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ORIGINAL RESEARCH

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Solar dimming decreased maize yield potential on the North China Plain

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Abstract

Solar dimming has been increasing in rapidly developing regions (China and India) and threatening food security. Although previous studies have summarized the effects of climate change-associated increases in temperature on agriculture, few have examined the effects due to solar dimming. Here, we analyzed the effects of solar dimming on maize on the North China Plain (NCP). It is reported that solar dimming intensified and maize yield potential decreased since the 1960s. The total decrease in solar radiation for the whole maize growing season of this period was 17%, and solar dimming explained 87% of the decrease in yield potential. Meanwhile, solar dimming was closely related to the level of anthropogenic fine particulate matter such as $PM_{2.5}$. The $PM_{2.5}$ concentration in the NCP averaged 56 μg/m^3 in 2014 and 2015, which was approximately three times greater than the global mean. Our results suggested that a 10 μg/m^3 increase of $PM_{2.5}$ concentration in this region was together with a 55 MJ/m^2 decrease in solar radiation. Solar dimming threatened food security in the NCP and probably in other areas of the world and has profound implications for ongoing and future efforts such as Clean Air Action and other measures.

KEYWORDS
climate change, food security, maize yield, solar dimming

1 | INTRODUCTION

In addition to greatly affecting climate, solar radiation is the ultimate energy source for crop production at the Earth's surface (Monteith, 1977; Wild et al., 2005). Solar dimming or brightening, which is commonly assessed as decreases or increases in decadal-level incident solar radiation, will substantially change the net radiation arriving at crop vegetation canopies and thereby affect crop photosynthesis and ultimately crop yield (Wild et al., 2005).

Large temporal and spatial variations in solar radiation change have been observed worldwide since 1950 (Wild, 2012). Solar dimming associated with the increases in air pollution and aerosol emissions was evident around the globe from the 1950s to the 1980s. Since then until 2000, however, global trends of radiation were more neutral with brightening in Europe, the United States (USA), and China and dimming in India. The latest updates on changes in solar radiation since 2000 no longer reveal any globally coherent trends (Wild, 2012). Since 2000, brightening sustains in Europe and the USA, renewed dimming associated with tremendous increases in emissions is evident in China, and dimming continues unabated in India. In China, the solar dimming from the 1960s to the 1980s, which had an average

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Qingfeng Meng and Baohua Liu contributed equally to this work.

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of 0.74 MJ/m^2 per decade, represented one of the largest trends in solar dimming globally (Ye, Li, Sun, & Guo, 2010). During the 1990s to 2000, China experienced a slight brightening trend, but since 2000, China has experienced a renewed dimming trend. Brightening or dimming has profound implications for ongoing and future efforts to improve crop production in changing climates.

Climate-change researchers have paid substantial attention on the effects of high temperature on crop production in both the past and future (Challinor et al., 2014; Lobell, Schlenker, & Costa-Roberts, 2011; Peng et al., 2004; Wild, 2012). Moreover, recent studies have quantified the effects of extreme heat on crops in the USA and France (Hawkins et al., 2013; Lobell et al., 2013). These studies on the effects of climate change on crop, however, generally presume that the solar radiation at the decadal scale has kept and will keep constant. Although the potential effects of solar radiation increase and decrease on crop yield have been frequently discussed, quantitative research remains very limited. One recent quantitative study attributed 27% of the increase in yield in the USA Corn Belt from 1984 to 2013 to solar brightening (Tollenaar, Fridgen, Tyagi, Stackhouse, & Kumudini, 2017). In general, however, it is still poorly understood for the response of crop yield to decadal-scale changes in solar radiation.

In this study, we examined how changes in solar radiation have affected maize production in the North China Plain (NCP). Maize in the NCP is mainly irrigated and accounts for one-third of the national maize production and about 6% of the global maize production (FAO, 2020; MOA, 2020). Although the NCP is an important agricultural area, it has become one of the most developed regions in China. The rapid economic growth and urbanization have generated severe air pollution caused by aerosol emission (Hu, Wang, Ying, & Zhang, 2014). The $PM_{2.5}$ (fine particulate matter with of $\leq$2.5 μm of an aerodynamic diameter) concentration in 2013, for example, was 77.0 μg/m^3 (Hu et al., 2014), which greatly exceeded the threshold of 10 μg/m^3 of the World Health Organization (WHO, 2005) and which would lead to a substantial decrease in solar radiation. As a case study, research on maize in the NCP would offer a model for quantifying the effects of decadal changes in solar radiation on crop yields in other rapidly developing regions of the world.

The relationship between solar radiation changes during whole maize growing season from the 1960s to 2015 and the related yield potential in the NCP was investigated in this study. As defined by Evans (1993), yield potential is the yield of a crop variety when grown in an adapted environment with sufficient supplies of nutrient and water, whereas pests and diseases are effectively controlled. To quantify the effect of changes in solar radiation on maize yield potential at 19 sites across the NCP, we used the Hybrid-Maize model (Yang, Dobermann, Cassman, & Walters, 2006; Yang et al., 2004). To identify the individual effect from solar radiation or temperature on maize yield potential, we used scenario analyses as described later. We also collected the $PM_{2.5}$ concentration data for each site in 2014 and 2015 to examine the relationships among changes in solar radiation, yield potential, and aerosol emission ($PM_{2.5}$ concentration).

2 | MATERIALS AND METHODS

2.1 | Study area

The NCP included seven provinces or municipalities (Hebei, Shandong, Henan, the northern part of Anhui and Jiangsu provinces, Beijing and Tianjin). In this area, the major agricultural system is a winter wheat and summer maize rotation. Winter wheat is sown in early October and harvested the next June. The summer maize is sown in early June after the harvest of the winter wheat and is harvested at the beginning of October. Maize is irrigated to obtain high yield.

2.2 | Climate and crop phenology

In this study, we collected climate data from 19 sites from China Meteorological Agency (CMA, 2020) (Table S1). It provided records of sunshine hours, temperatures, and precipitation for each day from 1961 to 2015. Solar radiation was calculated according to an equation such as Ångström formula (Black, Bonython, & Prescott, 1954; Jones, 1992), which has been widely used (Liu, Yang, Hubbard, & Lin, 2012). Taken Beijing station as an example, it indicated high consistency between calculated and measured daily solar radiation from 1961 to 2015 (Figure S1).

The dates of sowing, silking, and physiological maturity of maize were obtained from 1961 to 2015 from the 19 Agrometeorological Experimental Stations, which located in the same places as the meteorological sites or very near the sites. The phenological information was verified by interviewing 15 agronomists from the National Maize System of the NCP. Total growing degree days (GDD $\geq$ 10°C) was used to quantify variety maturity and for the model simulation. The details of the GDD information for each site were shown in Table S1.

2.3 | Crop modeling and simulation

The Hybrid-Maize model (https://hybridmaize.unl.edu/), developed by the University of Nebraska-Lincoln (Yang et al., 2004, 2006), was used in this research. The simulations for organ growth by the process-based model and assimilation and respiration functions by the generic crop models were both taken into accounts. It can simulate grain yield with irrigated and rainfed conditions. In the previous studies, we have calibrated the model and found it could simulate well for maize yield in NCP (Bai, 2009). In this study, most parameters for maize growth were set as the maximum for varieties in North China Plain to simulate the yield potential (Table S2).

For irrigated maize, the model requires daily solar radiation and temperatures. Meanwhile, variety's GDD, date of sowing, and plant population density were also needed. In the simulations, the sowing dates for each area was according to the record in Table S1. Plant density was set as 90,000 plants/ha at all sites. Grain yield with the climate of the 1960s, 1970s, 1980s, 1990s, and 2001–2015 was the average of the decade (or 15-year from 2001 to 2015) simulation from 1961 to 1970, 1971 to 1980, 1981 to 1990, and 2001 to 2015, respectively.

2.4 | $PM_{2.5}$ concentration

In this study, we used $PM_{2.5}$ measurements in 2014 and 2015 from the 19 sites to analyze the relationships among $PM_{2.5}$, solar radiation change, and yield potential change for the NCP. We also used the estimated long-term (1973–2013) $PM_{2.5}$ concentration using meteorological visibility data (Han, Zhou, & Li, 2016) to analyze the above relationships at the typical Beijing site. The trends were similar for the long-term data at the Beijing site and other sites in NCP (Figure S2).

The average $PM_{2.5}$ concentrations for the maize growing season (June to September) for each month of 2014 and 2015 were obtained from the Chinese Air Quality Monitoring Platform (CAQMP, 2017). Accordingly, we calculated the average of $PM_{2.5}$ concentration during the whole maize growing season for each of the 19 sites.

2.5 | Data analysis

For each site, we used linear-regression to analyze time trends from 1961 to 2015 for the following variables: solar radiation, temperatures, and simulated grain yield. The following relationships were also analyzed by the linear regression: changes in cumulative solar radiation versus yield potential from the 1960s to 2014–2015; changes in cumulative solar radiation from the 1960s to 2014–2015 versus $PM_{2.5}$ concentration as an average of 2014 and 2015; and changes in yield potential from the 1960s to 2014–2015 versus $PM_{2.5}$ concentration as an average of 2014 and 2015.

Three scenarios were considered in the simulation. In scenario 0 (S0), both actual solar radiation and temperature of the 55 years of were used. Scenario S1 used actual temperature data from 1961–2015 but held solar radiation at a constant value equal to the average of individual days of the 1960s, which could enable us to estimate the effects of temperature change in the absence of solar radiation change. Scenario S2 used the estimated solar radiation data from sunshine duration from 1961–2015 but held temperature at a constant value equal to the average of individual days of the 1960s, which could enable us to estimate the effects of solar radiation change in the absence of temperature change. Comparison of the three scenarios enabled us to estimate the separate effects of temperature change and solar dimming on yield potential.

3 | RESULTS

3.1 | Solar dimming since the 1960s

According to meteorological data from the 19 sites across the NCP, solar radiation decreased (i.e., solar dimming intensified) from the 1960s to 2001–2015, and the rate of dimming was greatest between the 1990s and 2001–2015 (Figure 1a). From the 1960s to the 1980s, we estimated that solar radiation decreased across this region by 2.8% or 56 MJ/m^2 per decade. From the 1980s to the 1990s, solar radiation stabilized in the NCP. From the 1990s to 2001–2015, solar radiation decreased by an average of 3.4% or 70 MJ/m^2 per decade in the NCP. Overall, solar dimming since the 1960s resulted in a 17% decrease of solar radiation during the whole maize season across the 19 NCP sites (range = 9 to 24%) (Figures 1a and S3).

3.2 | Impacts for yield potential

From the 1960s to 2001–2015, our analyses using the Hybrid-Maize model indicated that climate change reduced maize yield potential for the entire NCP by an average of 19% (2.66 t/ha), with a range of 5 to 26% across all 19 sites (Figures 1b and S4). For irrigated maize, model simulations indicated that the decrease in yield potential resulted from both solar dimming and temperature change (Figures 1c and S4–S7).

To separate the effects of solar dimming and temperature change on the decline in yield potential, the Hybrid-Maize model was used to simulate yield potential with three scenarios. The scenario analysis showed that solar dimming accounted for 87% of the yield potential decrease (2.31 t/ha) between the 1960s and 2001–2015, while temperature change accounted for the left of the yield potential decrease (Figure 1c). The contribution of solar dimming to the decrease in yield potential ranged from 32% to 170% among the 19 sites (Figure S8). However, the contributions of solar dimming and

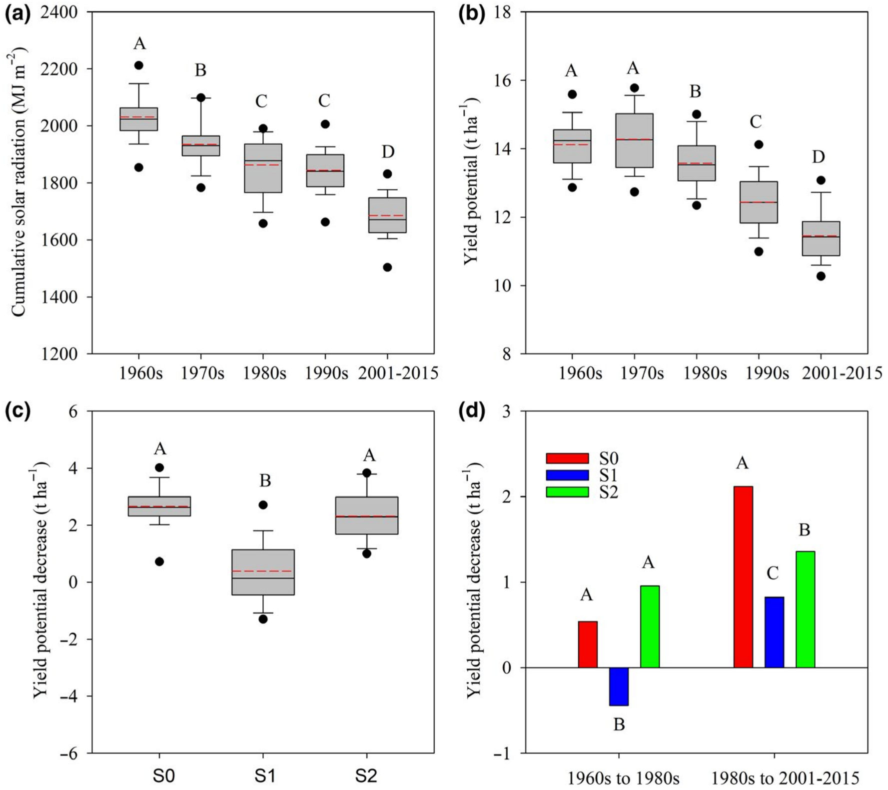

FIGURE 1 Cumulative solar radiation, maize yield potential in different periods, and yield potential decrease from the 1960s to 2001–2015 on the North China Plain. (a) Cumulative solar radiation during the maize growing season. (b) Maize yield potential. (c) Decrease in yield potential caused by climate change from the 1960s to 2001–2015 (S0, yield potential decrease caused by changes in both temperature and solar radiation. S1, yield potential decrease caused by temperature change alone. S2, yield potential decrease caused by solar radiation change alone). (d) Yield potential decrease caused by climate change from the 1960s to 1980s and from the 1980s to 2001–2015 (see definition of S0, S1, and S2 in c). In a, b, and c, solid black lines indicate the medians, and dashed red lines indicate the means. The box boundaries indicate upper and lower quartiles, the whisker caps indicate 90th and 10th percentiles, and the circles indicate the 95th and 5th percentiles. Columns labeled with the same letter are not statistically different at $p < .05$

temperature to changes in yield potential differed between the periods from the 1960s to the 1980s versus the period from the 1980s to 2001–2015 (Figure 1d). From the 1960s to 1980s, yield potential was decreased by dimming but enhanced by temperature change. Because the negative effect of dimming was greater than the positive effect by temperature change, yield potential was decreased. From the 1960s to 1980s, yield potential decreased by 4% (a 0.54 t/ha decrease), solar dimming caused a 177% decrease (i.e., dimming decreased yield potential by 0.96 t/ha), and temperature change caused an 82% increase (i.e., temperatures increased yield by 0.44 t/ha). From the 1980s to 2001–2015, yield potential was decreased by both dimming and temperature change, and the decrease in yield potential was much greater than in the previous period. From the 1980s to 2015, yield potential decreased by 16% (a 2.12 t/ha decrease), solar dimming caused a 64% of the decrease (i.e., dimming decreased yield potential by 1.36 t/ha), and temperature change caused a 39% of the decrease (i.e., increasing temperatures decreased yield by 0.82 t/ha).

3.3 | PM2.5, solar dimming, and yield potential

We collected data of $PM_{2.5}$ concentrations during the maize growing season (June to September) at the 19 sites in the NCP in 2014 and 2015. Over all sites and both years, the $PM_{2.5}$ concentration averaged 56 μg/m^3. The spatial distribution of solar dimming values was consistent with $PM_{2.5}$ concentrations, decreases in yield potentials among the 19 sites, and decreases in yield potential and solar radiation and $PM_{2.5}$ concentration were all highest in the northern part of the NCP (Figure 2a–c). Based on regression analysis of averages for the 19 sites, an increase of 10 μg/m^3 $PM_{2.5}$ is together with a solar dimming of 55 MJ/m^2 during the maize season (Figure 2e) and a 0.90 t/ha decrease in yield potential (Figure 2f). The historical data (1973–2013) of $PM_{2.5}$ concentrations at the Beijing site showed similar relationships between solar dimming and yield potential decrease (Figure S2).

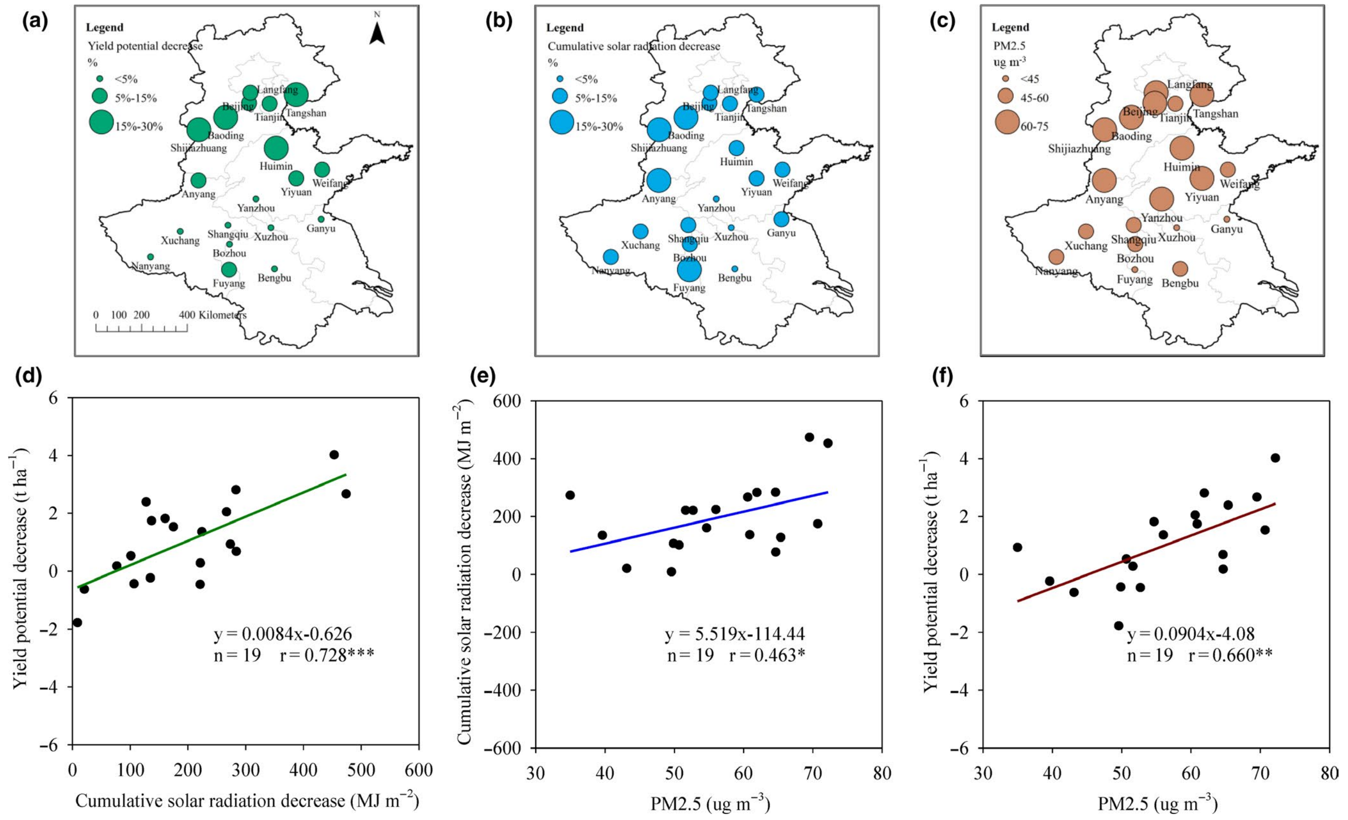

FIGURE 2 Spatial distribution of decreases in yield potential and cumulative solar radiation from the 1960s to 2014–2015 and PM2.5 concentrations in 2014–2015, and relationships among yield potential decrease, cumulative solar radiation decrease, and PM2.5 on the North China Plain. (a) Spatial distribution of decrease in yield potential from the 1960s to 2014–2015. (b) Spatial distribution of the decrease in cumulative solar radiation decrease from the 1960s to 2014–2015. (c) Spatial distribution of PM2.5 as an average of 2014 and 2015. (d) Relationship between decreases in yield potential and cumulative solar radiation from the 1960s to 2014–2015. (e) Relationship between cumulative solar radiation decrease from the 1960s to 2014–2015 and PM2.5 concentration as an average of 2014 and 2015. (f) Relationship between yield potential decrease from 1960s to 2014–2015 and PM2.5 concentration as an average of 2014 and 2015. *, **, and *** indicate significant at *p* < .05, <.01, and <.001, respectively

4 | DISCUSSION

We found solar dimming resulted in a 17% decrease in solar radiation during the whole maize season since the 1960s in the NCP (Figure 1). However, the change among different periods varied largely compared with the global areas. From the 1960s to the 1980s, the solar dimming is consistent with the global decrease in solar radiation (Wild, 2009, 2012). From the 1980s to the 1990s, solar radiation stabilized in the NCP, while many parts of Europe and the USA saw the mid-1980s as a turning point from dimming to brightening (Wild et al., 2009). From the 1990s to 2001–2015, solar radiation decreased (3.4% per decade) while the global trend was the opposite with an increase from 1.2% to 2.8% per decade. During this period, the USA Corn Belt saw an increase in solar radiation during the whole maize season by a total of 112 MJ/m^2 between 1984 and 2013 (Tollenaar et al., 2017). For solar brightening in USA since 1980s, governmental policies such as the Clean Air Act have been argued to play a prominent role (Ruckstuhl et al., 2008; Wild, 2012).

Solar dimming decreased maize yield substantially. Due to climate change (both solar radiation and temperature change), maize yield potential was reduced by 19% in NCP since 1960s (Figure 1b), which was substantially higher than the decrease for global maize yield (3.8%) due to climate change (Lobell et al., 2011). Solar dimming explained 87% of this decrease in the NCP (Figure 1b). Although many factors influenced the solar dimming, the further analysis showed solar dimming was closely related to the level $PM_{2.5}$ pollution (Figure 2). The $PM_{2.5}$ concentration in the NCP averaged 56 μg/m^3 in 2014 and 2015, nearly three times higher than the global average (van Donkelaar et al., 2010). Furthermore, a 10 μg/m^3 increase in $PM_{2.5}$ concentration in this region would be together with a 55 MJ/m^2 decrease in solar radiation.

Our findings indicate that the effects of solar dimming or brightening on crop yield warrant increased attention. Based on the effects of changes in both solar dimming/brightening and temperature on maize yields since the 1980s, maize-producing countries can be classified into three groups. For countries like the USA, solar brightening (Tollenaar et al., 2017) and a lack of warming (Lobell et al., 2011) have resulted in increased maize yield. For countries in Europe and Southern Hemisphere, the combined effects of solar brightening (Wild, 2012) and significant warming (Lobell et al., 2011) on crop production require further study. For countries like China and India, solar dimming combined with significant warming have resulted in reduced grain yields. While much research has focused on climate warming, our results indicate that solar dimming should be lessened or stopped to ensure the food security of the very large populations in China and India.

A main cause of solar dimming is atmospheric aerosols resulting from human activities (Ruckstuhl et al., 2008; Stern, 2006; Streets et al., 2009; Wild et al., 2005). Anthropogenic aerosol emissions increased from the 1960s to 1980s but then decreased in the Northern Hemisphere. This decrease resulted from the air quality controls as well as the reduced industrial activities. In Western industrial countries, such as the USA and Europe, brightening is unlikely to become more pronounced because aerosol emissions have already been at relatively low values. Aerosol emissions in China and India, in contrast, have been increasing (Auffhammer, Ramanathan, & Vincent, 2006; Burney & Ramanathan, 2014). Because of rapid economic development and industrial expansion, the NCP has higher aerosol emissions (e.g., $PM_{2.5}$ concentration) than other parts of China (Zhang & Cao, 2015). China and other countries with high levels of anthropogenic aerosol emissions should now implement policies that reduce pollution and that therefore support sustainable development.

In regions experiencing solar dimming, securing food supplies in the short-term will depend on increasing solar radiation use efficiency such as RUE, which shows the efficiency with which solar radiation is transformed into grain yield (Gosse et al., 1986). RUE in crop systems can be increased by novel agronomic strategies (*e.g.*, fertilization, irrigation, and high plant densities). RUE can also be increased by developing new varieties through breeding. Some new varieties of wheat and soybean, for example, have significantly improved RUE (Koester, Skoneczka, Cary, Diers, & Ainsworth, 2014; Shearman, Sylvester-Bradley, Scott, & Foulkes, 2005). For maize in USA, plant growth rate for new hybrid was 33% higher than the old, approximately 80% of the difference could be attributed to a higher RUE of the new hybrid (Tollenaar & Aguilera, 1992).

Since the 1960s, the statistical maize yield has increased significantly in farmers' fields in the NCP (MOA, 2020) although climate change has decreased maize yield potential substantially, which implicated great contributions from breeding and agronomic management. For China's maize production, 99.6%–141.6% contribution for maize yield increase from 1980 to 2010 was from technological advancement while −41.4% to 0.4% was from climate change (Guo, Zhao, Wu, Mu, & Xu, 2014).

Despite these observations, some aspects of the effects of air pollutants on maize production should be further addressed. The global insolation in this study is the total insolation of direct, diffuse, and reflected light. The effects of change in the diffuse fraction on yields was not distinguished. Beside reducing total insolation, air pollutants increase the fraction of sunlight which is scattered, which may, in turn, increase the RUE of crops (Gu et al., 2002; Proctor, Hsiang, Burney, Burke, & Schlenker, 2018). Furthermore, the changing pollution would also alter temperature and precipitation, which can impact yield (Burney & Ramanathan, 2014). Finally, the transparency of the atmosphere due to the clouds, aerosols, and radiatively active gases also influenced the observed solar radiation variations (Kim & Ramanathan, 2008) and they should be fully considered for the impacts of crop production in the future study.

5 | CONCLUSION

In conclusion, we found that, of the total decrease in maize yield potential due to climate in the NCP, 87% can be attributed to solar dimming from the 1960s to 2015. The substantial worsening in solar dimming is together with the substantial increases in $PM_{2.5}$ concentrations. This study highlights the importance of regulating fine particulate matter pollution not only for China, but also for the world. It provides a quantitative evidence that Clean Air Action is not only beneficial to human health in NCP (Chen, Ebenstein, Greenstone, & Li, 2013; Ebenstein, Fan, Greenstone, He, & Zhou, 2017), but also conducive to crop production. Finally, agricultural technology must be improved to offset the yield decreases caused by solar dimming.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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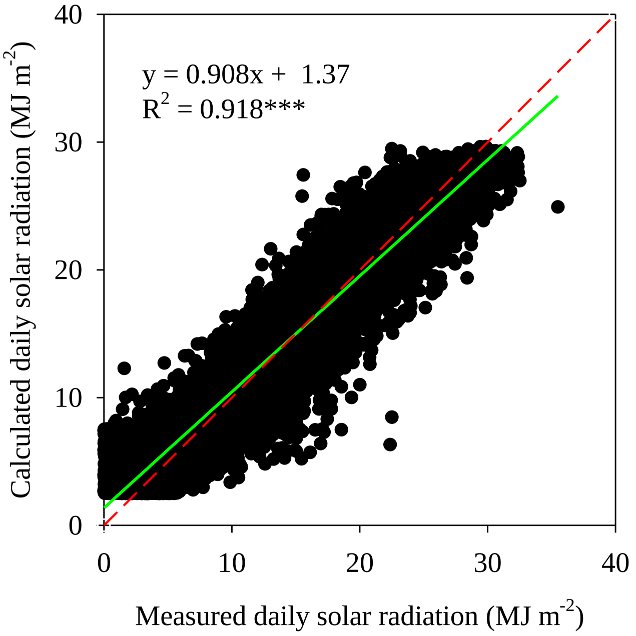

Figure S1 Relationship between measured and calculated daily solar radiation at Beijing from 1961 to 2015.

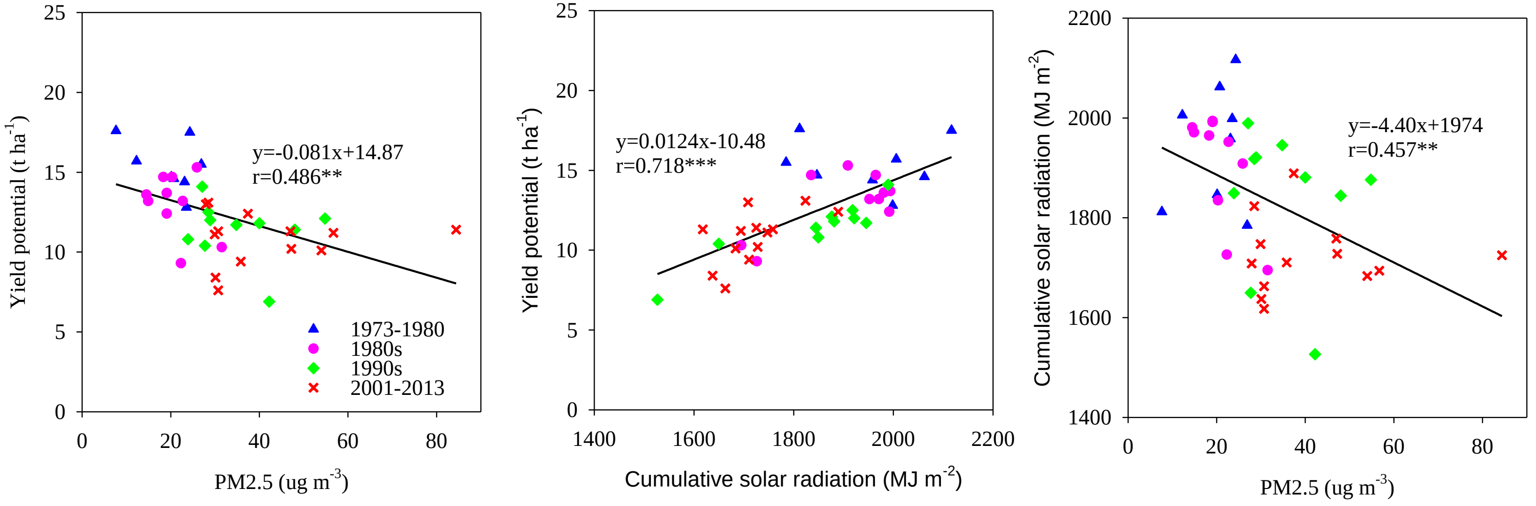

Figure S2 Relationships among yield potential, cumulative solar radiation and PM2.5 at Beijing site from 1973 to 2013. *Significant at $p<0.05$. ** Significant at $p<0.01$. *** Significant at $p<0.001$.

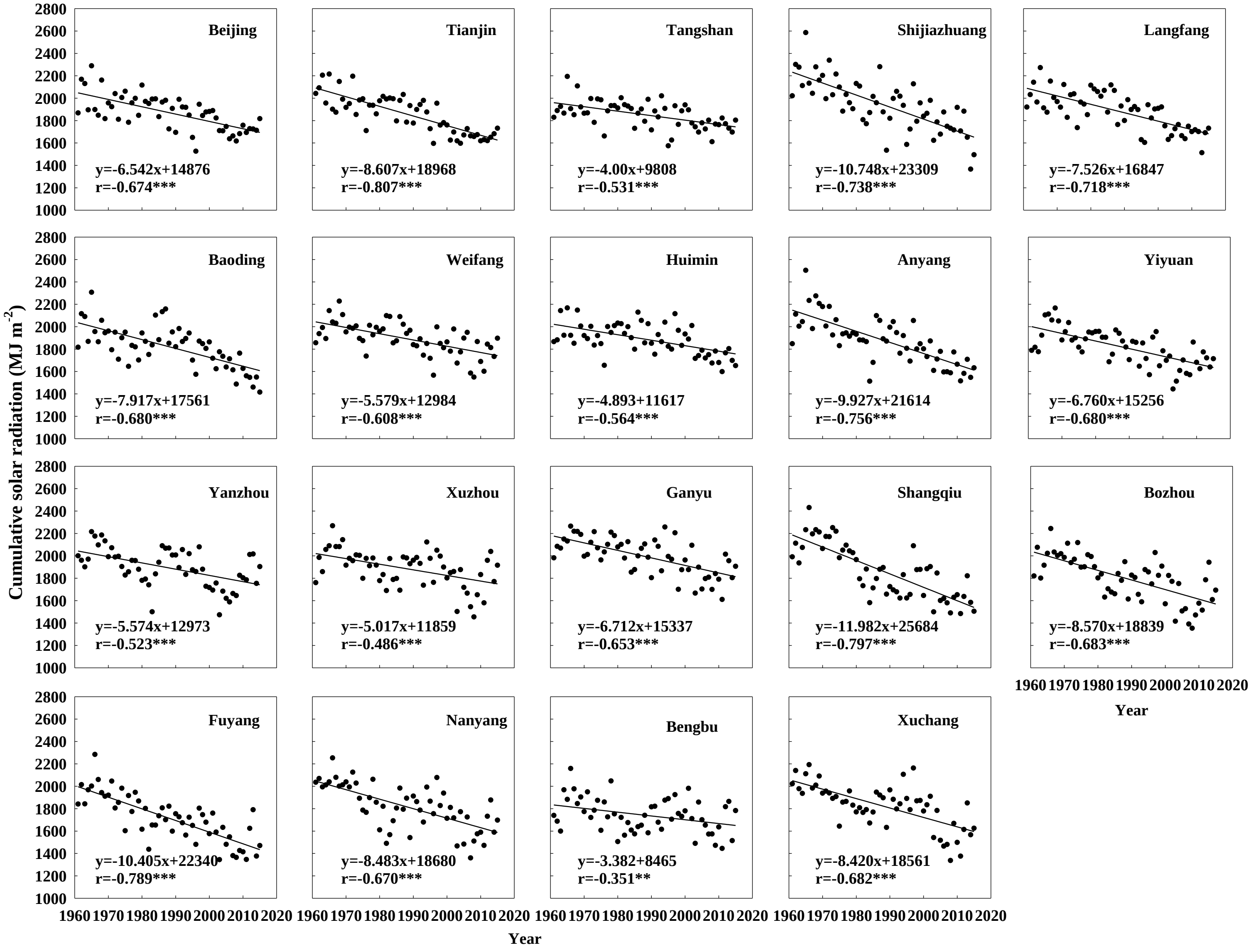

Figure S3 Cumulative solar radiation during maize growth season at 19 sites from 1961 to 2015. ** Significant at p<0.01. *** Significant at p<0.001.

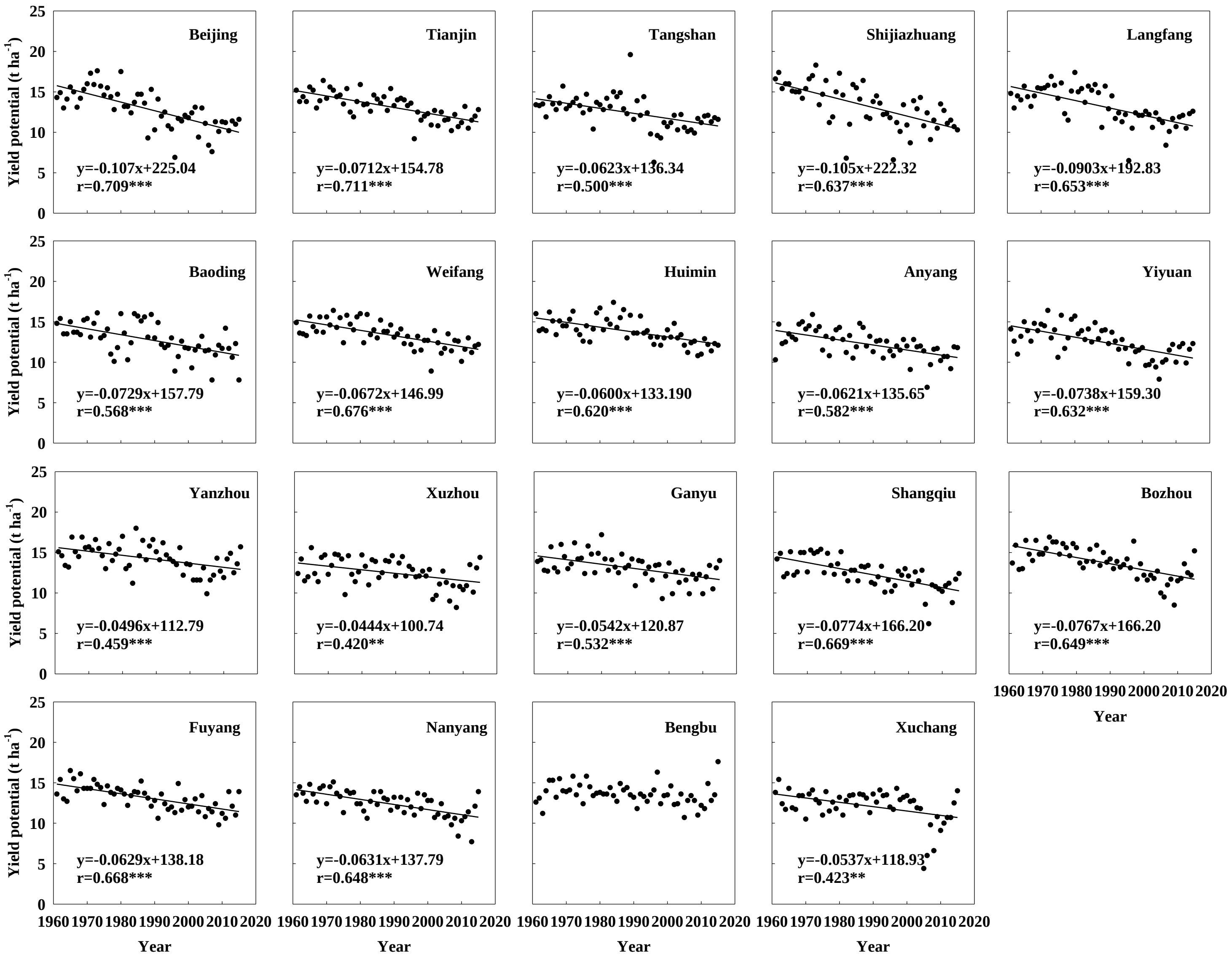

Figure S4 Yield potential simulated by Hybrid-Maize model at 19 sites from 1961 to 2015. ** Significant at $p<0.01$. *** Significant at $p<0.001$. Panels without regression indicate insignificant trend.

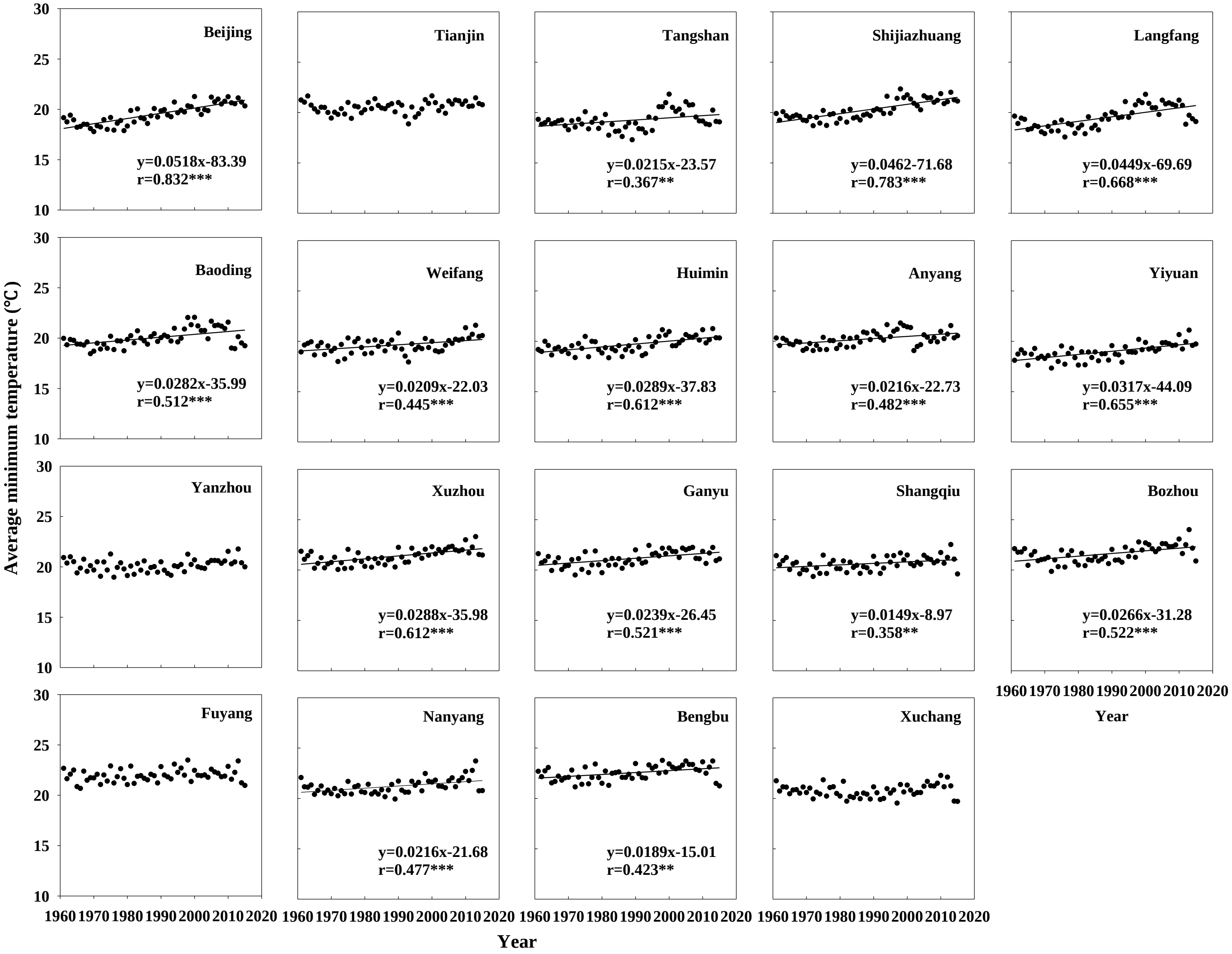

Figure S5 Annual average daily minimum temperature during maize growth season at 19 sites from 1961 to 2015. ** Significant at p<0.01. *** Significant at p<0.001. Panels without regression indicate insignificant trend.

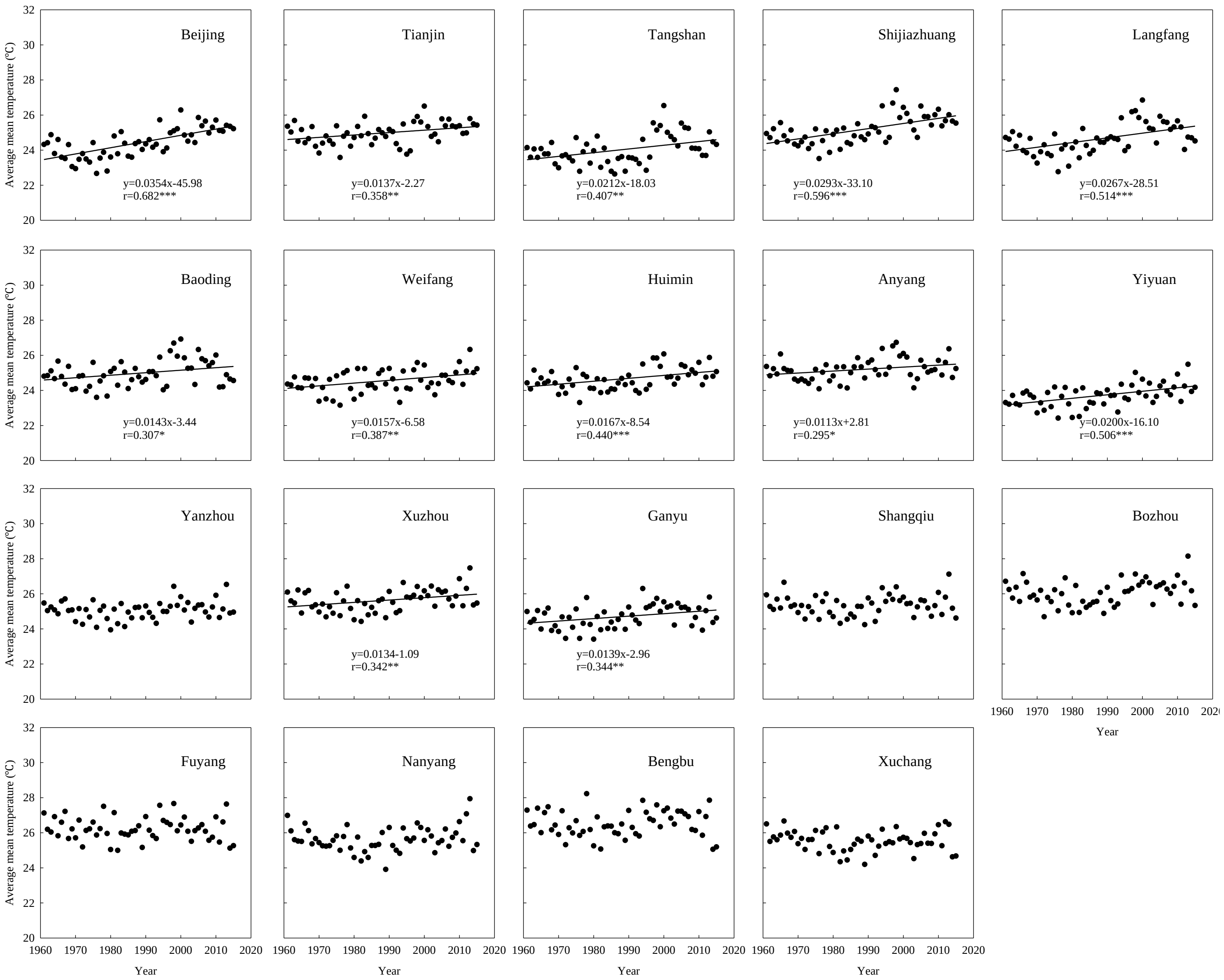

Figure S6 Annual average mean temperature during maize growth season at 19 sites from 1961 to 2015. *Significant at $p<0.05$. ** Significant at $p<0.01$. *** Significant at $p<0.001$. Panels without regression indicate insignificant trend.

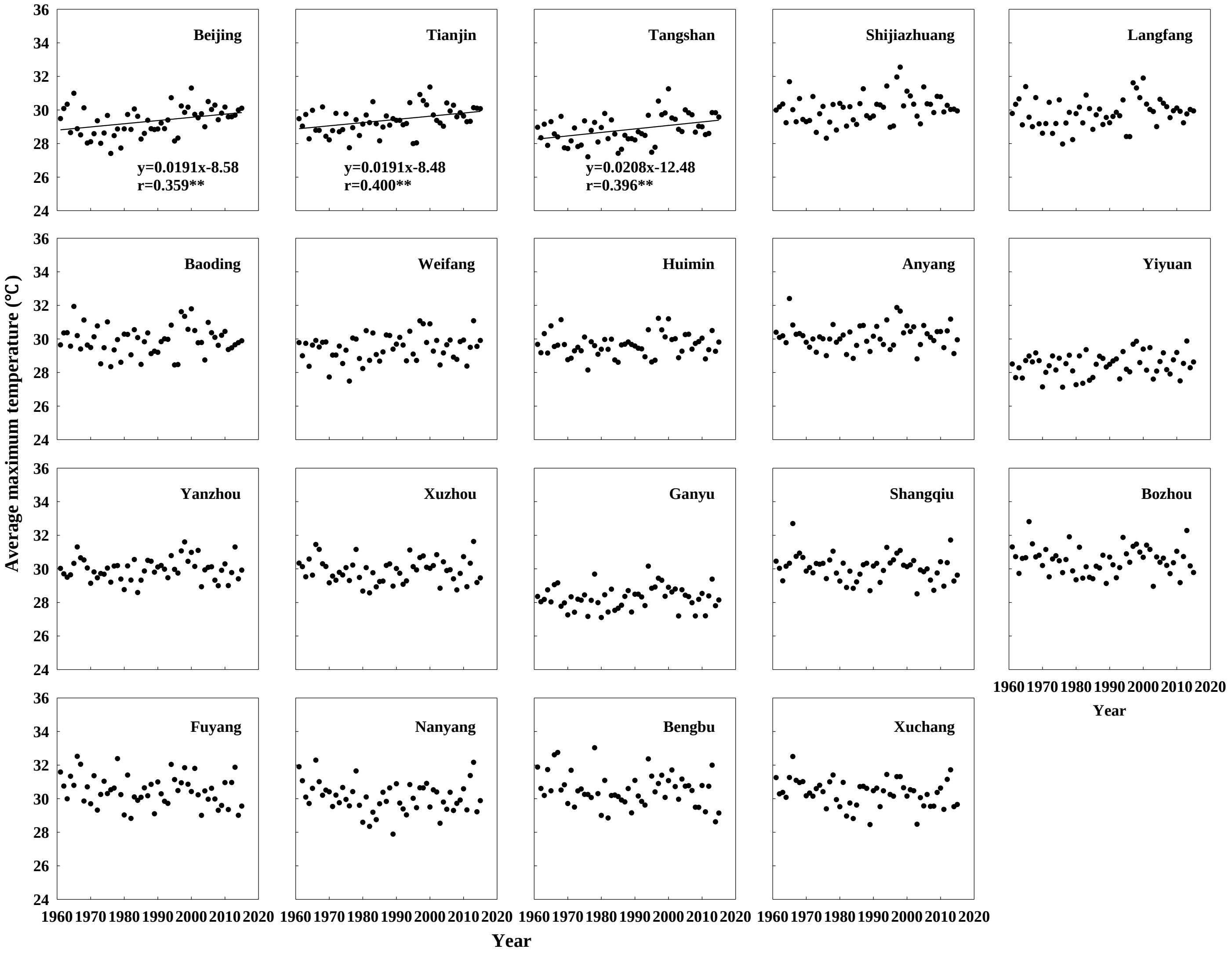

Figure S7 Annual average maximum temperature during maize growth season at 19 sites from 1961 to 2015. ** Significant at p<0.01. Panels without regression indicate insignificant trend.

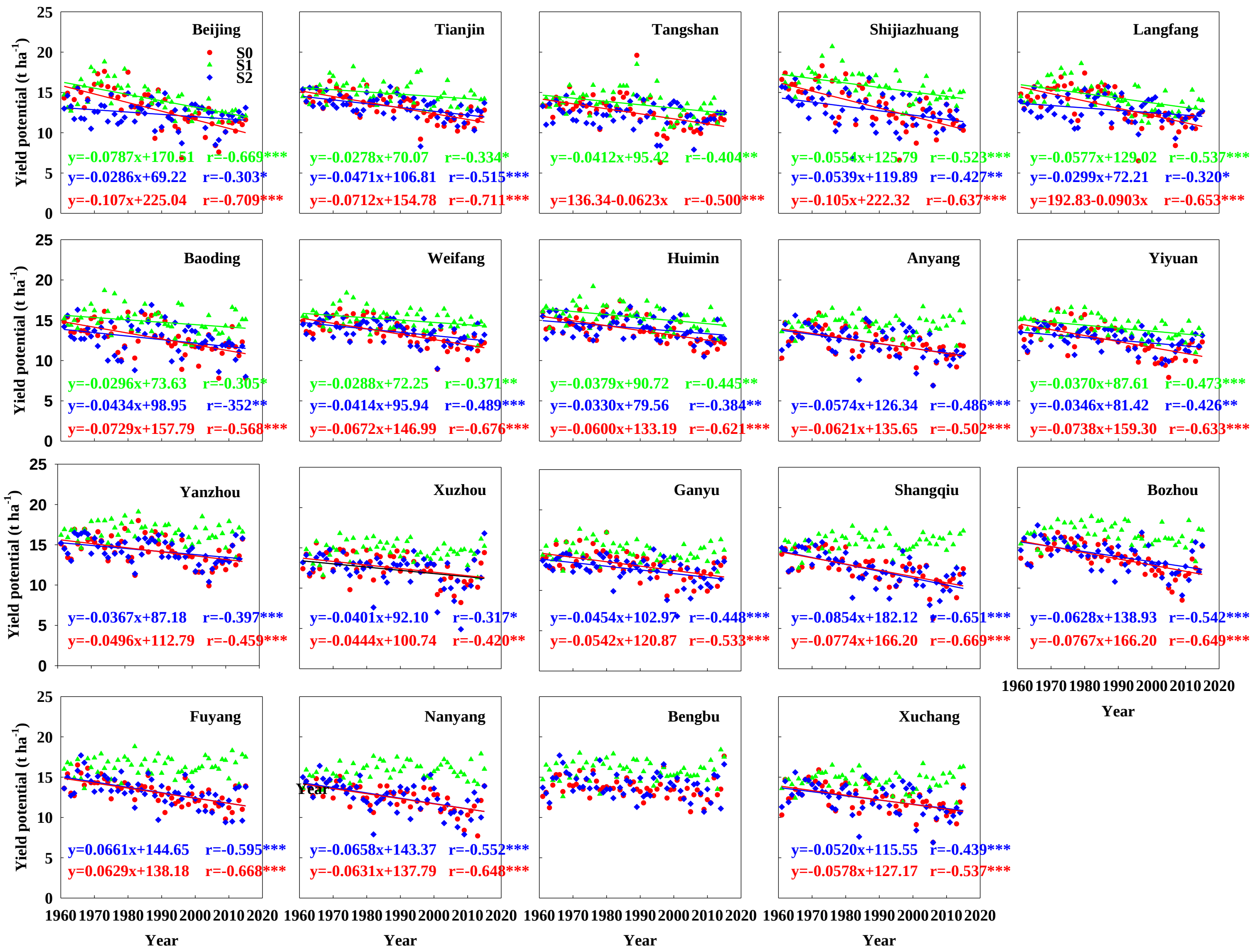

Figure S8 Yield potential in different climate change scenarios from 1961 to 2015 (S0 with red dots, yield potential due to both temperature and solar radiation change. S1 with green dots, yield potential due to temperature change. S2 with blue dots, yield potential due to solar radiation change). *Significant at $p<0.05$. ** Significant at $p<0.01$. *** Significant at $p<0.001$. Panels without regression indicate insignificant trend.

Table S1 Locations, management and variety GDD information at 19 sites.

Sites	Latitude	Longitude	Elevation, (m)	Planting date	Maturity data	Plant density (1000 ha^{-1})	GDD
Beijing	39.5	116.3	31	6.15	10.1	90	1533
Tianjin	39.1	117.0	3	6.15	10.1	90	1588
Tangshan	39.4	118.1	28	6.15	10.1	90	1488
Shijiazhuang	38.0	114.3	81	6.15	10.1	90	1615
Langfang	39.1	116.2	9	6.15	10.1	90	1561
Baoding	38.5	115.3	17	6.15	10.1	90	1596
Weifang	36.5	119.1	22	6.15	10.1	90	1543
Huimin	37.3	117.3	12	6.15	10.1	90	1582
Anyang	36.0	114.2	63	6.10	10.1	90	1613
Yiyuan	36.1	118.1	305	6.15	10.1	90	1454
Yanzhou	35.3	116.5	129	6.15	10.1	90	1626
Xuchang	34.0	113.5	67	6.10	10.1	90	1654
Ganyu	34.5	119.1	3	6.10	10.1	90	1564
Shangqiu	34.3	115.4	50	6.10	10.1	90	1632
Bozhou	33.5	115.5	38	6.15	9.28	90	1688
Fuyang	32.5	115.4	33	6.15	9.28	90	1707
Nanyang	33.0	112.4	129	6.10	10.1	90	1661
Bengbu	32.6	117.2	22	6.15	9.28	90	1738
Xuzhou	34.2	117.1	41	6.10	10.1	90	1659

Table S2 Crop model parameters for yield potential simulation.

Items	**Value**	**Unit**
Potential numbers of kernels per ear	675	
Potential kernel grain filling rate	8.70	Mg kernel^{-1} day^{-1}
Light extinction (k)	0.55	
Maximum photosynthetic rate	7.0	g CO2 m^{-2} leas area hr^{-1}
Initial light use efficiency	12.5	g CO2 MJ PAR