API data from the government was used in the present study to describe the daily air pollution situation in the study region.

To the best of our knowledge, there is still no report on the interrelations of air pollution and wheat production in the NCP. Therefore, the objectives of this study are to (1) analyze the effects of API on incoming solar radiation as well as other weather factors during the growing season of winter wheat at our study site in the NCP, (2) assess the effect of potential changes in total solar radiation on wheat yields using crop model based scenario-analysis.

Materials and Methods

A field study was conducted over 12 growing seasons at the Luancheng Experimental Station (37°53' N and 114°41'E; elevation of 50-m) in the NCP from 2001 to 2012. The experiment field is authorized by the Chinese Academy of Sciences. Winter wheat is planted in early October and harvested in early June generally followed by the cultivation of summer maize, which forms the dominant wheat-maize double cropping system of the region. The experimental station is located in a summer monsoon climatic zone, where only about 30% of annual precipitation occurs during winter wheat growing season [19].

Crop growth data collection

The field experiment data stems from an on-going long-term irrigation field experiment involving six irrigation treatments with four replicates. For the present study, the crop data were obtained from the 100% irrigation treatment, where plants were grown under non-limiting water conditions. Winter wheat cultivar "Shixin 733" (from 2001 to 2005) and "Kenong199" (from 2005 to 2012) were used for the 12 seasons. The two cultivars have similar yield and agronomic characteristics. Row spacing was 15-cm, and seeding rate was 300 viable seeds m^{-2}. Before planting, diammonium phosphate (DAP) at 450-kg ha^{-1}, urea at 150-kg ha^{-1} and potassium chloride at 150-kg ha^{-1} were broadcast and incorporated into the soil. An additional 225-kg ha^{-1} of urea was top-dressed at jointing stage in early April of each year.

Air pollution and weather factors

Daily air pollution data were available for Shijiazhuang, which is located approximately 25 km away from the experimental site, for 2001–2012 from the Ministry of Environmental Protection of the People's Republic of China (http://datacenter.mep.gov.cn/). Air pollution is expressed by the Air Pollution Index (API). It is calculated from the average concentrations of the principal pollutants (i.e., SO_2, NO_2) and inhalable particulates (PM_{10}) over a 24-hour period [17]. The maximum values of IPM_{10}, ISO_2, and INO_2 form the upper limit of the API. The factor "I" represents the 24-hr API score for the pollutant species of PM_{10}, SO_2, and NO_2. Generally, the inhalable particulates are the dominant air pollutants in China [16, 17].

Data on daily global solar radiation (GSR), photosynthetic active radiation (PAR), ultraviolet radiation (UVR), sunshine hours (SH), minimum temperature (TMIN) and maximum temperature (TMAX), diurnal temperature range (difference between daily minimum and maximum temperature; DTR), cloud cover (CC) and relative humidity (RH) were recorded at the experimental site. Daily data on top-of-atmosphere insulation at the research site extracted from the NASA POWER Agroclimatology webpage (http://power.larc.nasa.gov/cgi-bin/cgiwrap/solar/agro.cgi) was used as proxy for potential incoming radiation.

Simulation of winter wheat yield under different scenarios

The impact of air pollution on wheat growth and yield may be covered by the effect of inter-annual changes of more influential factors [11], therefore applying regression analysis to the twelve years' data was not able to detect the sole effect of changes in air pollution and consequential changes in incoming GSR on grain yield. To be able to separate the confounding effects of air pollution and various weather variables, the application of crop models to simulate single factor scenarios is a viable means [10]. Hence, to assess whether air pollution induced changes of incident global solar radiation are effective on grain yield under ceteris paribus conditions, scenario-analysis was conducted using the Agricultural Production Systems Simulator (APSIM) model. The APSIM model is a cropping systems simulation model developed by the agricultural production systems research unit of Australia. APSIM has been widely tested and used in Australia, the United States, Netherlands, North Africa, and China [20]. For China, validation results of the APSIM-Wheat module were summarized in [21]. APSIM was satisfactory in simulating crop growth, yield, and water use, and could explain over 80% of the variations in crop biomass and yield in the NCP [22]. In another study conducted in the NCP showed that the simulated results explained 85% of the variations in crop yield [23]. Therefore APSIM--Wheat is considered a suitable model to simulate wheat growth and development under the climatic and soil conditions of the NCP.

Hence, in the first step APSIM-Wheat was calibrated for the local field conditions and cultivars based on the available experimental data from 2001–2012. The detailed calibration

Table 1. The genetic parameters used in APSIM model for the winter wheat during the 2001–2012 seasons.

Parameters	Values
Emerg.to.endjuv (thermal time from emergence to end juvenile stage(°d)	620
Startgf.to.mat (thermal time from beginning of grain-filling to maturity(°d)	620
Potential grain filling rate (potential grain-filling rate (g per kernel per day))	0.0025
Grains per gram stem (coefficient of kernel number per stem weight at the beginning of grain-filling (g per stem))	26.5
Max grain size (potential maximum grain size (g per kernel))	0.0045
Phyllochron (phellochroninterval (°C d/leaf appearance))	85
Vern sens (sensitivity to vernalization)	1.6
Photop sens (sensitivity to photoperiod)	2.0

doi:10.1371/journal.pone.0162655.t001

procedure followed the steps in [24]. Soil physical parameters such as soil bulk density and soil texture were kept constant over all years and simulated scenarios. Irrigation was always set as full water supply. The cultivar specific calibration of APSIM-Wheat was conducted based on the field experimental results covering the parameters listed in Table 1. Due to the high similarity of the two cultivars grown over the 12 seasons, no differentiation was implemented in the model between the two.

In the next step, the calibrated model was available to assess the effect of potential changes in radiation on crop growth. Crop simulation models including APSIM are often used to simulate crop growth and development under altered conditions of incident solar radiation, which the analysis identified as the factor strongest influenced by air pollution [25–27]. However, APSIM as well as most other common crop simulation models do not distinguish between direct radiation, diffuse radiation and UVR, but just consider the total incoming global solar radiation (GSR) as driver of photosynthesis [27]. Therefore, any potential changes in the ratio of direct and diffuse radiation and in UVR under changing air pollution could not be considered in the present analysis.

To test the effect of potential changes in air pollution and related weather factors scenario-analysis was applied. The percentage reduction in radiation set up in the scenarios followed the possible effects of air pollution on total radiation. According to [16] total radiation is decreased by 8% at API-values between 100 and 200 compared to the radiation at API-values below 100. Based on the pre-analysis of API data (Fig 1), the growing period of winter wheat was separated into two growing phases: the early growing phase (from sowing to recovery after winter dormancy) and the late growing phase (from recovery to maturity). Thus, to assess the potential effects of changes in radiation on wheat yields, radiation changes were set at +/− 5% and +/− 10% for each growing phase in the scenario-analysis, which was run during 2001–2012 seasons (Table 2).

Statistical analysis

Due to the seasonal course of the sun and its consequential effect on the daily amount of potentially incoming radiation, the daily API data could not directly be related to the ground measured incident radiation data. Hence, to assess the effect of air pollution on plant available irradiance we first calculated the daily "relative radiation gaps" for the different types of radiation as follows.

$$GSR_{gap} = (GSR_p - GSR_i)/GSR_p \tag{1}$$

where GSR_{gap} is the global solar radiation gap, GSR_p is the potential global solar radiation

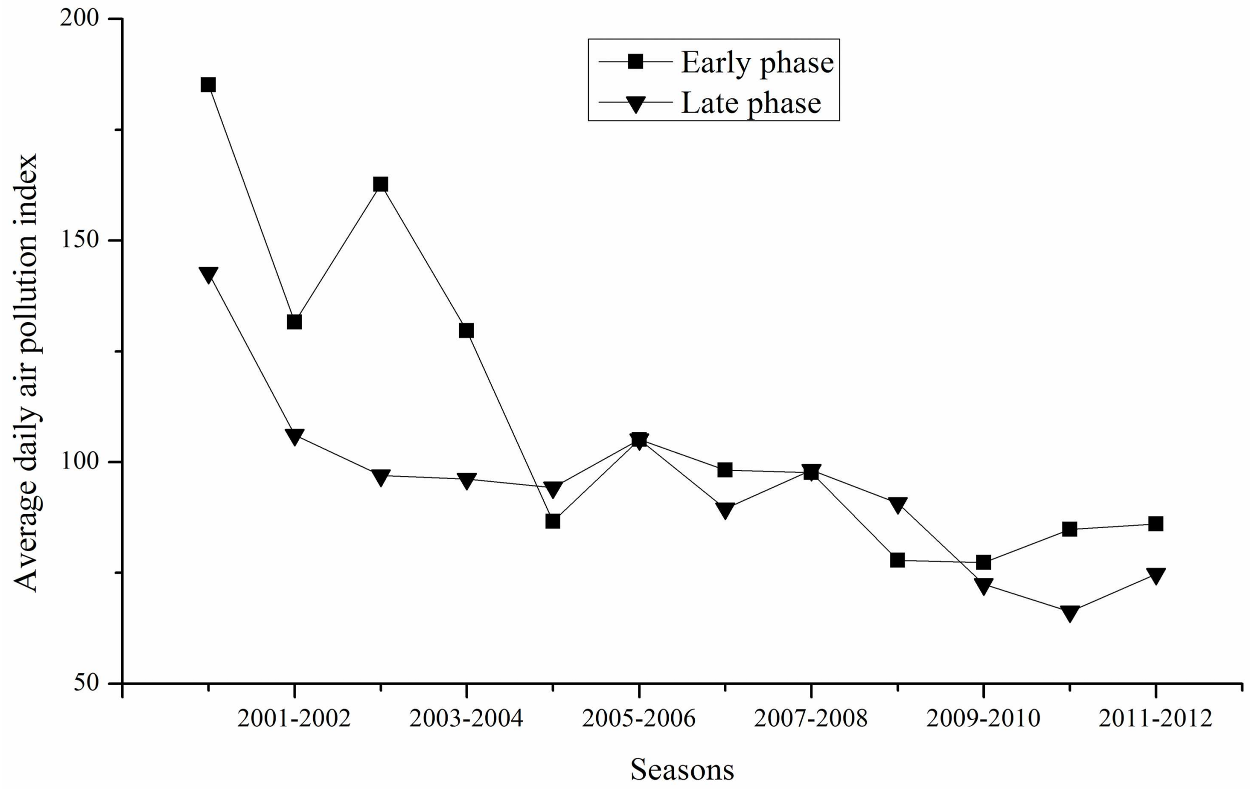

Fig 1. Development of average daily air pollution index during the early and late growing phases of winter wheat during 2001–2012.

doi:10.1371/journal.pone.0162655.g001

outside the atmosphere (MJ m^{-2} d^{-1}) and GSR_i is the incident global solar radiation measured on the ground (MJ m^{-2} d^{-1}).

The photosynthetic active radiation gap (PAR_{gap}) was calculated as follows,

$$PAR_{gap} = (PAR_p - PAR_i)/PAR_p \tag{2}$$

where PAR_p is the potential photosynthetic active radiation (mol m^{-2} d^{-1}) and PAR_i is the incident photosynthetic active radiation measured on the ground (mol m^{-2} d^{-1}), with PAR_p derived from GSR_p-data following the conversion recommended by [28] and recently proved viable for the region's latitude by [29],

$$PAR_p = GSR_p * 4.57/3.6 \tag{3}$$

Accordingly, the ultra-violet radiation gap (UVR_{gap}) was calculated as follows,

$$UVR_{gap} = (UVR_p - UVR_i)/UVR_p \tag{4}$$

Table 2. Overview of the combinations of changes in daily global solar radiation (GSR) applied in the APSIM based scenario analysis.

	Change in global solar radiation [%]				
Phases	**–10**	**–5**	**0**	**+5**	**+10**
Early phase only	Scenario $E_{-10\%}$	Scenario$E_{-5\%}$	CK	Scenario $E_{+5\%}$	Scenario$E_{+10\%}$
Late phase only	Scenario $L_{-10\%}$	Scenario$L_{-5\%}$	CK	Scenario $L_{+5\%}$	Scenario$L_{+10\%}$
Early and late phase	Scenario $EL_{-10\%}$	Scenario$EL_{-5\%}$	CK	Scenario $EL_{+5\%}$	Scenario$EL_{+10\%}$

doi:10.1371/journal.pone.0162655.t002

where UVR_p is the potential ultra-violet radiation (MJ m^{-2} d^{-1}) and UVR_i is the incident ultra-violet radiation measured on the ground (MJ m^{-2} d^{-1}), with UVR_p derived from GSR_o-data following the conversion recommended by [30],

$$UVR_p = UVR_p * 0.08 \tag{5}$$

Finally the daily sunshine hour gap (SH_{gap}) was calculated as follows,

$$SH_{gap} = (SH_p - SH_i)/SH_p \tag{6}$$

where SH_p is the potential sunshine hours (h) and SH_i is the incident sunshine hours measured on the ground (h), with SH_p derived as follows,

$$SH_p = SS - SR \tag{7}$$

where SS is time of sunset and SR is time of sunrise.

Apart from air pollution also cloud cover (CC) reduces atmospheric transmittance. Therefore, to account for the potential effect of CC on the different radiation gaps, partial correlation was applied using daily data over the 12 investigated winter wheat seasons with the different radiation gaps, i.e., GSR_{gap}, PAR_{gap}, UVR_{gap}, and SH_{gap} as dependent variable, API as independent variable and CC as controlling variable.

Seasonal changes and cloud cover may also affect the relation between API and other weather factors. Therefore, partial correlation analysis was applied accordingly to assess the relation of air pollution and other weather factors such as temperature and relative humidity including cloud cover and number of days after sowing as controlling variables. Finally, linear regression and correlation analyses were used to determine whether the relationships between the relative radiation gap as well as other weather variables with crop yield obtained from the field study were significant at the 95% confidence level using SPSS statistical analysis software (version 16.0).

Results

Effect of API on weather factors

For both growing phases the average daily API-values decreased strongly from 2001 to 2005. From 2005 onwards a continuous though only very slight decrease occurred (Fig 1). While in the first four winter wheat seasons significantly higher air pollution can be recognized during the early compared to the late growing phase, no significant differences can be recognized between the two growing phases from then onwards. Averaged over the 12 seasons the API-values for the early and the late growing phases were 110.5 and 85.6, respectively. Similarly [16] reported higher levels of air pollution in the region during winter and spring, which corresponds to the early growing phase of winter wheat.

The results of the partial correlation analysis presented in Table 3 show that during the early growing phase, all weather factors were significantly correlated with API. In contrast, no significant correlations were identified between the weather factors and API during late growing phase except for daily TMIN. Obviously air pollution significantly reduced radiation, i.e. increased the radiation gap, at early phase represented by all four radiation related variables (GSR, PAR, UVR, SH). During late growing phase no significant correlation was found between API and the radiation gaps. The difference in the effectiveness of API on weather variables during the two growing phases can largely be explained by the lower API-values during late growing phase compared to early growing phase. Additionally the contrary observations for early and late phase are a result of the difference in the angle of the sun during the two

Table 3. Partial correlation of air pollution index with weather factors controlled for cloud cover at different growing phases of winter wheat based on daily data of 12 winter wheat seasons.

Weather factors	Early growing phase	Late growing phase
GSR_{gap}	0.34**	0.14
PAR_{gap}	0.26**	0.13
UVR_{gap}	0.26**	0.03
SH_{gap}	0.28**	0.05
TMAX	−0.52**	0.17
TMIN	−0.50**	0.24*
DTR	−0.30**	−0.08
RH	0.21*	0.11

* indicates significance at P = 0.05;

** indicates significance at P = 0.01;

GSR_{gap}: relative radiation gap for global solar radiation; PAR_{gap}: relative radiation gap for photosynthetic active radiation; UVR_{gap}: relative radiation gap for ultraviolet radiation; SH_{gap}: relative gap for sunshine hours; TMAX: maximum air temperature, TMIN: minimum air temperature, DTR: diurnal temperature range, RH: relative humidity.

doi:10.1371/journal.pone.0162655.t003

phases. At our study region (in the northern hemisphere) the angle of the sun is highest at June 21 and lowest at December 21. During early season the sun beam passes the atmosphere in a lower angle, and thus needs to pass a longer distance through the atmosphere. This results in a higher dissipation of light, and thus a higher radiation reduction by the atmosphere compared to the late season, where the angle of the sun is higher and the sun beam passes the atmosphere on a shorter distance. The significantly reduced TMIN and TMAX values due to air pollution during early phase (but not during late phase) are likely a secondary effect of reduced radiation, which leads to less solar energy (heat) reach the earth's surface. It furthermore can be seen, that even though air pollution did not significantly affect radiation during late phase, air pollution significantly increased TMIN. This is likely a result of air pollution, which hinders the loss of reflected radiation from ground to the atmosphere leading to increased temperature, especially TMIN.

During early growing phase DTR was negatively correlated to API, which is most likely a result of reduced radiation and hence reduced incoming heat energy due to air pollution during daytime. During late growing phase API has no significant negative effect on radiation and thus also no significant negative effect on DTR. Furthermore, [11] and [31] reported that DTR is additionally affected by RH and daytime temperature, which were both not affected by API in the late growing phase. While RH was significantly positively related to API during the early phase, no significant correlation occurred during late phase. There is strong evidence, that during late phase, which coincides with the beginning of rainy season, RH is mainly driven by precipitation, compared to early phase, where rainfall and evapotranspiration are much lower.

Effect of weather changes on grain yield

In the next step we assessed whether the API induced changes in weather variables are effective on grain yield. The development of winter wheat yields under well managed non-water-limited conditions during 2001 to 2012 is presented in Fig 2. During the 12 seasons large deviations from mean yield occurred ranging from −24% to +18%. As similar cultivars and identical field management practices were applied, the differences in yield level provide a good possibility to analyze the effects of different weather factors on crop production.

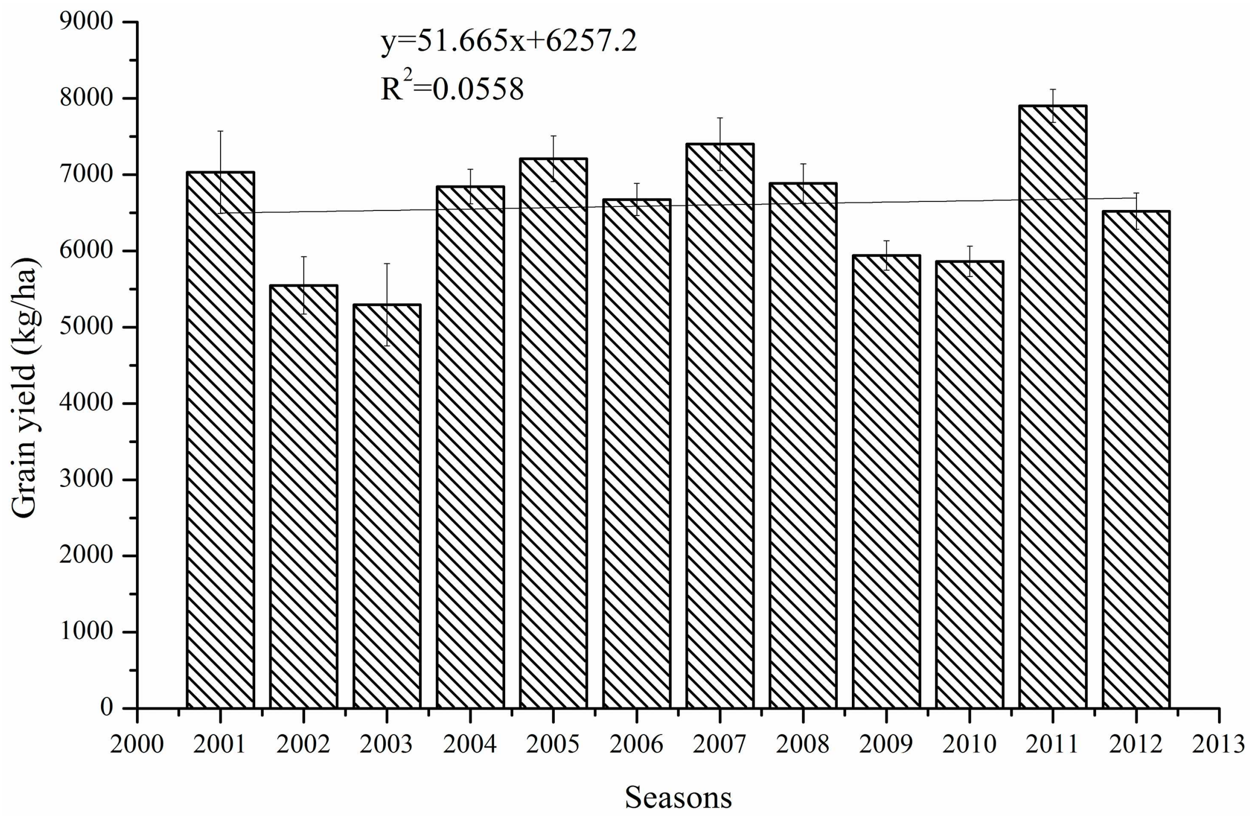

Fig 2. The seasonal yield variation of winter wheat from 2001 to 2012 under optimal management practices.

doi:10.1371/journal.pone.0162655.g002

Correlation analyses indicated that none the weather factors, which were significantly affected by air pollution in either of the two growing phases (Table 3) showed a significant correlation with final grain yield (Table 4). On the contrary, several weather variables, which were not significantly influenced by air pollution, were significantly correlated with yield at the late growing phase, namely GSR_{gap}, SH_{gap}, DTR and RH. Obviously, the inter-annual differences in weather factors during the late growing phase played a more important role in the yield formation process of wheat compared to the weather conditions during early growing phase. The API measured during the late growing phase was generally lower than the values in the early growing phases and hence did not affect yield related weather factors.

Table 4. Relationships of relative radiation gap with the final grain yield of winter wheat during the early and late growing phases during 2001–2012.

Phases	GSR_{gap}	PAR_{gap}	UVR_{gap}	SH_{gap}	TMAX	TMIN	DTR	RH
Early phase	−0.27	−0.42	0.49	−0.28	0.04	0.06	0.02	−0.45
Late phase	−0.60*	−0.48	0.22	−0.61*	0.45	0.21	0.54*	−0.66*

* indicates significance at P = 0.05;

GSR_{gap}: relative radiation gap for global solar radiation, PAR_{gap}: relative radiation gap for photosynthetic active radiation, UVR_{gap}: relative radiation gap for ultraviolet radiation, SH_{gap}: relative gap for sunshine hours, TMAX: maximum air temperature, TMIN: minimum air temperature, DTR: diurnal temperature range, RH: relative humidity.

doi:10.1371/journal.pone.0162655.t004

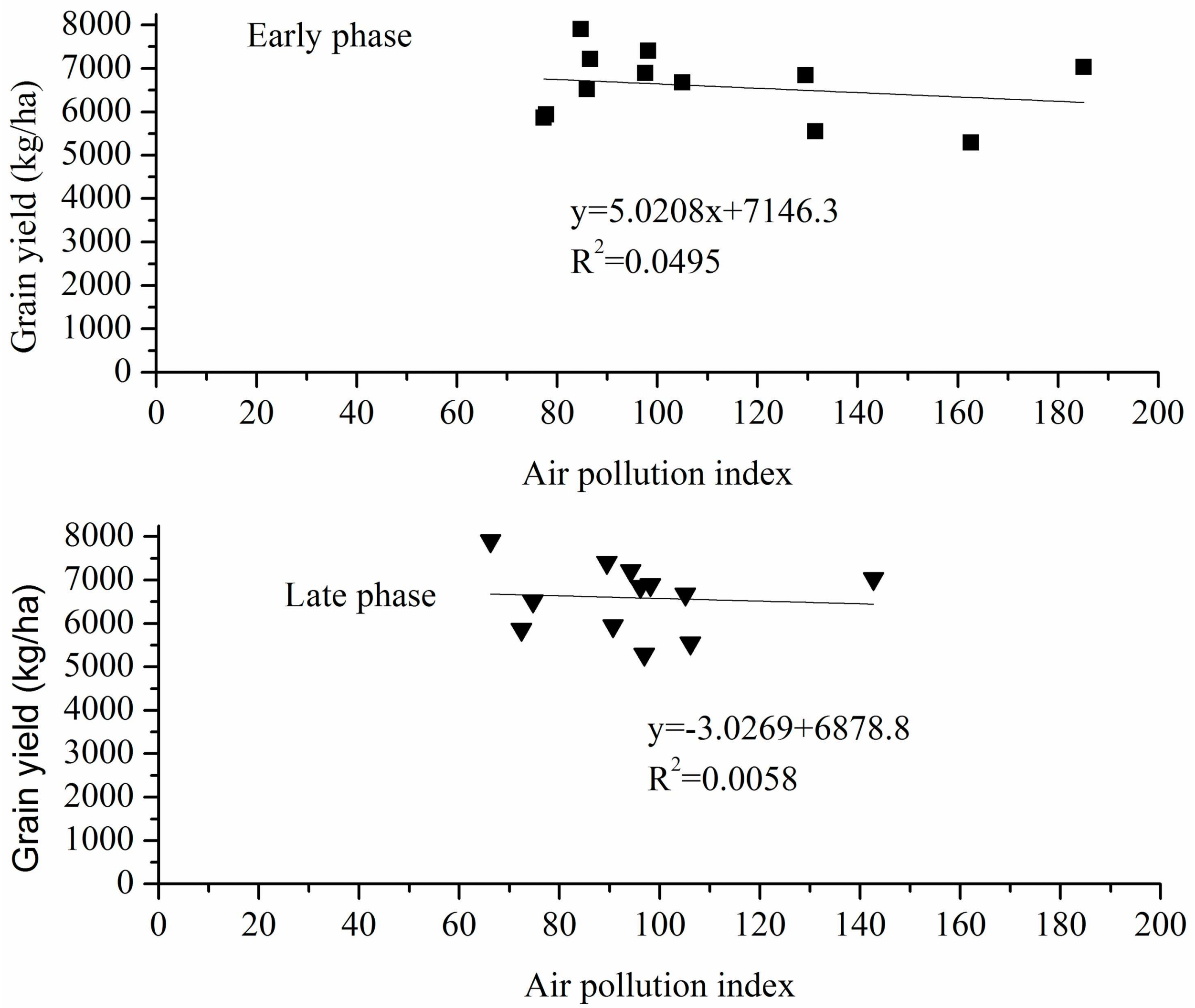

Fig 3. The relationships between air pollution index at different growing phases with grain yield of winter wheat.

doi:10.1371/journal.pone.0162655.g003

Consequently, an impact of air pollution induced weather factors changes on winter wheat yield could not be detected.

Accordingly, also no significant correlation could be detected, when correlating the average API-values for the early and late growing phase with final wheat yield data from 2000–2012 (Fig 3). However, as mentioned above, the effect of air pollution on wheat growth and yield may just be covered by the effect of inter-annual changes of more influential factors [11, 32, 33], i.e. those weather variables showing a significant correlation with wheat yield (GSP_{gap}, SH_{gap}, DTR and RH during late phase).

Hence, crop modeling was used to assess whether air pollution induced changes of incident global solar radiation are effective on grain yield under ceteris paribus conditions. The APSIM-Wheat model was calibrated satisfactorily (Fig 4) and could be used to simulate the isolated effect of changes in GSR on grain yield. Table 5 shows the simulated grain yield under the different GSR change scenarios. Compared to the control (CK), which was simulated under the actually observed GSR-conditions, the average crop yields increased under increased GSR. Accordingly, when GSR was reduced, simulated crop yields were also reduced. For both, the

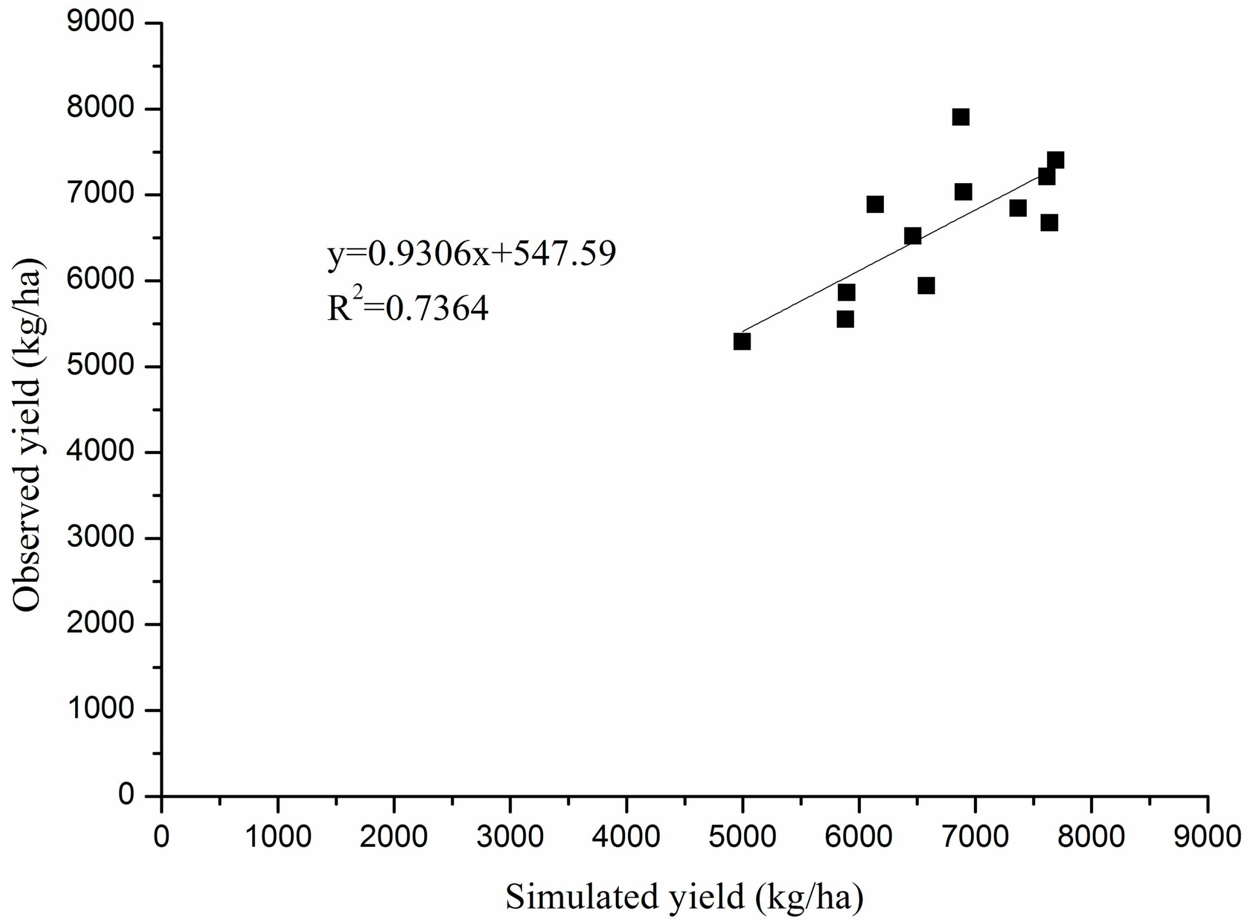

Fig 4. Validation plots of the APSIM-Wheat model simulation with field-observed crop yield.

doi:10.1371/journal.pone.0162655.g004

GSR increase and the GSR decrease scenarios, GSR changes during early phase were less yield effective compared to GSR changes during late growing phase. This corresponds to the regression results (Table 4), where no significant yield effect of GSR_{gap} during early phase, but a significant effect during late phase was detected.

For all tested phases (early only, late only, early and late), the radiation reductions affected yield levels more strongly (negatively), compared to the radiation increases (positively). As such, during early phase a GSR reduction by 5% and 10% caused yield reductions of 3.16% and 5.20%, respectively, while a GSR increase by 5% and 10% caused yield increase by only 0.55% and 2.06%, respectively. Similarly, GSR reductions by 10% during the late phase and during both phases reduced grain yields by 9.57% and 10.40%, respectively, while GSR increases by 10% during the late phase and during both phases increased grain yields by only 5.29% and 7.41%, respectively. This provides evidence that the incident GSR conditions in the study region during the 2000–2012 period were already situated at the lower end of wheat radiation requirements. In accordance [11] and [23] report that GSR has been decreasing in the region over the past 30 years, which excerpts a negative effect on crop yield potential [14]. Hence, a further increase in air pollution and the consequential reduction in incident GSR may have a strong detrimental effect on wheat yields, while a reduction in air pollution and the consequential increase in incident GSR would act positive on wheat yields, however at a lower increment.

Table 5. Average values and standard deviations (kg/ha) of simulated wheat yields over the 12 growing seasons for different scenario combinations of increasing and decreasing radiation during early and late growing phases during 2001–2012; percentage changes compared to the observed yields under actual radiation conditions during 2001–2012 are given in brackets.

Phases	Change in global solar radiation [%]				
	–10	–5	0	+5	+10
Early phase only	6234±929	6368±952	6576±1024	6612±1005	6712±1020
	(–5.20%)	(–3.16%)	(0%)	(+0.55%)	(+2.06%)
Late phase only	5964±1013	6208±974	6576±1024	6735±990	6924±1020
	(–9.57%)	(–5.60%)	(0%)	(+2.42%)	(+5.29%)
Early and late phase	5892±934	6080±957	6576±1024	6828±1016	7064±1034
	(–10.40%)	(–7.54%)	(0%)	(+3.84%)	(+7.41%)

doi:10.1371/journal.pone.0162655.t005

Discussion and Conclusions

Previous research has shown that air pollution and consecutive reduction in PAR negatively affect plant growth [34, 35]. However, so far no study aimed at investigating the effect of air pollution on winter wheat yields in the air pollution hotspot North China Plain. Our analysis showed that over the 12 growing seasons air pollution was generally higher in the early growing phase compared to the late growing phase. Accordingly, air pollution (expressed by API) showed significant correlations with various weather factors including radiation, temperature and humidity, during the early but not the late growing phase. Only TMIN was positively correlated with API in the late phase. However, we could neither detect a direct correlation between API and grain yield, nor could we identify that the air pollution induced changes in weather variables exerted a significant impact on grain yield.

However, grain yield was highly associated with several weather variables at the late growing phase, which were not affected by air pollution. These factors comprise DTR and RH as well as the radiation related GSR_{gap} and SH_{gap}. While higher DTR acted positively on yield, reduced radiation and increased RH were negatively related. This confirms the findings of a recent study for the same experimental site [11], which indicated that grain yield of winter wheat was positively related to DTR and SH, while it was negatively related to RH. Regarding the effect of DTR on grain yield contrasting results are obtained in previous studies. While under non-irrigated conditions increasing DTR is often negatively associated with wheat yield [36, 37], a positive correlation was identified for irrigated wheat in our study region [38]. Furthermore, [11] showed that DTR itself was affected by a combination of RH, sunshine hours, and daytime temperature, with the number of sunshine hours and the daytime maximum temperature acting positive and RH acting negative on DTR [31]. Hence, there is evidence that clear days with high TMAX and dry air lead to a high DTR, which under sufficient water supply (as investigated in our study), acts positive on yield.

There is evidence that the negative relationship between RH and grain yield may be related to stomatal conductance (SC). In an environment with high humidity, the potential evaporation is generally lower and the consequential reduction in SC may result in a decreased photosynthetic rate [39, 40]. Furthermore, higher RH generally leads to higher risk of infection by fungal diseases [41, 42], which may additionally excerpt negative effects on wheat yields.

The observed challenge of identifying the impact of a single factor on crop yields due to confounding effects is confirmed by several previous studies [36, 43]. To overcome this challenge we employed crop model based scenario-analysis, which allowed us to separate the confounding effects and assess the isolated effect of changing a single weather factor, as also recommended by [10]. Incident GSR, as the factor most strongly influenced by API, was selected for the analysis. For both growing phases increasing GSR led to increasing yield and decreasing

GSR led to decreasing yield, with the effects being stronger for the late compared to the early growing phase. It is likely that changes in radiation are more effective during the late phase, as the greater part of biomass growth and photosynthetic activity occurs after winter recovery [44]. The results furthermore showed that for all growth phases the negative yield effects of reduced radiation were stronger, than the positive yield effects of increased radiation. With the incident GSR continuously decreasing in China over the last decades [12], it is very likely that wheat production in the NCP is already situated at the lower end of required radiation. Any further increase of air pollution and consequential reduction in incident GSR may act strongly negative on wheat yields. Accordingly, [26] and [27] identified decreasing wheat yields in consequence of reduced radiation.

However, it also needs to be considered, that APSIM-Wheat does so far not account for changes in the ratio of direct and diffuse radiation, but just runs with total GSR as radiation input [27, 45]. This may lead to certain overestimations of the negative effects of air pollution induced radiation reductions on crop yields. The reason is that increasing air pollution leads to an increasing fraction of diffuse radiation in total radiation [35, 46, 47, 48], which significantly increases the light availability and hence photosynthesis in the shaded (and normally light deficient) part of the crop canopy [49]. This positive effect generally overcompensates for the negative photosynthetic effect in the sunlit (and normally light saturated) part of the canopy, which is caused by air pollution induced reduction in direct radiation [50]. In China, where optically-scattering aerosols, such as sulfate, organic carbon, nitrate, ammonium and mineral aerosols are dominant [51], high air pollution conditions are reported to increase the share of diffuse radiation to more than 60% of total radiation [47].

With regard to changed solar radiation composition, reduced UVR in consequence of high air pollution may also be beneficial for early growth of winter wheat. Air pollution is often associated with ozone depletion [52], with negative consequences for plants, since biologically active short-wavelength ultraviolet-B radiation increases under reduced ozone concentrations [53]. Accordingly, our regression analysis revealed a positive, though insignificant, relationship of reduced UVR and wheat yield.

The above described potential benefits of air pollution induced changes in the radiative properties of solar insolation on crop growth, which may partly compensate for some of the negative effects of reduction in total GSR, can so far not be simulated with APSIM-Wheat. Hence to better capture effects of air pollution on wheat growth and yield future improvements of APSIM should include the consideration of radiation properties beyond sole GSR. As measured data on the shares of diffuse and direct radiation are generally rare, a module should be integrated in APSIM that estimates the shares of both radiation components based on measured total radiation, latitude and day of year, e.g., following [54, 55]. Then the effects of changes in the shares of direct and diffuse radiation on canopy assimilation need to be simulated following, e.g., [50, 56].

Acknowledgments

This study was supported by the Special Fund for Agro-scientific Research in China (201203077 and 201303133) and Hebei S&T Project (14227007D). Special appreciation is extended to Dr. Xuejun Dong for his help in improving the English writing of this paper.

Author Contributions

Conceptualization: XYZ XWL.

Data curation: XWL HYS TF XYZ.

Formal analysis: XWL HYS TF XYZ.

Funding acquisition: XYZ.

Investigation: XWL HYS XYZ LWS SYC.

Methodology: XWL HYS TF.

Project administration: XYZ.

Resources: XWL HYS XYZ LWS SYC.

Supervision: XYZ.

Validation: XWL HYS XYZ SYC.

Visualization: XWL.

Writing – original draft: XWL XYZ.

Writing – review & editing: XWL TF XYZ.

References

1. Wild M, Gilgen H, Roesch A, Ohmura A, Long CN, Dutton EG, et al. From dimming to brightening: Decadal changes in solar radiation at Earth's surface. Science. 2005; 308(5723):847–850. doi: 10.1126/science.1103215 PMID: 15879214
2. Norris JR, Wild M. Trends in aerosol radiative effects over China and Japan inferred from observed cloud cover, solar "dimming," and solar "brightening". Journal of Geophysical Research: Atmospheres (1984–2012). 2009; 114(D10). doi: 10.1029/2008JD011378
3. Streets DG, Wu Y, Chin M. Two-decadal aerosol trends as a likely explanation of the global dimming/brightening transition. Geophysical Research Letters. 2006; 33(15). doi: 10.1029/2006GL026471
4. Li W, Hou M, Xin J. Low-cloud and sunshine duration in the low-latitude belt of South China for the period 1961–2005. Theoretical and applied climatology. 2011; 104(3–4):473–478. doi: 10.1007/s00704-010-0360-1
5. Coe H. Aerosol chemistry and the deepwater horizon spill. Science. 2011; 331(6022):1273–4. doi: 10.1126/science.1203019 PMID: 21393532
6. Massie ST, Torres O, Smith SJ. Total Ozone Mapping Spectrometer (TOMS) observations of increases in Asian aerosol in winter from 1979 to 2000. Journal of Geophysical Research: Atmospheres (1984–2012). 2004; 109(D18). doi: 10.1029/2004JD004620
7. Andreae MO, Schmid O, Yang H, Chand D, Yu JZ, Zeng LM, et al. Optical properties and chemical composition of the atmospheric aerosol in urban Guangzhou, China. Atmospheric Environment. 2008; 42(25):6335–6350. doi: 10.1016/j.atmosenv.2008.01.030
8. Sun Y, Wang Z, Dong H, Yang T, Li J, Pan X, et al. Characterization of summer organic and inorganic aerosols in Beijing, China with an Aerosol Chemical Speciation Monitor. Atmospheric Environment. 2012; 51:250–259. doi: 10.1016/j.atmosenv.2012.01.013
9. Liu Y, Wang E, Yang X, Wang J. Contributions of climatic and crop varietal changes to crop production in the North China Plain, since 1980s. Global Change Biology. 2010; 16(8):2287–2299. doi: 10.1111/j.1365-2486.2009.02077.x
10. Asseng S, Foster I, Turner NC. The impact of temperature variability on wheat yields. Global Change Biology. 2011; 17(2):997–1012. doi: 10.1111/j.1365-2486.2010.02262.x
11. Zhang X, Wang S, Sun H, Chen S, Shao L, Liu X. Contribution of cultivar, fertilizer and weather to yield variation of winter wheat over three decades: A case study in the North China Plain. European journal of agronomy. 2013; 50:52–59. doi: 10.1016/j.eja.2013.05.005
12. Che H, Shi G, Zhang X, Arimoto R, Zhao J, Xu L, et al. Analysis of 40 years of solar radiation data from China, 1961–2000. Geophysical Research Letters. 2005; 32(6). doi: 10.1029/2004GL022322
13. Tao F, Yokozawa M, Xu Y, Hayashi Y, Zhang Z. Climate changes and trends in phenology and yields of field crops in China, 1981–2000. Agricultural and Forest Meteorology. 2006; 138(1):82–92. doi: 10.1016/j.agrformet.2006.03.014
14. Chameides WL, Yu H, Liu S, Bergin M, Zhou X, Mearns L, et al. Case study of the effects of atmospheric aerosols and regional haze on agriculture: An opportunity to enhance crop yields in China

through emission controls? Proceedings of the National Academy of Sciences. 1999; 96(24):13626–13633. doi: 10.1073/pnas.96.24.13626

15. Cogliani E. Air pollution forecast in cities by an air pollution index highly correlated with meteorological variables. Atmospheric Environment. 2001; 35(16):2871–2877. doi: 10.1016/S1352-2310(01)00071-1
16. Wang Y, Yang Y, Zhao N, Liu C, Wang Q. The magnitude of the effect of air pollution on sunshine hours in China. Journal of Geophysical Research: Atmospheres (1984–2012). 2012; 117(D21). doi: 10.1029/2011JD016753
17. Wang Y, Yang Y, Han S, Wang Q, Zhang J. Sunshine dimming and brightening in Chinese cities (1955–2011) was driven by air pollution rather than clouds. Climate research. 2013; 56(1):11–20. doi: 10.3354/cr01139
18. Wang Y, Yang Y, Zhou X, Zhao N, Zhang J. Air pollution is pushing wind speed into a regulator of surface solar irradiance in China. Environmental Research Letters. 2014; 9(5):054004. http://dx.doi.org/10.1088/1748-9326/9/5/054004
19. Zhang X, Chen S, Sun H, Shao L, Wang Y. Changes in evapotranspiration over irrigated winter wheat and maize in North China Plain over three decades. Agricultural Water Management. 2011; 98 (6):1097–1104. doi: 10.1016/j.agwat.2011.02.003
20. Asseng S, Van Keulen H, Stol W. Performance and application of the APSIM Nwheat model in the Netherlands. European journal of agronomy. 2000; 12(1):37–54. doi: 10.1016/S1161-0301(99)00044-1
21. Wang E, Van Oosterom E, Meinke H, Asseng S, Robertson M, Huth N, et al., editors. The new APSIM-Wheat model—performance and future improvements. Solutions for a Better Environment: Proceedings of the 11th Australian Agronomy Conference Geelong, Victoria; 2003.
22. Chen C, Wang E, Yu Q, Zhang Y. Quantifying the effects of climate trends in the past 43 years (1961–2003) on crop growth and water demand in the North China Plain. Climatic Change. 2010; 100(3–4):559–578. doi: 10.1007/s10584-009-9690-3
23. Xiao D, Tao F. Contributions of cultivars, management and climate change to winter wheat yield in the North China Plain in the past three decades. European journal of agronomy. 2014; 52:112–122. doi: 10.1016/j.eja.2013.09.020
24. Sun H, Zhang X, Wang E, Chen S, Shao L. Quantifying the impact of irrigation on groundwater reserve and crop production—A case study in the North China Plain. European journal of agronomy. 2015; 70:48–56. doi: 10.1016/j.eja.2015.07.001
25. Munz S, Feike T, Chen Q, Claupein W, Graeff-Hönninger S. Understanding interactions between cropping pattern, maize cultivar and the local environment in strip-intercropping systems. Agricultural and Forest Meteorology. 2014; 195:152–164. doi: 10.1016/j.agrformet.2014.05.009
26. Xiao D, Shen Y, Zhang H, Moiwo JP, Qi Y, Wang R, et al. Comparison of winter wheat yield sensitivity to climate variables under irrigated and rain-fed conditions. Frontiers of Earth Science. 2015:1–11. doi: 10.1007/s11707-015-0534-3
27. Wang J, Wang E, Yin H, Feng L, Zhao Y. Differences between observed and calculated solar radiations and their impact on simulated crop yields. Field Crops Research. 2015; 176:1–10. doi: 10.1016/j.fcr.2015.02.014
28. McCree KJ. Test of current definitions of photosynthetically active radiation against leaf photosynthesis data. Agricultural Meteorology. 1972; 10:443–453.
29. Akitsu T, Kume A, Hirose Y, Ijima O, Nasahara KN. On the stability of radiometric ratios of photosynthetically active radiation to global solar radiation in Tsukuba, Japan. Agricultural and Forest Meteorology. 2015; 209:59–68. doi: 10.1016/j.agrformet.2015.04.026
30. Moan J. Visible Light and UV radiation. In: Brune D, Hellborg R, Persson B, Paakkonen R, editors. Radiation at Home, Outdoors and in the Workplace. Oslo: Scandinavian Publisher. 2001; pp. 69–85.
31. Wang F, Zhang C, Peng Y, Zhou H. Diurnal temperature range variation and its causes in a semiarid region from 1957 to 2006. International Journal of Climatology. 2014; 34(2):343–354. doi: 10.1002/joc.3690
32. Sun H, Zhang X, Chen S, Shao L. Performance of a Double Cropping System under a Continuous Minimum Irrigation Strategy. Agronomy journal. 2014; 106(1):281–289. doi: 10.2134/agronj2013.0309
33. Kolář P, Trnka M, Brázdil R, Hlavinka P. Influence of climatic factors on the low yields of spring barley and winter wheat in Southern Moravia (Czech Republic) during the 1961–2007 period. Theoretical and applied climatology. 2014; 117(3–4):707–721. doi: 10.1007/s00704-013-1037-3
34. Gu L, Fuentes JD, Shugart HH, Staebler RM, Black TA. Responses of net ecosystem exchanges of carbon dioxide to changes in cloudiness: Results from two North American deciduous forests. Journal of Geophysical Research: Atmospheres (1984–2012). 1999; 104(D24):31421–31434. doi: 10.1029/1999JD901068
35. Niyogi D, Chang HI, Saxena V, Holt T, Alapaty K, Booker F, et al. Direct observations of the effects of aerosol loading on net ecosystem CO2 exchanges over different landscapes. Geophysical Research Letters. 2004; 31(20). doi: 10.1029/2004GL020915

36. Lobell DB, Ortiz-Monasterio JI. Impacts of day versus night temperatures on spring wheat yields. Agronomy journal. 2007; 99(2):469–477. doi: 10.2134/agronj2006.0209

37. Anwar MR, O'Leary G, McNeil D, Hossain H, Nelson R. Climate change impact on rainfed wheat in south-eastern Australia. Field Crops Research. 2007; 104(1):139–147. doi: 10.1016/j.fcr.2007.03.020

38. Zhang T, Huang Y. Estimating the impacts of warming trends on wheat and maize in China from 1980 to 2008 based on county level data. International Journal of Climatology. 2013; 33(3):699–708. doi: 10.1002/joc.3463

39. Leuning R. A critical appraisal of a combined stomatal-photosynthesis model for C3 plants. Plant Cell Environ. 1995; 18(4):339–355. doi: 10.1111/j.1365-3040.1995.tb00370.x

40. Mott K, Parkhurst D. Stomatal responses to humidity in air and helox. Plant, Cell & Environment. 1991; 14(5):509–515. doi: 10.1111/j.1365-3040.1991.tb01521.x

41. Moschini R, Pérez B. Predicting wheat leaf rust severity using planting date, genetic resistance, and weather variables. Plant disease. 1999; 83(4):381–384.

42. Liu N, Lei Y, Gong G, Zhang M, Wang X, Zhou Y, et al. Temporal and spatial dynamics of wheat powdery mildew in Sichuan Province, China. Crop Protection. 2015; 74:150–157. doi: 10.1016/j.cropro.2015.05.001

43. Ciais P, Reichstein M, Viovy N, Granier A, Ogée J, Allard V, et al. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature. 2005; 437(7058):529–533. doi: 10.1038/nature03972 PMID: 16177786

44. Sun H, Shao L, Chen S, Wang Y, Zhang X. Effects of sowing time and rate on crop growth and radiation use efficiency of winter wheat in the North China Plain. International Journal of Plant Production. 2013; 7(1):117–138.

45. Zheng B, Chenu K, Doherty A, Chapman L. The APSIM-Wheat Module (7.5 R3008), APSRU Toowoomba, Australia. 2014; Available: https://www.apsim.info/Documentation/Model,CropandSoil/CropModuleDocumentation/Wheat.aspx.

46. Mercado LM, Bellouin N, Sitch S, Boucher O, Huntingford C, Wild M, et al. Impact of changes in diffuse radiation on the global land carbon sink. Nature. 2009; 458(7241):1014–1017. doi: 10.1038/nature07949 PMID: 19396143

47. Jing X, Huang J, Wang G, Higuchi K, Bi J, Sun Y, et al. The effects of clouds and aerosols on net ecosystem CO 2 exchange over semi-arid Loess Plateau of Northwest China. Atmospheric Chemistry and Physics. 2010; 10(17):8205–8218. doi: 10.5194/acp-10-8205-2010

48. Alton P, North P, Los O. The impact of diffuse sunlight on canopy light-use efficiency, gross photosynthetic product and net ecosystem exchange in three forest biomes. Global Change Biology. 2007; 13 (4): 776–787. doi: 10.1111/j.1365-2486.2007.01316.x

49. Roderick M, Farquhar G, Berry S, Noble I. On the direct effect of clouds and atmospheric particles on the productivity and structure of vegetation. Oecologia. 2001; 129: 21–30. doi: 10.1007/s004420100760

50. Bodin P, Franklin O. Efficient modeling of sun/shade canopy radiation dynamics explicitly accounting for scattering. Geoscientific Model Development. 2012; 5 (2):535–541. doi: 10.5194/gmd-5-535-2012

51. Zhang X, Wang Y, Niu T, Zhang X, Gong S, Zhang Y, et al. Atmospheric aerosol compositions in China: spatial/temporal variability, chemical signature, regional haze distribution and comparisons with global aerosols. Atmospheric Chemistry and Physics. 2012; 12(2):779–799. doi: 10.5194/acp-12-779-2012

52. Butler JH, Battle M, Bender ML, Montzka SA, Clarke AD, Saltzman ES, et al. A record of atmospheric halocarbons during the twentieth century from polar firn air. Nature. 1999; 399(6738):749–755. doi: 10.1038/21586

53. Gao W, Grant RH, Heisler GM, Slusser JR. Ultraviolet-B radiation in a row-crop canopy: an extended 1-D model. Agricultural and Forest Meteorology. 2003; 120(1):141–151. doi: 10.1016/j.agrformet.2003.08.026

54. Spitters CJT. Separating the diffuse and direct component of global radiation and its implications for modeling canopy photosynthesis Part II. Calculation of canopy photosynthesis. Agricultural and Forest Meteorology. 1986; 38 (1–3): 231–242. doi: 10.1016/0168-1923(86)90061-4

55. Roderick ML. Estimating the diffuse component from daily and monthly measurements of global radiation. Agricultural and Forest Meteorology.1999; 95 (3): 169–185. doi: 10.1016/S0168-1923(99)00028-3

56. Spitters CJT, Toussaint HAJM, Goudriaan J. Separating the diffuse and direct component of global radiation and its implications for modeling canopy photosynthesis Part I. Components of incoming radiation. Agricultural and Forest Meteorology. 1986; 38 (1–3): 217–229.