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Intermediate Aerosol Loading Enhances Photosynthetic Activity of Croplands

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Key Points:

- Soybean sun and shade leaf photosynthesis show a quadratic response to aerosols, peaking at aerosol optical depth of 0.76 and 1.13, respectively
- The changes in radiation regimes and concurrent high relative humidity lead to such nonlinear responses of leaf photosynthesis
- Solar-induced chlorophyll fluorescence in the North China Plain also demonstrate that intermediate aerosols enhance crop photosynthesis

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Aerosols can affect crop photosynthesis by altering radiation and meteorological conditions. By combining field observations, mechanistic modeling, and satellite-retrieved solar-induced chlorophyll fluorescence (SIF), we assessed aerosols' impacts on crop photosynthesis from leaf to regional scale. We found that the initial increase in aerosol optical depth (AOD) enhanced photosynthesis of sun leaves, shade leaves, and canopy, which reached their maximum at AOD = 0.76, 1.13, and 0.93, respectively, and then decreased. Aerosol-induced changes in radiation regime and the concurrent high relative humidity led to such nonlinear responses. Similarly, the SIF of croplands in the North China Plain (NCP) also showed a bell-shaped response to aerosols. The optimal AOD level at which SIF reached the maximum value varied from 0.56 to 1.04, depending on the background meteorological conditions. Approximately 76%–90% of the NCP exceeded the optimal AOD level, suggesting that stringent aerosol pollution control could promote cropland productivity in this region.

Plain Language Summary

High aerosol loading could produce either a positive or negative impact on crop photosynthesis. However, experimental tools for manipulating aerosol loading in the field are lacking, creating significant uncertainty in assessing the impact of aerosols on crop yields. The cyclical fluctuations in aerosol loading in the North China Plain (NCP) provide a unique opportunity to study aerosols' effect on crop productivity. We found that the photosynthesis of sun and shade leaves and canopy reached their maximum at a moderate level of aerosol loading. Similarly, satellite-observed solar-induced chlorophyll fluorescence across the NCP also demonstrated that intermediate aerosols enhance crop photosynthesis at regional scales. The further analysis indicated that the changes in direct and diffuse radiation and the concurrent high air humidity together led to the nonlinear response of soybean photosynthesis to aerosol loading. Our findings suggested that stringent aerosol pollution control will increase crop productivity in the NCP.

1. Introduction

The rapid increase in anthropogenic aerosols has significantly decreased incoming total solar radiation over the past few decades (Qian et al., 2006; Wang et al., 2009; Yang et al., 2018). On the other hand, aerosols also increase the fraction of diffuse radiation due to the strong scattering effect (Mahowald et al., 2011). The decreasing total incoming radiation and the increasing diffuse radiation have opposite effects on photosynthesis, and the combined outcome could differ among various terrestrial ecosystems. Crops are generally light-demanding species and croplands could be more sensitive to radiation regime changes than other ecosystems. Therefore, the combined effects of aerosols on photosynthesis and crop yields are crucial for understanding how agricultural ecosystems respond to global change as well as assessing food security under different pollution scenarios.

Modeling studies had reported both negative and positive effects of rising aerosol loading on crop yields. Chameides et al. (1999) and Xiong et al. (2012) have suggested that because of the reduction in total radiation, rising aerosol loading has resulted in a 5%–30% reduction in crop yields in China, which is similar to the assessed reduction caused by climate change and ozone pollution (Tian et al., 2016). However, other studies (Cohan et al., 2002; Liu et al., 2016) also suggested that the negative impacts of aerosols on crop yields may be overestimated due to the ignorance of the presence of aerosols that could promote the penetration of solar radiation into the canopy and enhance the photosynthesis of shaded leaves (Farquhar & Roderick, 2003; Kanniah et al., 2012; Mercado et al., 2009; Roderick et al., 2001). Process-based model studies that considered the diffuse fertilization effect did find that aerosols promoted crop yields (Greenwald et al., 2006; Schiferl & Heald, 2018).

Several field observations also confirmed the positive effect of aerosols on ecosystem photosynthesis. For example, measurements from eddy covariance towers have found that higher diffuse radiation caused by aerosols enhanced photosynthesis in temperate and tropical forests (Cirino et al., 2014; Gu et al., 2003; Niyogi et al., 2004; Strada et al., 2015). The field observation-based positive effects, however, appeared to be relatively low or not significant in croplands (Bai et al., 2012; Niyogi et al., 2004; Strada et al., 2015). The different responses of croplands from forests may be associated with the crop breeding that tends to select species with upright canopy architectures. Both field observations and model simulations indicated that photosynthesis of ecosystems that have complex canopy structures would be more promoted by increasing diffuse radiation (Alton et al., 2007; Matsui et al., 2008; Wohlfahrt et al., 2008). Therefore, for agricultural ecosystems with simple canopy structures, the negative effect of reduced total radiation under high aerosol loading may partially offset, or even surpass, the benefit from the increased diffuse radiation.

Meanwhile, the aerosols' effects could be confounded with the meteorological effects on crop photosynthesis due to the interaction between the aerosols and meteorological drivers. For example, the decreased solar radiation under elevated aerosol may cause a cooler ground temperature and higher air humidity (Ramanathan et al., 2001; Steiner et al., 2013; Yang et al., 2016). The higher relative humidity (RH) may further promote the hygroscopic growth of aerosol particles, and increase the aerosol scattering and backscattering coefficients (Zang et al., 2019; Zhang et al., 2015). In other words, in addition to the changes in radiation regimes, these changes in temperature and humidity under elevated aerosol could greatly mediate stomatal conductance and thus exert impacts on photosynthesis as well (Steiner & Chameides, 2005; Wang et al., 2018; Wohlfahrt et al., 2008). However, the relative contributions of these concurrent changes in meteorological conditions on photosynthesis remain unquantified. To more accurately predict the response of crop photosynthesis to aerosols, we need to take into account the impacts of both the radiation and these co-varying meteorological conditions.

The North China Plain (NCP) is one of the most air-polluted regions in China and also the major agricultural zone in China. Grain production in this area accounts for about 30% of China (National Bureau of Statistics of China, 2019). Daily mean AOD during the growing season fluctuates periodically over a wide range of 0.10–1.78 (Wang et al., 2018), providing a unique opportunity for studying the response of crop photosynthesis to elevated aerosol concentrations at a large spatial scale. In this study, we first conducted site-level field experiments in the northern NCP. By combining with the mechanistic model, we explored how crop photosynthesis responds to elevated aerosols at leaf and canopy scales. We then expanded the experiments to the larger NCP area by using multiple sets of satellite data. From the experiments spanning over multiple scales, we tested the hypotheses that:

1. Intermediate aerosols would promote canopy photosynthesis mainly due to the enhancement of photosynthesis in shade leaves; high aerosols should suppress canopy photosynthesis through decreasing photosynthesis of both sun and shade leaves
2. Aerosol-induced radiation changes and the co-varying meteorological conditions should have different impacts on sun and shade leaf photosynthesis. Because the two leaf types have distinct physiological characters and grow in different microenvironments, their photosynthesis should have varied sensitivities to changes in light, air temperature, and humidity
3. The aerosol effects on crop photosynthesis would exhibit a similar pattern in spatial variation, that is, the areas with intermediate aerosol concentrations have higher photosynthesis than those with either low or high aerosols

2. Materials and Methods

2.1. Site Description

The field experiment was conducted at the Beijing Forest Experimental Station of the Institute of Botany, Chinese Academy of Sciences (39.98°N, 116.20°E), Beijing, located in the north of NCP. The NCP area has a typical temperate continental monsoon climate with hot humid summer and cold dry winter. The mean annual air temperature is 10°–15°C. The mean annual precipitation is 500–900 mm, and most rainfall events occur from June to August. The main cropping systems are winter wheat-soybean or winter wheat-maize double cropping.

The experimental plots were established in late March 2012. Six 1 × 1 m^2 plots were arranged as 2 columns × 3 rows. The buffer zone between plots was one-half meter. Two soybean (*Glycine max*) cultivars with different agronomic characteristics were selected: Zhonghuang 13 (ZH13) is a dwarf cultivar with an average height of 75 cm, while Zhonghuang 16 (ZH16) is higher, with an average height of 97 cm. The seeds of each soybean variety were randomly planted in three plots in late May of 2012 and 2013. Sixteen soybean seedlings with a 4 × 4 arrangement were retained in each plot.

2.2. Field Measurements of Aerosol Loading and Meteorological Drivers

Ground AOD at 500 nm was measured with a MICROTOPS II handheld sunphotometer (Solar Light Inc.) every half hour between 9:00 and 11:00 a.m. during cloud-free days in 2012–2014. Total and diffuse solar radiation were recorded automatically every half hour by SPN1 sunshine pyranometer (Delta-T Devices Ltd) in 2014. The total incident photosynthetically active radiation (PAR) received by sun and shade leaves was measured using a Li-Cor Quantum Sensor (LI-COR Inc.) simultaneously when we conducted the measurements of leaf photosynthesis in 2012 and 2013. Furthermore, air temperature (T_{air}) and air RH at 1 h intervals were obtained from a nearby weather station (Haidian Park, 39.98°N, 116.29°E) in 2012 and 2013.

2.3. Field Measurements of Leaf-Scale Photosynthesis

During the growing seasons (i.e., June to September) of 2012 and 2013, we monitored photosynthesis of soybean sun, and shade leaves in situ between 9:00 and 11:00 a.m. during cloud-free days. The measurements were conducted using a portable gas exchange system LI-6400 (LI-COR Inc.) with a standard leaf chamber. In each soybean plot, we selected three healthy and mature sun leaves that were located in the third or fourth branch from the top of the soybean canopy, and three healthy and fully shaded leaves that were located at the bottom of the soybean canopy. For each leaf, the photosynthesis rate, hereinafter defined as photosynthesis capacity (P_c), was measured under 1,500 μmol m^{-2} s^{-1} Photosynthetic Photon Flux Density, supplied by a red-blue LED light source and in a 30°C chamber temperature. Sun or shade leaf P_c of this plot were estimated by averaged values of the three replicate measurements.

2.4. Modeling of Real-Time Photosynthesis at Leaf and Canopy Scales

We matched field observations of AOD, PAR, T_{air}, and RH described in Section 2.2 with P_c measurements by the measuring time. Based on these field observations, we simulated the real-time leaf photosynthesis using Farquhar, von Caemmerer, and Berry (FvCB) approach coupled with the Ball-Berry stomatal conductance model (Ball et al., 1987; Farquhar et al., 1980; Method S1). Briefly, we first inversed the maximum carboxylation rate (V_{cmax25}) for each measurement of sun and shade leaf using the field measured P_c as the model input. We then simulated the actual real-time leaf photosynthesis rates (A_n) with the in situ measured environmental data (PAR, air temperature, RH) and the inversed V_{cmax25} through the coupled FvCB-Ball-Berry model. Leaf light use efficiency (LUE) was estimated by dividing simulated A_n by PAR. The leaf model was validated by measured A-ci curves (Figure S1). Finally, we estimated the photosynthesis for the entire canopy (An_{canopy}) by combining photosynthesis of the sun and shade leaves simulated from the sun/shade model (Dai et al., 2004; De Pury & Farquhar, 1997). Details of the modeling simulations were described in the supporting information.

2.5. Satellite Data Preparation for Regional-Scale Study in the North China Plain

The regional-scale study was based on satellite-retrieved data from 2007 to 2018. MODIS AOD was used to estimate the aerosol conditions in the NCP. Solar-induced chlorophyll fluorescence (SIF), which has been suggested to be a direct proxy of ecosystem photosynthesis, especially for heavily managed agricultural ecosystems, was used to approximate ecosystem photosynthetic activity of the croplands (Guanter et al., 2014; Miao et al., 2018, 2020; Sun et al., 2017). We used the new long-term GOME-2A SIF data set with SIFTER v2 algorithm, which corrected the instrument degradation of GOME-2A satellite (Kooreman et al., ; van Schaik et al., 2020). SIF retrievals at daily scale were prescreened to exclude data with cloud fraction ≥ 0.4 (van Schaik et al., 2020). Satellite-retrieved data sets of daily diffuse PAR (difPAR), air temperature (T_{air}), and RH, and yearly land cover were also collected for the NCP area (Method S3). Satellite observations of daily AOD, difPAR, T_{air}, and RH were filtered by including grids with valid SIF data.

All the data sets were first resampled to 0.5° spatial resolution using the nearest neighbor method. To minimize the effects of vegetation phenology and climate seasonality, we only used data sets of the peak growing seasons (July and August) in this study. We then overlapped all the data sets with the land cover products to identify the grids that were consistently croplands (crop fraction > 60%) throughout the entire study period. Only the cropland grids were involved in the following analysis.

2.6. Data Analysis

We first conducted univariate regressions between aerosols (AOD), environmental factors (light, air temperature, and RH), and crop response (leaf and canopy photosynthesis) at the site level. To fit the relationship pattern, we compared linear, quadratic, exponential, and logarithmic models and ranked the model with the Akaike information criterion (AIC) score (Burnham & Anderson, 1998; Table S1). The lower AIC, the better fit. We only included the measurements from middle July to late August to minimize the effects of seasonality. Still, several variables exhibited seasonal trends (Figures S2–S4). To remove the potential impacts of seasonality, we added dummy variables for each week-of-year and each year for further analysis. We then calculated clustered standard errors by year and week for each regression coefficient of the selected model to test their significances (Cameron et al., 2011). The model with significant regression coefficients and a lower AIC score was the final choice (Table S2).

We further conducted model experiments using the coupled FvCB-Ball-Berry model to estimate the total effect of elevated aerosols and the partial effects of co-varying changes in PAR, T_{air}, RH, and V_{cmax25} on the sun and shade leaf photosynthesis under elevated aerosol conditions. Briefly, we first separated the observations into three subsets: low, medium, and high aerosol conditions according to the turning point of the quadratic relationship between AOD and canopy photosynthesis. We then simulated leaf photosynthesis under nine scenarios: SL with model driven by PAR, T_{air}, RH, and V_{cmax25} under low aerosol condition; SM1 to SM4 and SH1 to SH4 for medium and high aerosol conditions, respectively, with model driven by different combinations of co-varying drivers under medium or high aerosols: PAR (SM1, SH1), PAR + T_{air} (SM2, SH2), PAR + T_{air} + RH (SM3, SH3) and PAR + T_{air} + RH + V_{cmax25} (SM4, SH4; Table S3). The total and partial effects of elevated aerosols were estimated from the differences between nine scenarios (Table S4).

In the regional-scale study, to minimize the degradation effect of GOME-2A satellite while covering sufficient AOD ranges, we binned the data by 4-year interval (2007–2010, 2011–2014, and 2015–2018), and performed the same analyses for the three periods separately. For each time period, we first assessed how the spatial autocorrelation could affect the relationship between AOD and SIF (Table S1). We established various spatially contiguous group by resolutions of 1°, 2°, 3°, 4°, and 5°, respectively. We then assessed whether the relationship between AOD and SIF persisted when clustering the standard errors by these spatially contiguous groups (Table S5). Different from the site-level study that investigated from the seasonal-variation perspective, we divided the regional data into two levels of aerosol conditions, and then conducted multiple linear regression (SIF ~ $Crop_f$ + AOD + difPAR + T_{air} + RH) to partition the effect of crop fraction ($Crop_f$), aerosol loading and environmental factors on cropland SIF for each aerosol condition from the spatial-variation perspective. The relative contributions of each predictor in the model were quantified using the Lindeman-Merenda-Gold relative importance method with R package "*relaimpo*". The 95% confidence interval for the relative importance of each predictor was estimated using 1,000 bootstrap replicates.

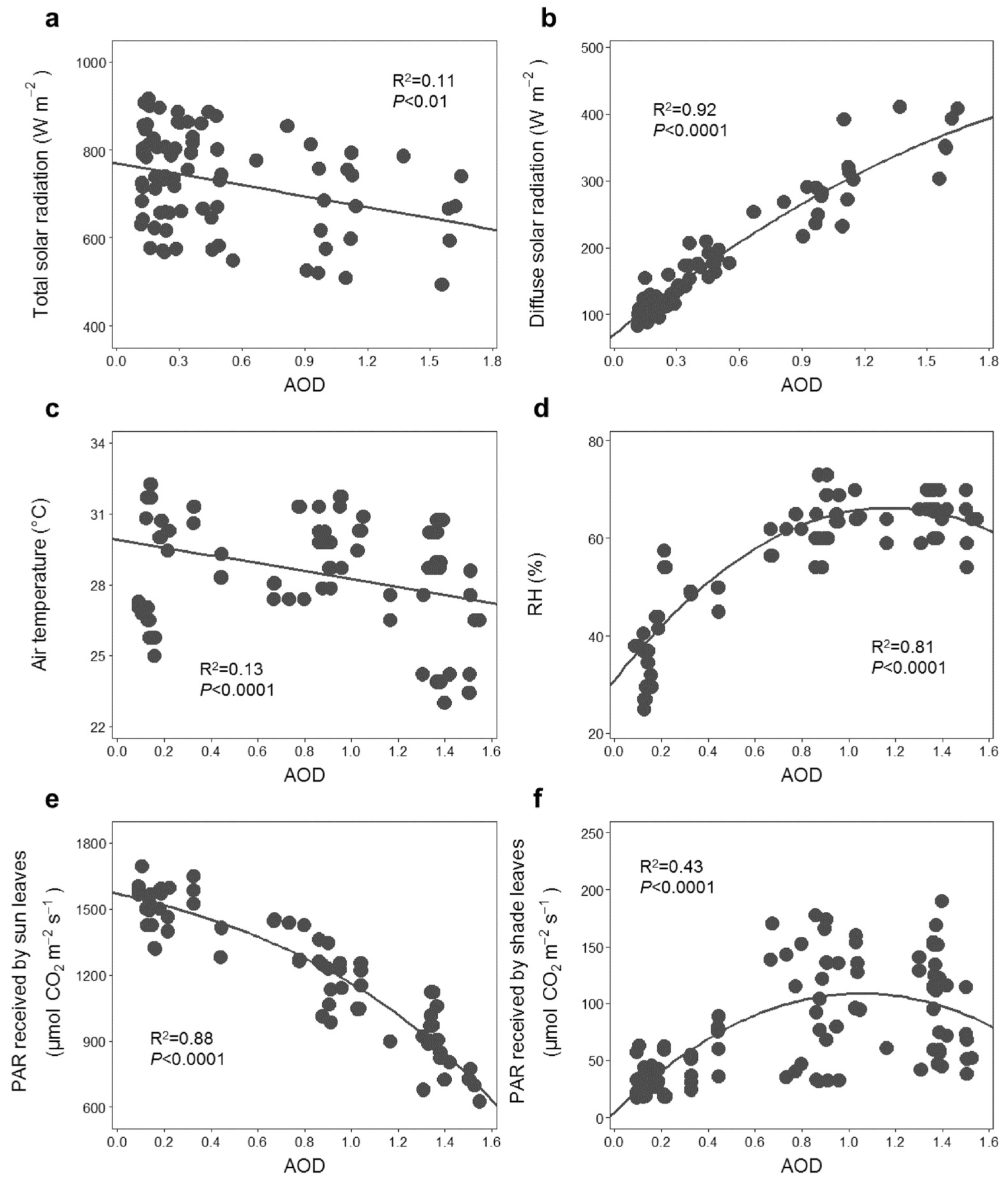

Figure 1. Changes in total solar radiation (a), diffuse solar radiation (b), air temperature (c), relative humidity (RH) (d), photosynthetically active radiation (PAR) received by sun leaves (e), and shade leaves (f) as aerosol optical depth (AOD) increased.

The analysis flowcharts for the site experiment and regional-scale study were shown in Figures S5–S6. The analyses were performed using R (version 3.5.3), and $P < 0.05$ was considered statistically significant.

3. Results

3.1. The Responses of Leaf and Canopy Photosynthesis to Aerosol Loading

The microclimate for the soybean canopy was altered under different aerosol loadings. Total solar radiation decreased, while diffuse solar radiation increased significantly with increasing AOD (Figures 1a and 1b). Air temperature decreased significantly with AOD (Figure 1c). Relative humidity (RH) first increased with AOD, peaked at AOD = 1.17, and then started to decline (Figure 1d). PAR received by sun leaves decreased with increasing AOD (Figure 1e). PAR received by shade leaves first increased with AOD, reached a peak at AOD = 1.05, and then declined (Figure 1f). The inversed V_{cmax25} of sun and shade leaves were not correlated

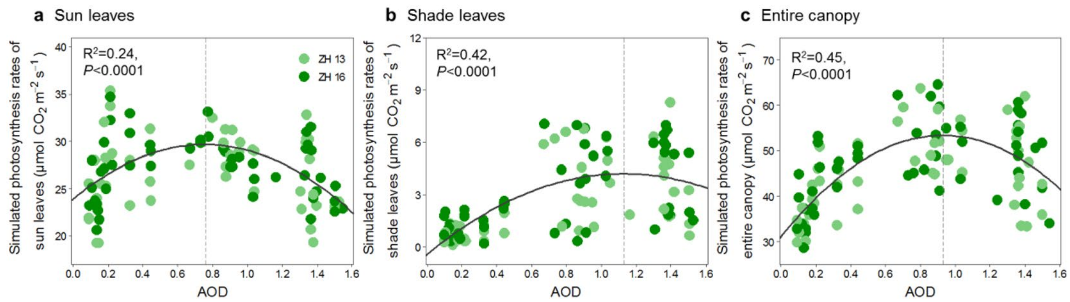

Figure 2. Changes in simulated photosynthesis rates of soybean sun leaves (a), shade leaves (b), and the entire canopy (c) under different aerosol optical depths (AODs). ZH13 and ZH16 represent two soybean varieties. The m^2 in the unit of photosynthesis rates refers to leaf area for sun and shade leaves (a), (b), and ground area for canopy (c). The dashed gray lines represent the turning point of the quadratic response.

with AOD (Figure S7). The statistical significance of the regression coefficients in the above analyses was based on standard errors clustered by year and week (Table S2).

Simulated photosynthesis rates of sun leaves, shade leaves, and the entire canopy showed quadratic responses to aerosol loading (Figure 2), and the patterns were similar between the two soybean varieties (Figure S8). These quadratic relationships remained significant after considering the seasonality impacts by adjusting the standard errors for clustering by year and week (Table S2). The photosynthesis rate reached the maximum at the AOD of 0.76 for sun leaves, 1.13 for shade leaves, and 0.93 for the entire canopy, and then declined (Figure 2). In contrast, the LUE of both sun and shade leaves increased significantly with increasing AOD (Figure S9).

The modeling experiments demonstrated that the increased photosynthesis of sun leaves under medium aerosol condition mainly resulted from the positive effect of increased RH (Figure 3a). By contrast, the decreased photosynthesis of sun leaves under high aerosol condition was caused primarily by the negative effect of PAR reduction despite the remained positive effect of high RH (Figure 3a). The photosynthesis of shade leaves, different from sun leaves, increased under both medium and high aerosol conditions, which was suggested resulting from the positive effects of increased inner-canopy PAR (Figure 3b). T_{air} and V_{cmax25} had minor effects on sun and shade leaf photosynthesis under both medium and high aerosol conditions (Figure 3).

3.2. Aerosol Loading and Its Impacts on Cropland SIF in the North China Plain

MODIS AOD, SIF, diffuse PAR (difPAR), $T_{air,}$ and RH during the peak growing season (July to August) exhibited high spatial heterogeneity across the cropland area in the NCP (Figure 4; Figures S10–S12). The mean MODIS AOD decreased from 1.2 to 0.7 in the cropland area from 2007 to 2018 (Figure S13). The average difPAR ranged from 113 to 189 W m^{-2} (Figure S12).

Similar to the site-level photosynthesis, SIF of croplands during 2007–2010 showed a quadratic response to MODIS AOD spatially, peaking at AOD = 1.04 (Figure 4c). The quadratic relationship remained significant after considering the impacts of spatial correlation (Table S5). Results of multiple linear regression showed that, crop fraction ($Crop_f$), AOD, difPAR, T_{air}, and RH jointly explained 83.04% of spatial variations of SIF for the low-AOD regions (AOD < 1.04) and 77.71% for the high-AOD regions (AOD > 1.04; Figure 4d). AOD contributed to 10.03% and 8.34% of the variation in SIF for the low-AOD and high-AOD regions, respectively (Figure 4d). SIF and AOD in the NCP during 2011–2014 and 2015–2018 showed the same overall spatial patterns but with lower values (Figures S10–S11). Similar to 2007–2010, SIF of croplands showed a quadratic response to MODIS AOD spatially, peaking at AOD = 0.83 and 0.56 during 2011–2014 and 2015–2018, respectively (Figures S10–S11). Furthermore, the background meteorological conditions (difPAR, T_{air}, and RH) were important predictors for SIF spatial variations (Figures 4 and S10–S11).

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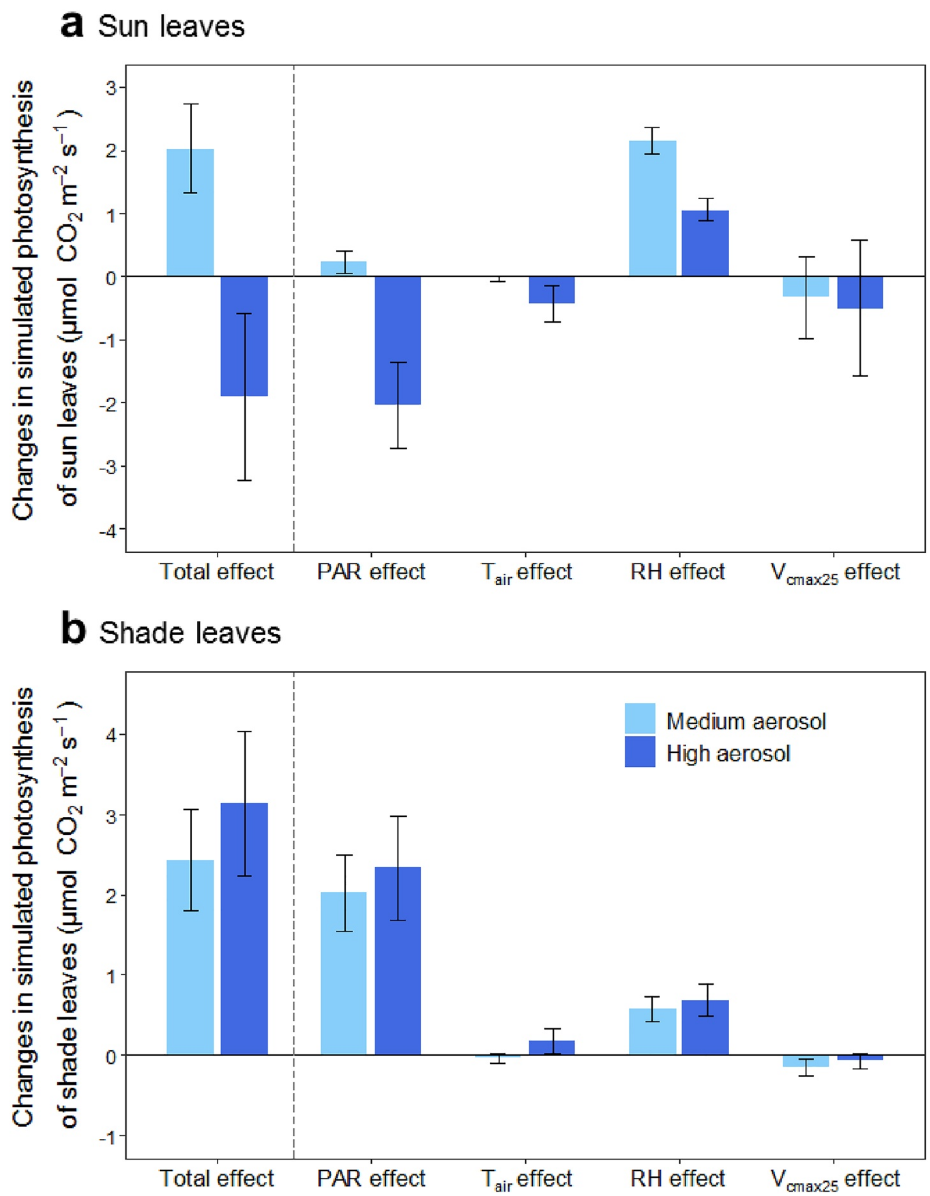

Figure 3. The total and partial effects of elevated aerosols on sun (a) and shade (b) leaf photosynthesis of soybean. Three levels of aerosol conditions were defined according to the quadratic response between canopy photosynthesis and AOD: low aerosol, AOD < 0.32 (for SL); medium aerosol, 0.32 < AOD < 1.36 (for SM1–SM4); high aerosol, AOD > 1.36 (for SH1–SH4). The cutoff points of 0.32 and 1.36 were calculated from the medians of the two subsets (AOD < 0.93 and AOD > 0.93), respectively. The effects of elevated aerosols are estimated by the difference between simulated photosynthesis under medium (0.32 < AOD < 1.36) or high aerosols (AOD > 1.36) and that under low aerosol (AOD < 0.32) with different combinations of varying drivers including photosynthetically active radiation (PAR), air temperature (T_{air}), relative humidity (RH), and the maximum carboxylation rate at 25°C (V_{cmax25}; Tables S3 and S4). The error bars show 95% confidence intervals.

4. Discussion

Our study showed that aerosol loading had a quadratic impact on the photosynthesis of soybean leaves (Figure 2). The modeling experiments indicated that the responsive mechanisms differed between sun and shade leaves. For sun leaves that are usually light-saturated, their photosynthesis rate was not significantly affected by the decreased PAR under medium aerosol condition but was promoted by the accompanying high RH, which was probably associated with the increasing stomatal conductance (Figures 1, 3, and S14; Moriana et al., 2002). By contrast, under high aerosol condition, the negative effects of decreased PAR

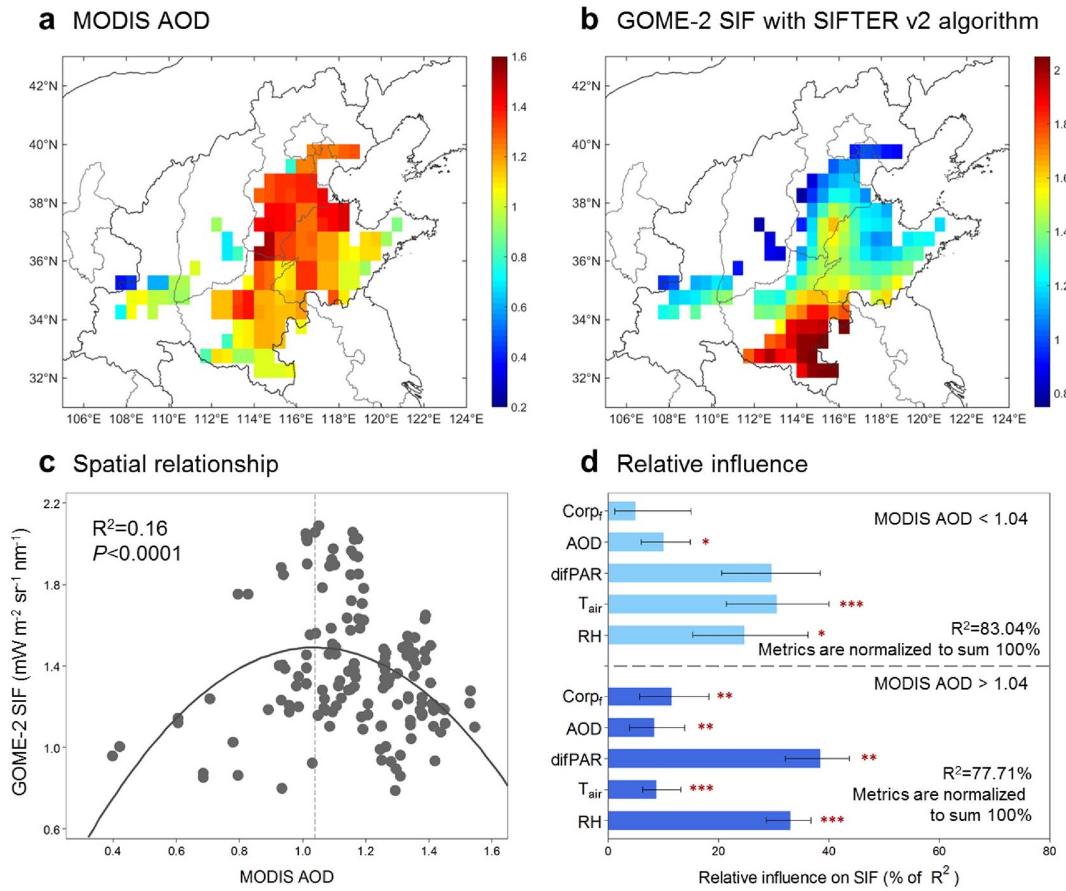

Figure 4. Spatial patterns of aerosols and the impacts on sun-induced chlorophyll fluorescence (SIF) of cropland in the North China Plain during 2007–2010. The spatial distributions of the MODIS AOD (a); the spatial distributions of the GOME-2 SIF with SIFTER v2 algorithm (mW m^{-2} sr^{-1} nm^{-1}) (b); The spatial relationship between MODIS AOD and the GOME-2 SIF (c); the relative importance metrics of aerosol (AOD) and climate factors (difPAR, T_{air}, and RH) as predictors of GOME-2 SIF (d). For (a) and (b), the value of each 0.5° × 0.5° grid cell is the average of the 2007–2010 growing season (i.e., July and August). The dashed gray line in (c) represents the turning point of the quadratic response. The red stars in (d) indicate the coefficient of the factor in MLR is significant. * indicates $0.01 < P < 0.05$. ** indicates $0.001 < P < 0.01$. *** indicates $P < 0.001$. The error bars show 95% confidence intervals. $Crop_f$: crop fraction. AOD: aerosol optical depth. difPAR: diffuse photosynthetically active radiation. T_{air}: air temperature. RH: relative humidity.

exceeded the positive effects of concurrent high RH, and the photosynthesis of sun leaves declined (Figures 1, 3, and S14). For shade leaves that are often light-limited, their photosynthesis was enhanced due to the increased diffuse radiation induced by aerosols (Figures 1, 3, and S14; Kanniah et al., 2012). As aerosol loading continued to increase and substantially reduced the total radiation, the light intensity of the inner canopy decreased, and the photosynthesis of shade leaves began to decrease as well (Figures 1, 3, and S14). Changes in air temperature and leaf V_{cmax25} had relatively small impacts on photosynthesis of both sun and shade leaves (Figure 3).

However, it should be noted that the estimation of the relative contribution of different factors relied on the physiological responses assumed in the FvCB-Ball-Berry model even though our photosynthesis simulations were driven by field measured environmental factors, which is one of the uncertainties in the current study. In addition, V_{cmax25} was calibrated empirically with constant PAR and T_{air} under different aerosol conditions. The assumption of constant light and temperature should have limited impacts on V_{cmax25} as leaf nitrogen concentration and leaf age are usually the major drivers of V_{cmax25} variation on weekly to monthly time scale (Ali et al., 2015; Suzuki et al., 2001; Walker et al., 2014; Wilson et al., 2001). Still, the accuracy of V_{cmax25} inversion and thus its contribution to leaf photosynthesis responses need to be validated.

The nonlinear responses of sun and shade leaves together led to a quadratic relationship between canopy photosynthesis and aerosol loading. The single-peaked response of soybean differed from the linearly positive response of aspen observed at the same experimental site (Wang et al., 2018). This difference could be associated with the species-specific sensitivity to light, air temperature, and RH. High aerosol levels causing decreased solar radiation might have greater negative effects on high-light demand agricultural ecosystems than forests. In addition, plants' sensitivity to aerosols could be also influenced by canopy structures and leaf optical properties. While crop breeding tends to select varieties with more vertical leaves in the top layer and more horizontal leaves in the bottom layer (Long et al., 2006), this canopy structure may reduce the benefits of diffuse radiation effects under elevated aerosol conditions (Proctor et al., 2018). On the contrary, forests have a more complex canopy architecture and could gain more benefit from the aerosol diffuse fertilization effects (Alton et al., 2007; Matsui et al., 2008; Niyogi et al., 2004). These findings highlight the importance of incorporating ecosystem-specific sensitivities into models when assessing large-scale aerosol impacts. Furthermore, as aerosol's impact on canopy photosynthesis is mainly associated with changes in radiation distribution within the canopy, improving the accuracy of canopy microclimate simulation, especially the radiative transfer modeling, would help reduce the uncertainty when upscaling leaf-level photosynthesis to canopy level (Roger et al., 2017; Wu et al., 2017).

Consistent with the effects of aerosols at the leaf and canopy scales, we also found a quadratic relationship between aerosol loading and SIF (a proxy of photosynthesis) of cropland in the NCP. Furthermore, we found that the optimal AOD level decreased from 1.04 in 2007–2010 to 0.56 in 2015–2018. Similarly, Yue and Unger (2017) also found that simulated ecosystem net primary productivity in this region showed a quadratic response to AOD loadings but with a lower optimal AOD level of 0.5. The variation in the optimal AOD levels may be related to the co-varying meteorological conditions. The RH in the NCP decreased by 0.6/year from 2007 to 2018 (Figure S15). The concurrent high RH under elevated aerosol tends to promote the stomatal conductance and thus enhance photosynthesis (Figure 3; Cirino et al., 2014; Wang et al., 2018), which may explain the optimal AOD level decreased during our study periods.

Further analysis revealed that AOD had significant effects on SIF spatial variation for both low- and high-AOD regions in spite of the relatively low contribution. However, we only assessed the effect of aerosols on crop photosynthesis. More studies are still needed to evaluate whether the stimulation of photosynthesis will lead to a proportional increase in crop production. Socioeconomic factors, such as industrialization and farming activities, could alter both pollution and agricultural productivity across the study region, which might confound the spatial relationship between SIF and AOD. In addition, the current algorithm employed for GOME-2 SIF retrieval cannot completely eliminate the impacts of aerosol on the transmission of SIF through the atmosphere (van Schaik et al., 2020). Moreover, the overpass time of GOME-2 is drifting toward the early morning, when plants are less stressed and inclined solar angles increase the diffuse radiation fraction. These might also bring potential uncertainties to the estimation of the relationship between AOD and SIF.

In summary, our analysis with ground and satellite observations consistently found that there was a quadratic response of crop photosynthesis to aerosol loading. The current aerosol levels in most areas of NCP already exceeded the optimal aerosol condition. Stringent air pollution controls implemented since the 2000s have resulted in a significant decline in aerosol loading in this region (Figure S13; An et al., 2019; Li et al., 2019), which might promote crop productivity in the long term. In addition, aerosols' impacts on crop photosynthesis and subsequently crop yields also depend on its interaction with meteorological factors, such as RH and cloud cover (Chen & Zhuang, 2014; Cirino et al., 2014; Yue & Unger, 2017). Particularly, our leaf-level simulations revealed that RH contributed to a substantial portion of the total effect of AOD on photosynthesis. As RH plays a vital role in enhancing AOD level (Zang et al., 2019) and at the same time promoting leaf photosynthesis rate (Franks & Farquhar, 1999; Moriana et al., 2002), more field and model efforts are needed to evaluate how RH modifies the impact of AOD on crop photosynthesis under future climate scenarios.

Data Availability Statement

The data that support the findings of the study are available in the Figshare persistent repository (https://figshare.com/articles/Database_for_Intermediate_Aerosol_Loading_Enhances_Photosynthetic_Activity_of_Croplands_/12442865).

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