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The fertilization effect of global dimming on crop yields is not attributed to an improved light interception

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Abstract

Global dimming, a decadal decrease in incident global radiation, is often accompanied with an increase in the diffuse radiation fraction, and, therefore, the impact of global dimming on crop production is hard to predict. A popular approach to quantify this impact is the statistical analysis of historical climate and crop data, or use of dynamic crop simulation modelling approach. Here, we show that statistical analysis of historical data did not provide plausible values for the effect of diffuse radiation versus direct radiation on rice or wheat yield. In contrast, our field experimental study of 3 years demonstrated a fertilization effect of increased diffuse radiation fraction, which partly offset yield losses caused by decreased global radiation, in both crops. The fertilization effect was not attributed to any improved canopy light interception but mainly to the increased radiation use efficiency (RUE). The increased RUE was explained not only by the saturating shape of photosynthetic light response curves but also by plant acclimation to dimming that gradually increased leaf nitrogen concentration. Crop harvest index slightly decreased under dimming, thereby discounting the fertilization effect on crop yields. These results challenge existing modelling paradigms, which assume that the fertilization effect on crop yields is mainly attributed to an improved light interception. Further studies on the physiological mechanism of plant acclimation are required to better quantify the global dimming impact on agroecosystem productivity under future climate change.

KEYWORDS
acclimation, diffuse radiation, fertilization effect, global dimming, radiation use efficiency, rice, wheat, yield

1 | INTRODUCTION

Global dimming has been a worldwide phenomenon over the past few decades (Wild et al., 2005), and this decadal decrease in incident global radiation was dominated by the increase in atmospheric aerosols (Folini & Wild, 2011; Wang, Dickinson, Wild, & Liang, 2012). While some regions such as the United States and Europe have observed a reversal from decrease to increase in incident global radiation since the late 1980s (Wild, 2012), China has continuously experienced dimming due to the increasing aerosol pollution associated with the rapid urbanization and economic development (Tollenaar, Fridgen, Tyagi, Stackhouse, & Kumudini, 2017).

Global dimming reduces incident global radiation but increases the fraction of diffuse radiation (Li, Wagner, Peng, Yang, & Mauzerall, 2017; Wild, 2009). Changes both in the amount of incident global radiation and in the fraction of diffuse radiation can have a fundamental consequence on ecosystem productivity (Mercado et al., 2009; Proctor, Hsiang, Burney, Burke, & Schlenker, 2018; Williams, Rastetter, Van der Pol, & Shaver, 2014). Quantifying the impact of global dimming on gross primary productivity (GPP) or net primary productivity (NPP) has received an increasing attention for either natural ecosystems (Alton, North, & Los, 2007; Gu et al., 2003; Rap et al., 2018; Urban et al., 2007) or agroecosystems (Greenwald et al., 2006; Schiferl & Heald, 2018; Xin, Gong, Suyker, & Si, 2016).

Various approaches have been used to quantify the impact of global dimming. A popular approach is to quantify agroecosystem productivity, crop yields, in response to incident global radiation and diffuse radiation fraction changes by using historical climate and crop yield data (Lobell & Asner, 2003; Proctor et al., 2018; Tollenaar et al., 2017; Yang et al., 2013; Zhang, Li, Yue, & Yang, 2017), but these results were usually beset by the collinearity among climate variables (especially among solar radiation, temperature, precipitation; Lobell & Burke, 2009; Lobell, Schlenker, & Costa-Roberts, 2011). Other studies on GPP or NPP of natural ecosystems (Cirino, Souza, Adams, & Artaxo, 2014; Rap et al., 2015; Urban et al., 2012) and agroecosystems (Niyogi et al., 2004; Xin et al., 2016) in response to diffuse radiation are based on flux measurements using eddy covariance techniques. A common belief is that compared with direct radiation, diffuse radiation is more uniformly distributed over all the leaves in a canopy, thereby, resulting in an improved whole-canopy light distribution and interception (Kanniah, Beringer, North, & Hutley, 2013; Li & Yang, 2015; Wang et al., 2018). Such a spatial distribution in a canopy allows the incoming radiation being more efficiently utilized by plants (Farquhar & Roderick, 2003; Williams et al., 2014). Furthermore, an increased fraction of diffuse radiation avoids the photosynthetic saturation of top leaves in a canopy, thereby, leading to another common belief that global dimming enhances radiation use efficiency (RUE; Gu et al., 2002; Yue & Unger, 2017). Therefore, the increased fraction of diffuse radiation has a fertilization effect on GPP and NPP of natural (Mercado et al., 2009; Rap et al., 2018) and agricultural (Proctor et al., 2018; Schiferl & Heald, 2018) ecosystems. This fertilization effect can, either partly (Alton, North, et al., 2007; Kobayashi, Matsunaga, & Hoyano, 2005; Proctor et al., 2018) or fully (Gu et al., 2003; Mercado et al., 2009; Moreira et al., 2017; Rap et al., 2018), offset the effect of the decreased amount of global radiation.

Land-surface (Alton, Ellis, Los, & North, 2007; Kobayashi et al., 2005; Matsui, Beltrán-Przekurat, Niyogi, Pielke, & Coughenour, 2008; Strada & Unger, 2016) and crop (Cohan, Xu, Greenwald, Bergin, & Chameides, 2002; Greenwald et al., 2006; Schiferl & Heald, 2018) simulation models have been developed to assess the impact of global dimming, based on the above common beliefs. These models may assume that there is an enhanced light interception under global dimming. Some models, using nonlinear equations for describing photosynthetic light response curves (Alton, Ellis, et al., 2007; Cohan et al., 2002; Strada & Unger, 2016), indirectly recognizing the positive effect of global dimming on RUE, whereas others directly modify RUE as an empirical function of the diffuse radiation fraction (Greenwald et al., 2006; Kobayashi et al., 2005; Matsui et al., 2008; Schiferl & Heald, 2018). Whether light interception is really improved and whether the nonlinearity in photosynthetic light response curves accounts for an increased RUE under global dimming have not been examined critically. Also, empirical models have limited abilities in extrapolating the relationships to different conditions. To assess the impacts of global dimming under various environmental conditions, a mechanistic understanding of diffuse radiation fertilization effect is urgently needed. To this end, it is probably important to experimentally manipulate the dimming intensity, rather than merely investigating the consequences of dimming created by 'natural' processes. This is particularly relevant for agroecosystems, where crop productivity or yield, depends not only on NPP but also on harvest index (HI, the dry-weight ratio of grains to all above-ground organs; Long, Zhu, Naidu, & Ort, 2006; Tollenaar et al., 2017) and HI is probably also affected by dimming (Gao et al., 2017; Li, Jiang, Wollenweber, Dai, & Cao, 2010).

In this study, we first followed many previous studies in collecting historical climate data as well as crop data from four stations in the middle and lower reaches of the Yangtze River, one of the main wheat and rice production areas in China (Li, Liu, Wang, Yang, & Zhang, 2012). We analysed whether the impacts of global dimming on wheat and rice yields can be quantified by using these statistical data. We also conducted a comprehensive field study on the two crops, in which incident global radiation and fraction of diffuse radiation were experimentally manipulated. For the first time by analysing both historical and experimental data, we aim to quantify to what extent such combined effort could add to our understanding for better prediction of the impact of global dimming on crop productivity.

2 | MATERIALS AND METHODS

2.1 | Historical crop and climate data

We collected historical crop data (including phenology and yields) and daily climate data for the middle and lower reaches of the Yangtze River from observations at the agro-meteorological experimental stations of China Meteorological Administration. The climate data included daily mean, minimum and maximum air temperature, precipitation, incident global (the sum of direct and diffuse radiation) and diffuse radiation. Since there were only few stations with solar radiation observations, we selected four stations located in the region that had good records of more than 10 year crop data as well as solar radiation data either from the station or a nearby station where climate conditions are similar. Crops were well irrigated and fertilized at these stations; therefore, no drought or nutrient stress was involved. All stations had temperature, precipitation and incident global radiation data from 1961 to 2016, but no data were available for diffuse radiation and crop yields during some of these years (Table S1).

To avoid the confounding effects of extreme climate events (extreme cold, heat and heavy precipitation) in estimating the impacts of global dimming on crop yields, we excluded the data from the extreme years. Remaining data were combined to a panel regression model to estimate the impacts of global dimming on crop yields (see Supporting Information for details).

2.2 | Field experiments

2.2.1 | Crop cultivation

Field experiments with winter wheat (*Triticum aestivum* L. cv Ningmai 13) and rice (*Oryza sativa* L. cv Nangeng 46) were conducted during 2013–2016 at the experimental station of Jiangsu Academy of Agricultural Sciences (32°03′N, 118°87′E), Nanjing, China. The basic topsoil before the experiment in 2013 had organic carbon content of 18.8 g/kg, total nitrogen content of 1.5 g/kg and 95.3 mg/kg of available nitrogen. For wheat, seeds were sown, respectively, on 9 November 2013, 6 November 2014 and 12 November 2015 in a row space of 25 cm with a density of 250 plants/m^2. Note that the entire growing season of wheat covers 2 years, with the seeds sown in winter of the first year and the main active growing period occuring in the second year. Hence, we used the second year to mark the experimental year for wheat hereafter. For rice, seeds were sown, respectively, on 9 May 2013, 11 May 2014, 10 May 2015, and three-leaf stage seedlings (31 days after sowing) were manually transplanted at a density of three seedlings per hill at a spacing of 19 cm × 21 cm. The nutrient content and water were well managed according to local standard cultivation practices for each crop.

2.2.2 | Experimental setup

Three types of ordinary white polyethylene films (0.04, 0.06 and 0.12 mm in thickness) were used as cover materials in shading treatments. Our group in Nanjing previously demonstrated that these films showed little change in the spectrum and its spatial distribution of visible light (Wang, Li, et al., 2015), in line with the reports of Espi, Salmeron, Fontecha, García, and Real (2006) and Oyaert, Volckaert, and Debergh (1999). In each crop growing season, there were two shading treatments (T1 and T2, plots covered with films) and a control (CK, plots without cover). Plot with an area of 4 × 5 m^2

TABLE 1 Layers and thickness of polyethylene films used in wheat and rice field experiments, and radiation conditions from the onset of shading treatment to harvest under different treatments

Crop	Year	Treatment	Layers of films	Thickness of films (mm)	R_{GR} (MJ/m^2)	Relative decrease in R_{GR} (%)	F_{diff} (%)	Increment in F_{diff} (%)
Wheat	2014	CK			1,240		53.7	
		T1	1	0.12	1,094	11.8	62.6	8.9
		T2	3	0.12	935	24.6	74.1	20.4
	2015	CK			1,138		54.5	
		T1	1	0.12	989	13.1	61.9	7.4
		T2	3	0.12	873	23.3	71.9	17.4
	2016	CK			1,080		56.2	
		T1	1	0.12	910	15.8	66.2	10.0
		T2	3	0.12	805	25.5	75.6	19.4
Rice	2013	CK			1,652		41.1	
		T1	3	0.04[a]	1,372	17.0	51.4	10.3
		T2	3	0.06[a]	1,271	23.1	57.2	16.1
	2014	CK			1,539		59.8	
		T1	1	0.12	1,310	14.9	70.8	11.0
		T2	3	0.12	1,079	29.9	81.6	21.8
	2015	CK			1,593		53.6	
		T1	1	0.12	1,397	12.3	61.5	7.9
		T2	3	0.12	1,233	22.6	70.9	17.3

Abbreviations: R_{GR}, the incident global radiation; F_{diff}, the fraction of diffuse radiation, that is, ratio of incident diffuse radiation to the incident global radiation. CK treatments were under natural conditions.

[a]The two types of films (0.04 and 0.06 mm in thickness) used in the 2013 rice experiment were later found to be easily broken. So for all subsequent experiments, we used a film of 0.12 mm in thickness. Our group previously demonstrated that the three films showed little change in the spectrum and its spatial distribution of visible light (see text).

and three replicas for each treatment, was arranged in a randomized block design. In each plot, the area that remained continuously under shading for >4 hr/day during the main growing seasons was ca. 4 m^2 (Wang, Li, et al., 2015), due to hourly and daily variations of solar zenith. All measurements were using plants within this 4 m^2 area. The layers and thickness of films used in each treatment are described in Table 1. Films were installed at a height of 2 m above the ground to ensure a good ventilation condition and avoid the confounding influences of other climatic factors except solar radiation on crops.

Shading treatments were imposed from the mid-March till harvest for wheat and from ca. 30 days after transplantation till harvest for rice, to ensure a uniformity of crop establishment before treatment. Since shading can lead to a very small increase in the fraction of diffuse radiation on overcast days when the diffuse fraction is already very high (Cohan et al., 2002; Greenwald et al., 2006), we only covered the treatment plots on sunny days (date of shading is shown in Figure S1; the number of days under shading during the experimental periods is shown in Table 2) from 8:00 a.m. to 17:00 p.m. The two shading treatments (Table 1) mimicked well the decreased global radiation and increased diffuse radiation fraction under moderate and severe air pollution, respectively, in terms of air quality index (see Wang, Li, et al., 2015). The treatments were also comparable with the changes shown in our historical data for Nanjing in that the global radiation decreased by ca. 22%, whereas the diffuse radiation fraction increased by ca. 13%.

2.2.3 | Weather data collection

In each experiment, incident global (short-wave) radiation and diffuse radiation at a height of 1.5 m above the ground in CK and shading treatments were monitored automatically by a SPN1 Sunshine Pyranometer (Delta-T Devices Ltd.) and the 30 min average data were recorded by a GP1 Data Logger (Delta-T Devices Ltd.). Air temperature at a height of 1.5 m above the ground in CK and shading treatments was monitored automatically and the 30 min average data were saved using a datalogger (CR1000; Campbell Scientific Inc.). Each temperature sensor was covered by a naturally ventilated radiation shield to minimize the influence of shortwave radiation and longwave radiative exchange on air temperature reading. Daily incident global radiations are shown in Figure S1, while air temperatures are shown in Figure S2, for different treatments during the experimental period.

2.2.4 | Crop sampling and measurements

We measured canopy light distribution and leaf area index (LAI) during tillering (only for rice), stem-elongation, booting, heading,

TABLE 2 Growth duration and the number of days under shading in wheat and rice field experiments

					Shading[a] to heading		Heading to maturity	
Crop	Year	Treatment	Days from sowing to maturity	Days from sowing to shading[a]	Days from shading[a] to heading	Days of shading	Days from heading to maturity	Days of shading
Wheat	2014	CK	190	126	23		41	
		T1	192	126	24	17	42	20
		T2	194	126	26	19	42	20
	2015	CK	196	135	26		35	
		T1	198	135	28	20	35	23
		T2	199	135	28	20	36	24
	2016	CK	188	125	25		38	
		T1	191	125	27	20	39	22
		T2	193	125	28	21	40	22
Rice	2013	CK	157	66	53		38	
		T1	159	66	55	32	38	20
		T2	160	66	55	32	39	20
	2014	CK	160	57	65		38	
		T1	162	57	66	30	39	28
		T2	164	57	68	30	39	29
	2015	CK	163	66	60		37	
		T1	165	66	61	31	38	22
		T2	166	66	62	31	38	23

Note: CK treatments were under natural conditions. T1 and T2 treatments were covered by different layers and thickness of polyethylene films (see Table 1).
[a]Shading is the onset of shading treatment.

and grain-filling stages. Canopy light distribution, that is, the photosynthetically active radiation (PAR) at the top (PAR_{top}) and bottom (PAR_{bottom}) of the crop canopy, was measured using an AccuPAR LP-80 (Decagon Devices). Plants (other than roots) were sampled at the above stages and also at harvest, with 10 plants per plot for wheat and one hill per plot for rice. Samples were separated into leaves, stems and ears. Leaf samples were measured for green leaf area using a LI-3100C leaf area meter (Li-Cor Inc.). Considering that most of leaves have turned to yellow, we only sampled but not measured green leaf area at harvest. Data for green leaf area were converted to LAI, which is defined as the total green leaf area to ground area ratio.

Ears sampled at harvest were hand-threshed and partially-filled and unfilled grains were separated from well-filled grains by hand to count the number of the total grains and filled grains per ear. After completing the above measurements, all plant parts were oven-dried at 105°C for 30 min and then at 80°C to constant weight. Thousand grain mass was measured from filled grains, and HI was calculated as the oven-dried weight ratio of grains to all above-ground parts. Nitrogen concentration in each plant organ was then measured by using the Kjeldahl digestion method, and nitrogen content was calculated by multiplying nitrogen concentration with biomass. Finally, plants of 2 m^2 ground areas that were unaffected by previous samplings were harvested to count the number of ears per unit area, and to measure grain yields (containing 14% moisture content). We did not measure dry weight of 2 m^2 above-ground plant parts due to the limited capacity of the ovens. The final above-ground biomass at harvest was determined from HI and the dry-mass of grains.

Response curves of net photosynthesis rate (A_n) to incident light (I_{inc}) levels, the $A_n - I_{inc}$ curves, were measured on the first and third leaves counted from top downwards, using the LI-Cor 6400XT system (Li-Cor Inc.) at stem-elongation, booting, heading and grain-filling stages. Leaves were placed in the leaf cuvette at I_{inc} of 2,000 μmol m^{-2} s^{-1}. Ten minutes later, I_{inc} in the cuvette was controlled in a decreasing series of 1,500, 1,000, 800, 500, 200, 100, 50, 20 and 0 μmol m^{-2} s^{-1}, while keeping the ambient CO_2 concentration at about 380 μmol/mol.

2.3 | Analysis of experimental data

2.3.1 | Identifying any diffuse radiation fertilization effect on crop

During our field experiments, daily mean and maximum air temperature changed little between control and shading treatments, and the seasonal average temperatures for natural conditions in different experimental years also had no significant changes (Figure S2). Differences in time when the maximum air temperature occurred among treatments were also negligible (data not shown). Therefore, crop yields in our experiments were only influenced by the changes in solar radiation. Since diffuse radiation is possibly more efficiently utilized by crops compared with direct radiation, we used the following equation to describe crop yield or above-ground biomass:

$$Y = a \cdot R_{dir} + b \cdot R_{diff}, \tag{1}$$

where Y is the crop yield or above-ground biomass; R_{dir} and R_{diff} are the cumulative direct radiation and diffuse radiation from the onset of shading treatment to harvest respectively. Equation (1) assumes a zero intercept to agree with the expectation that crop cannot grow in the absence of radiation.

To identify whether there is diffuse radiation fertilization effect on crop when the fraction of diffuse radiation increased under global dimming, we rewrite Equation (1) to:

$$Y = a \cdot R_{GR} + (b - a) \cdot R_{GR} \cdot F_{diff}, \tag{2}$$

where R_{GR} is the cumulative global radiation and F_{diff} is the fraction of diffuse radiation from the onset of shading treatment to harvest [i.e., $R_{diff} = F_{diff} \cdot R_{GR}$ and $R_{dir} = (1 - F_{diff}) \cdot R_{GR}$]. A higher estimate of coefficient b than coefficient a would indicate that the increased fraction of diffuse radiation has a fertilization effect. Differentiating Equation (2) gives:

$$\begin{aligned} dY &= \frac{\partial Y}{\partial R_{GR}} \cdot dR_{GR} + \frac{\partial Y}{\partial F_{diff}} \cdot dF_{diff} \\ &= [a + (b - a) \cdot F_{diff}] \cdot dR_{GR} + (b - a) \cdot R_{GR} \cdot dF_{diff}. \end{aligned} \tag{3}$$

Equation (3) allows an examination of the extent to which the increased fraction of diffuse radiation can offset the crop yield or biomass loss caused by the decreased incident global radiation in shading treatments, relative to the CK treatment. By setting $dY = 0$, we came up with an equation to quantitatively calculate the required increase of F_{diff} in order to completely offset the yield or biomass loss caused by the decreased R_{GR}, relative to the CK treatment:

$$dF_{diff} = \frac{[a + (b - a) \cdot F_{diff}] \cdot dR_{GR}}{(a - b) \cdot R_{GR}}. \tag{4}$$

2.3.2 | Assessing the parameters that contributed to the fertilization effect

Crop yields are determined by R_{GR}, the fraction of the incident radiation intercepted by the canopy (FIR), RUE and HI such that: $\text{Yield} = \text{HI} \cdot \text{RUE} \cdot \text{FIR} \cdot R_{GR}$. We examined the importance of the four individual components in this equation in determining the variation of yield, in order to understand how diffuse radiation fertilization effect came into existence.

Crop season-long overall RUE was estimated as the slope of the linear relationship between the accumulated above-ground biomass versus the cumulative daily intercepted global radiation, by forcing the regressions through the origin. Daily intercepted global radiation was calculated as the daily incident global radiation multiplied by the daily FIR_i. FIR_i was calculated by:

$$FIR_i = 1 - \exp(-k_i \cdot LAI_i), \tag{5}$$

where k_i and LAI_i were the daily canopy light extinction coefficient and LAI, and they were obtained by polynomial interpolation of measured values at the sampling dates. The value of light extinction coefficient (k) at a sampling date was calculated by:

$$k=\frac{-\ln\left(\frac{PAR_{bottom}}{PAR_{top}}\right)}{LAI}. \quad (6)$$

2.3.3 | Estimation of leaf photosynthetic parameters

From the $A_n - I_{inc}$ curves, we first estimated initial light-use efficiency (ε) and day respiration rate (R_d) as the slope and intercept, respectively, of the linear regression of A_n against I_{inc} under limiting light ($I_{inc} \le 200\ \mu mol\ m^{-2}\ s^{-1}$). Using the estimated ε and R_d as input, light-saturated gross photosynthetic rate ($A_{g,max}$) was then estimated from fitting the following equation (Goudriaan & Laar, 1994) to the entire light response curve of leaf photosynthesis:

$$A_n = A_{g,max}\cdot\left[1-\exp\left(-\frac{\varepsilon\cdot I_{inc}}{A_{g,max}}\right)\right]-R_d. \quad (7)$$

2.4 | Statistical analysis

Data were analysed with SPSS statistical software (version 23.0; SPSS Inc). Relationships among temperature, solar radiation (incident global radiation, direct and diffuse radiation) and yield or biomass were evaluated using regression analyses. Differences between treatment means in field experiments were determined by using ANOVA based on the least significant difference test at the .05 or .01 probability level.

3 | RESULTS

3.1 | Effects of global dimming on crop yields assessed using historical data

Using historical data in the middle and lower reaches of the Yangtze River, during 1961–2016 (Table S1), the linear regression of yield against temperature and incident global radiation (R_{GR}) has shown that neither the effect of R_{GR} nor the effect of temperature was found significant and the effect of temperature was highly variable (Table S2), probably because these effects confounded each other. When separating R_{GR} into direct (R_{dir}) and diffuse (R_{diff}) radiation, yields were positively correlated with R_{dir}, but largely negatively with R_{diff} (Table S2). These results were largely in contrast to theoretical expectations. It was impossible to come to a definite conclusion about the relative effects of R_{dir} and R_{diff} on crop yields from the collected historical data of the four sites (see Supporting Information for details).

3.2 | Effects of field shading on growth duration, yield and above-ground biomass

In our field experiments, using the polyethylene film significantly reduced the incident global radiation levels in T1 and T2 treatments compared with CK treatment ($p < .01$, based on data of measured PAR_{top} at sampling dates; Table 1). The shading treatments slightly prolonged crop growth durations, by 2–5 days in wheat and 2–4 days in rice (Table 2). This prolongation occurred more during preheading phase than during postheading phase (Table 2).

Both yields and above-ground biomass in wheat and rice were significantly reduced by shading treatments (Figure 1). Similar relative effects of shading on yields and biomass per day were found (Figure S3), despite the prolongation of growth duration. The percentages of reduction in yields and above-ground biomass (Figure 1) were lower than the percentages of reduction in R_{GR} (Table 1), except T1 treatment in 2013 rice growing season. Moreover, shading reduced the number of ears per unit area, the number of total grains and filled grains per ear, and thousand grain mass (Table 3). Among these yield components, the number of filled grains per ear had the biggest percentage of reduction (Table 3). Compared with wheat, rice had a more reduction in filled grains but a less reduction in the ear number (Table 3).

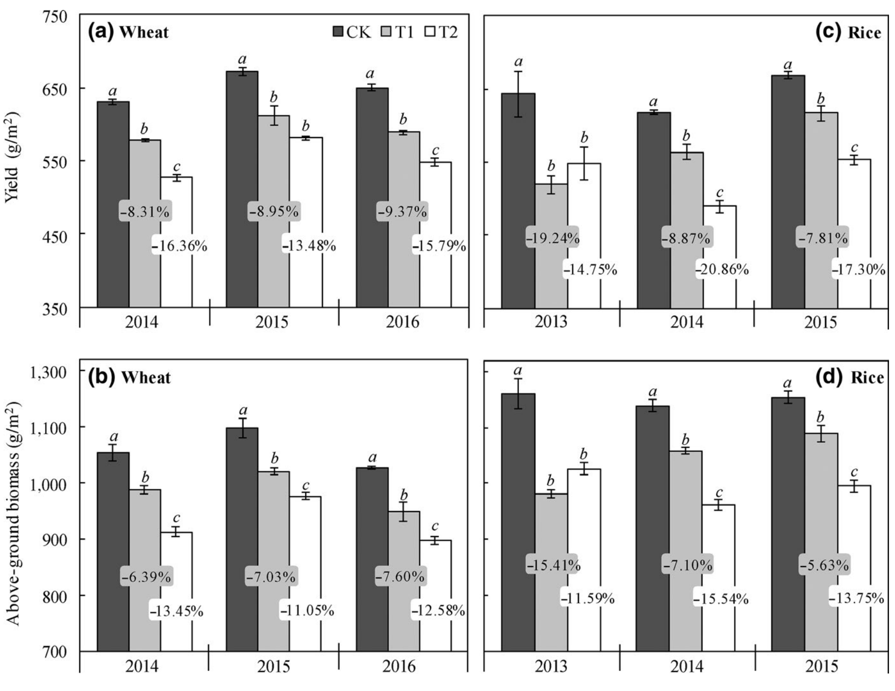

FIGURE 1 Yield (a, c) and above-ground biomass (b, d) of three treatments, and the changes of shading treatments (T1 and T2) relative to the CK treatment (the numbers inside columns), of wheat (a, b) and rice (c, d) field experiments in 3 years. CK treatments were under natural conditions. T1 and T2 treatments were covered by different layers and thickness of polyethylene films (see Table 1). Error bars represent standard errors of the means (n = 3). Different italic letters (*a*, *b*, *c*) on the column bars indicate significant differences (p < .05) among treatments within a year

TABLE 3 Yield components, and the reduction of T1 and T2 treatments relative to the CK treatment for wheat and rice in the field experiments

Crop	Year	Treatment	Ear number		Total grains		Filled grains		Thousand grain mass	
			Ear number (m^{-2})	Reduction (%)	Total grains (ear^{-1})	Reduction (%)	Filled grains (ear^{-1})	Reduction (%)	Thousand grain mass (g)	Reduction (%)
Wheat	2014	CK	434 ± 5.0a				48 ± 0.4a		41.8 ± 0.1a	
		T1	417 ± 13.4ab	3.81			43 ± 0.5b	9.93	40.1 ± 0.4b	4.08
		T2	395 ± 7.1b	8.87			41 ± 0.2c	15.63	38.7 ± 0.8c	7.38
	2015	CK	464 ± 2.7a		53 ± 0.3a		49 ± 0.5a		42.3 ± 0.7a	
		T1	439 ± 6.0b	5.47	51 ± 0.6b	4.45	46 ± 0.8b	6.57	41.4 ± 0.5a	2.25
		T2	418 ± 3.4c	9.96	49 ± 0.8c	7.53	44 ± 0.9c	10.47	38.5 ± 0.9b	8.96
	2016	CK	449 ± 5.4a		50 ± 0.1a		45 ± 0.4a		40.8 ± 0.5a	
		T1	437 ± 3.5b	2.71	49 ± 0.2b	3.44	43 ± 0.7ab	4.13	39.8 ± 1.0a	2.36
		T2	420 ± 3.3c	6.42	48 ± 0.6b	4.76	42 ± 0.6b	6.57	38.7 ± 0.6a	5.04
Rice	2013	CK	273 ± 2.8a		143 ± 3.5a		133 ± 3.7a		24.2 ± 0.1a	
		T1	270 ± 2.6ab	1.12	111 ± 3.3b	22.03	101 ± 3.1b	23.66	23.5 ± 0.1b	2.95
		T2	261 ± 0.5b	4.50	114 ± 2.9b	20.05	105 ± 2.3b	21.08	22.3 ± 0.3c	8.13
	2014	CK	267 ± 1.9a		140 ± 2.0a		132 ± 2.6a		23.7 ± 0.1a	
		T1	263 ± 1.5a	1.20	133 ± 0.4b	4.59	123 ± 0.6b	6.78	23.6 ± 0.2a	0.76
		T2	261 ± 1.5a	1.95	101 ± 0.5c	27.55	92 ± 0.6c	30.54	22.4 ± 0.2b	5.63
	2015	CK	269 ± 1.4a		140 ± 1.2a		130 ± 0.9a		23.3 ± 0.2a	
		T1	262 ± 1.1b	2.86	134 ± 1.6b	4.19	123 ± 1.4b	5.50	22.6 ± 0.2a	3.17
		T2	258 ± 1.5b	4.05	121 ± 1.4c	13.40	109 ± 1.6c	16.02	21.7 ± 0.2b	7.16

Note: Mean ± *SE* (n = 3). CK treatments were under natural conditions. T1 and T2 treatments were covered by different layers and thickness of polyethylene films (see Table 1). Different letters (a, b, c) in a column indicate significant differences ($p < .05$) among treatments within a year for a given crop. We did not count the total grain number of wheat in 2014.

TABLE 4 Coefficients (with probability of significance in parentheses) of Equation (1), estimated from 3 year field experimental data

Coefficient (unit)	Wheat		Rice	
	Yield	Biomass	Yield	Biomass
a (g/MJ)	0.34 (1.41×10^{-4})	0.48 (4.42×10^{-5})	0.31 (2.58×10^{-13})	0.51 (9.19×10^{-16})
b (g/MJ)	0.74 (1.70×10^{-14})	1.27 (2.08×10^{-17})	0.49 (3.45×10^{-21})	0.94 (1.14×10^{-25})
R^2	0.994	0.996	0.998	0.999
Data points	27	27	27	27

Note: Equation (1) was the linear regression of yield (or above-ground biomass at harvest) against the cumulative direct radiation (R_{dir}) and diffuse radiation (R_{diff}), that is, $Y = a \cdot R_{dir} + b \cdot R_{diff}$.

3.3 | Diffuse radiation fertilization effect

Through regression analysis using Equation (1), we found that wheat and rice yields and above-ground biomass were significantly positively correlated with R_{dir} and R_{diff} (Table 4). The correlations of yields (or above-ground biomass) with R_{diff} were more significant than with R_{dir}, and the difference between R_{dir} and R_{diff} effects is greater in wheat than in rice (Table 4). In addition, the correlations of above-ground biomass with R_{diff} in each growth subphase were also more significant than with R_{dir} for both crops (Table S3). It should be noted that the value of variance inflation factor (VIF = 1.11 for wheat and 1.06 for rice, calculated from the average daily radiation of the growing season) was small, suggesting that there was little collinearity between direct and diffuse radiation in our experiments. These results revealed that the increased fraction of diffuse radiation had a fertilization effect on wheat and rice yields and above-ground biomass. However, the reduced yields and above-ground biomass (Figure 1) in the shading treatments relative to the CK treatment meant that the diffuse radiation fertilization effect did not compensate completely for the losses caused by decreased R_{GR}.

In our experiments, R_{GR} decreased by 11.8%–25.5% in wheat growing seasons, and F_{diff} actually increased by 7.4%–20.4%, relative to the CK treatment (Table 1). The F_{diff} that had to increase in order to completely offset losses, as estimated by Equation (4), was 16.5%–38.8% and 13.6%–32.6% for yield and above-ground biomass respectively (Table 5). For rice, R_{GR} decreased by 12.3%–29.9%, and F_{diff} actually increased by 7.9%–21.8% (Table 1). To completely offset yield and above-ground biomass losses, estimated F_{diff} was required to increase by 28.6%–71.6% and 21.0%–53.1% respectively (Table 5). More increment in estimated F_{diff} was required to completely compensate loss in yield than in above-ground biomass, especially for rice (Table 5), meaning a greater diffuse radiation fertilization effect on above-ground biomass than on the yield.

TABLE 5 The estimated fraction of diffuse radiation (F_{diff}) is required to increase, relative to the CK treatment, in order to offset yield or biomass loss caused by decreased global radiation in field experiments (calculated by Equation 4 using the coefficients given in Table 4)

Crop	Year	Treatment	Estimated F_{diff} needed to increase to offset yield loss (%)	Estimated F_{diff} needed to increase to offset biomass loss (%)
Wheat	2014	T1	16.5	13.6
		T2	34.4	28.4
	2015	T1	18.4	15.2
		T2	32.7	27.0
	2016	T1	22.4	18.6
		T2	38.8	32.6
Rice	2013	T1	37.5	27.0
		T2	50.9	36.6
	2014	T1	35.7	26.4
		T2	71.6	53.1
	2015	T1	28.6	21.0
		T2	54.5	40.5

Note: CK treatments were under natural conditions. T1 and T2 treatments were covered by different layers and thickness of polyethylene films (see Table 1).

3.4 | Dissecting the diffuse radiation fertilization effect

In our experiments, shading treatments hardly altered FIR (Table 6), although they decreased R_{GR} from the onset of shading to grain-filling significantly ($p < .01$, based on data of measured PAR_{top} at sampling dates). This was because FIR is determined by both LAI and *k* (see Equation 5). Relative to the control treatment, LAI under shading treatments increased (Figure 2), but *k* decreased significantly (Figure 3), at each growth stage. Shading decreased HI consistently, and this trend was more significant in rice than in wheat (Table 6). The RUE was enhanced by shading except for the rice RUE of T1 in 2013 (Table 6).

To assess the contributions of the above individual parameters to wheat and rice yields, we regressed yield against R_{GR}, FIR, RUE and HI (Table S4). Both wheat and rice yields were positively correlated with R_{GR}, RUE and HI. Surprisingly there was no significant correlation between yield and FIR. As expected, R_{GR} had the strongest effects on both crops. The increased RUE had significant positive effects, and the HI also had significant effects. These results together indicated that the increases in RUE were the consistent major cause for the fertilization effect of shading, but the decrease in HI (especially for rice) discounted this effect on yield.

TABLE 6 Incident global radiation (R_{GR}), fraction of R_{GR} intercepted (FIR), radiation use efficiency (RUE) from the onset of shading treatment to grain-filling stage and harvest index (HI) in wheat and rice field experiments

Crop	Year	Treatment	R_{GR} (MJ/m^2)	FIR	RUE (g/MJ)	HI
Wheat	2014	CK	585	0.89 ± 0.001a	1.10 ± 0.014a	0.51 ± 0.009a
		T1	520	0.88 ± 0.003a	1.11 ± 0.010a	0.50 ± 0.006a
		T2	441	0.89 ± 0.003a	1.12 ± 0.015a	0.50 ± 0.007a
	2015	CK	590	0.90 ± 0.004a	1.35 ± 0.003c	0.53 ± 0.008a
		T1	521	0.89 ± 0.004a	1.36 ± 0.003b	0.52 ± 0.009a
		T2	454	0.89 ± 0.002a	1.37 ± 0.004a	0.51 ± 0.005a
	2016	CK	550	0.90 ± 0.001a	1.32 ± 0.031b	0.54 ± 0.005a
		T1	471	0.90 ± 0.003a	1.35 ± 0.014ab	0.53 ± 0.010a
		T2	408	0.90 ± 0.002a	1.42 ± 0.038a	0.52 ± 0.007a
Rice	2013	CK	1,213	0.89 ± 0.001a	0.96 ± 0.012b	0.48 ± 0.016a
		T1	1,033	0.90 ± 0.001a	0.95 ± 0.014b	0.46 ± 0.009b
		T2	967	0.88 ± 0.001b	1.06 ± 0.013a	0.46 ± 0.014b
	2014	CK	1,059	0.84 ± 0.001a	1.11 ± 0.008a	0.47 ± 0.005a
		T1	920	0.84 ± 0.004a	1.13 ± 0.015a	0.46 ± 0.005ab
		T2	759	0.84 ± 0.001a	1.13 ± 0.008a	0.44 ± 0.005b
	2015	CK	1,184	0.86 ± 0.003a	0.95 ± 0.003b	0.50 ± 0.004a
		T1	1,057	0.85 ± 0.003a	0.96 ± 0.005ab	0.49 ± 0.004ab
		T2	946	0.85 ± 0.001a	0.97 ± 0.009a	0.48 ± 0.003b

Note: Mean ± *SE* (n = 3). CK treatments were under natural conditions. T1 and T2 treatments were covered by different layers and thickness of polyethylene films (see Table 1). Different letters (a, b, c) in a column indicate significant differences (p < .05) among treatments within a year for a given crop. Radiation was monitored in only one plot (without replica) in CK and T1 treatments, so there is no sign for R_{GR} of significant differences.

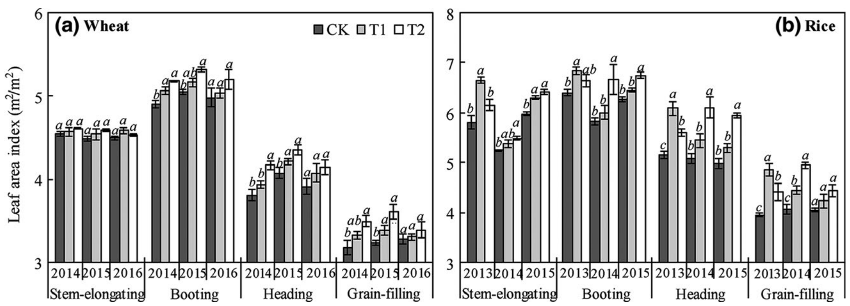

FIGURE 2 Leaf area index (LAI) of wheat (a) and rice (b) at four growth stages (i.e. stem-elongation, booting, heading and grain-filling) in 3 year field experiments. CK treatments were under natural conditions. T1 and T2 treatments were covered by different layers and thickness of polyethylene films (see Table 1). Error bars represent standard errors of the means (n = 3). Different italic letters (*a*, *b*, *c*) on the column bars indicate significant differences (p < .05) among treatments within a year

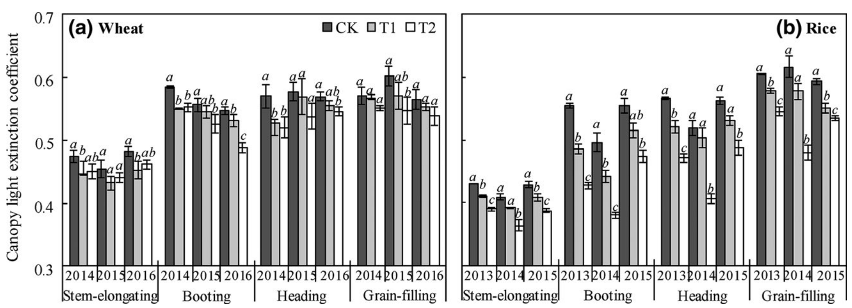

FIGURE 3 Canopy light extinction coefficient (k) of wheat (a) and rice (b) at four growth stages (i.e. stem-elongation, booting, heading and grain-filling) in 3 year field experiments. CK treatments were under natural conditions. T1 and T2 treatments were covered by different layers and thickness of polyethylene films (see Table 1). Error bars represent standard errors of the means (n = 3). Different italic letters (*a*, *b*, *c*) on the column bars indicate significant differences (p < .05) among treatments within a year

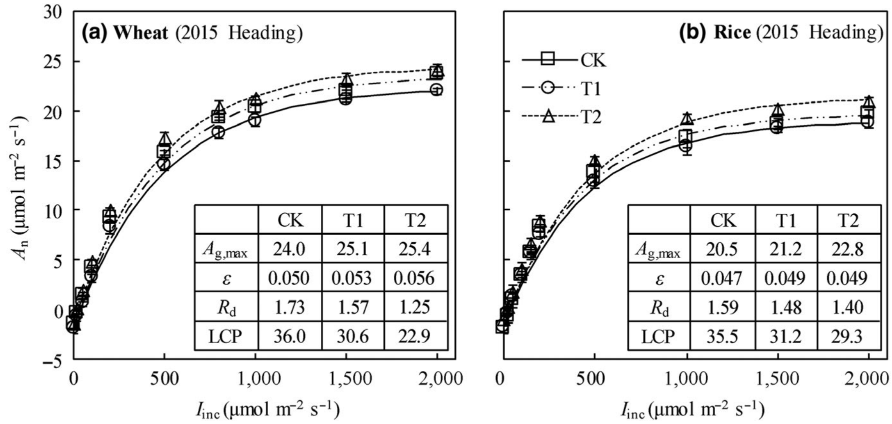

FIGURE 4 Response curves of net photosynthesis rate (A_n) to incident light (I_{inc}) levels, $A_n - I_{inc}$ curves, for wheat (a) and rice (b) at the heading stage in 2015. CK treatments were under natural conditions. T1 and T2 treatments were covered by different layers and thickness of polyethylene films (see Table 1). Error bars represent standard errors of the means (n = 3) for A_n. Curves are drawn from Equation (7) with estimated values of parameters $A_{g,max}$, ε and R_d as given in the panels. ε, initial light-use efficiency (mol/mol); $A_{g,max}$, light-saturated gross photosynthetic rate (μmol m^{-2} s^{-1}); LCP, calculated light compensation point (μmol m^{-2} s^{-1}); R_d, day respiration rate (μmol m^{-2} s^{-1})

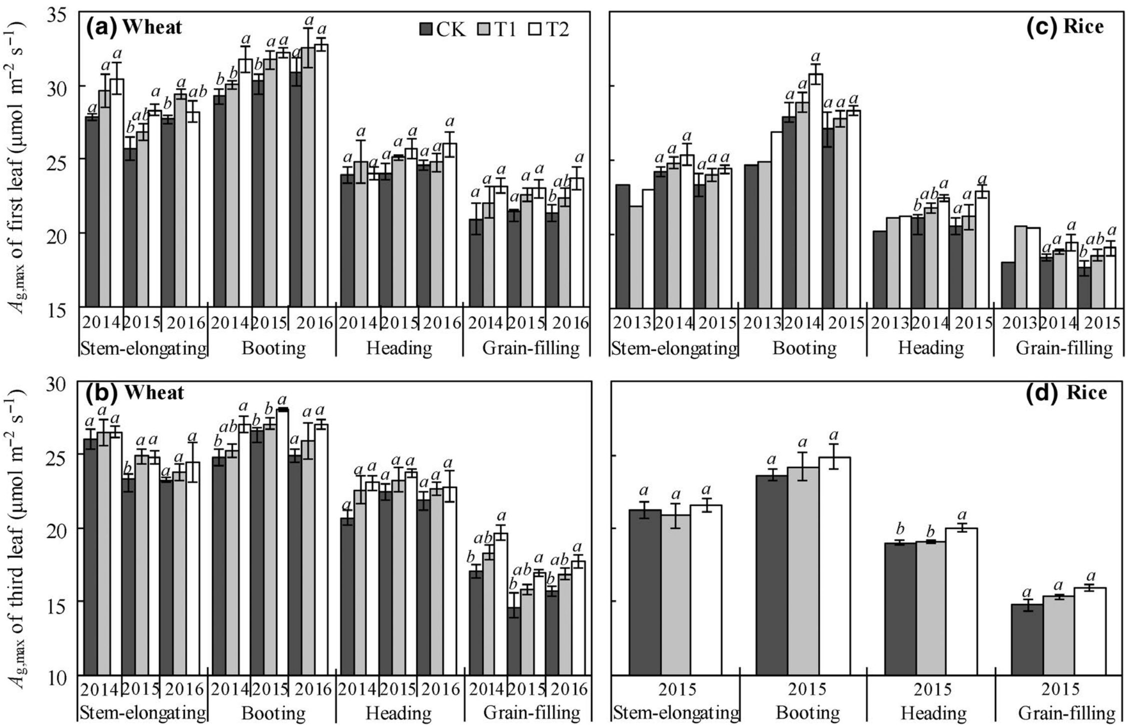

FIGURE 5 Light-saturated gross photosynthetic rate ($A_{g,max}$) of wheat (a, b) and rice (c, d) at four growth stages (i.e. stem-elongation, booting, heading and grain-filling) in 3 year field experiments. CK treatments were under natural conditions. T1 and T2 treatments were covered by different layers and thickness of polyethylene films (see Table 1). Leaf rank was counted from the top respectively. Error bars represent standard errors of the means (n = 3). Different italic letters (*a*, *b*, *c*) on the column bars indicate significant differences ($p < .05$) among treatments within a year. There is no error bar in the 2013 rice growing season as only one light response curve was measured for each treatment

3.5 | The effect of shading on photosynthetic parameters underlying RUE

Crop RUE is primarily determined by season-long canopy photosynthetic efficiency, and the latter efficiency is determined by leaf photosynthesis and the extent to which the distribution of leaf photosynthetic resources (like leaf nitrogen) matches that of light in the canopy (Yin & Struik, 2015). We found that the distribution of leaf nitrogen relative to that of light in the canopy had no consistent changes by shading in our experiments (Results not shown).

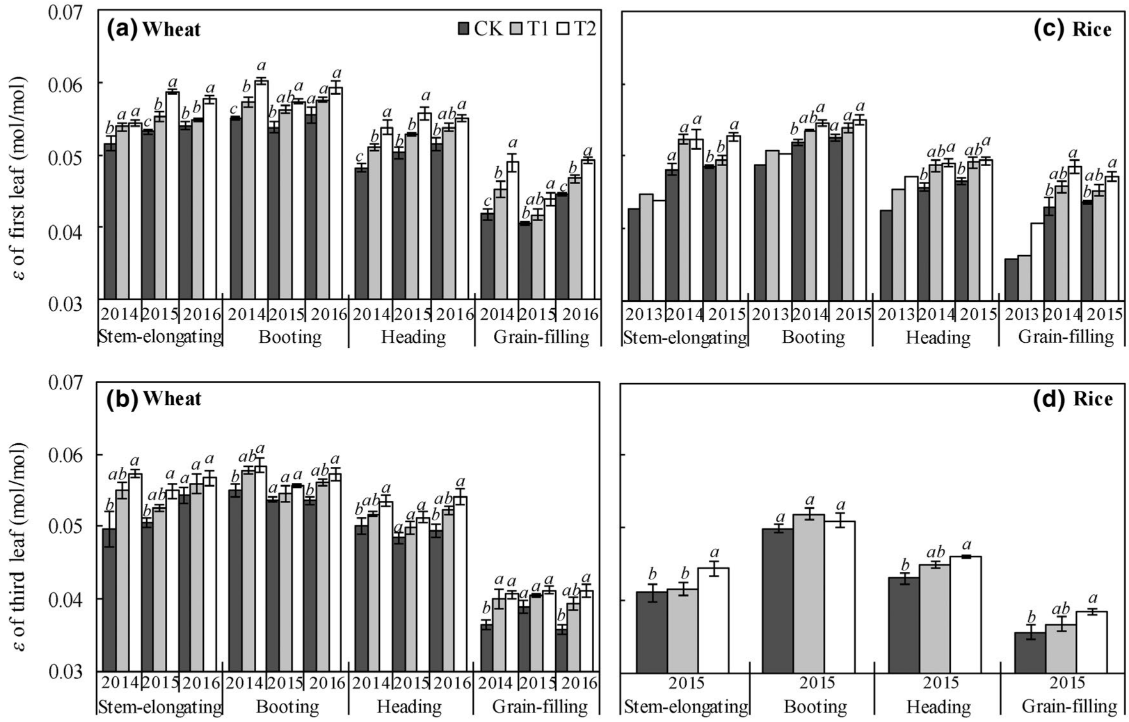

FIGURE 6 Initial light-use efficiency (ε) of wheat (a, b) and rice (c, d) at four growth stages (i.e. stem-elongation, booting, heading and grain-filling) in 3 year field experiments. CK treatments were under natural conditions. T1 and T2 treatments were covered by different layers and thickness of polyethylene films (see Table 1). Leaf rank was counted from top downwards. Error bars represent standard errors of the means (n = 3). Different italic letters (*a*, *b*, *c*) on the column bars indicate significant differences (p < .05) among treatments within a year. There is no error bar in the 2013 rice growing season as only one light response curve was measured for each treatment

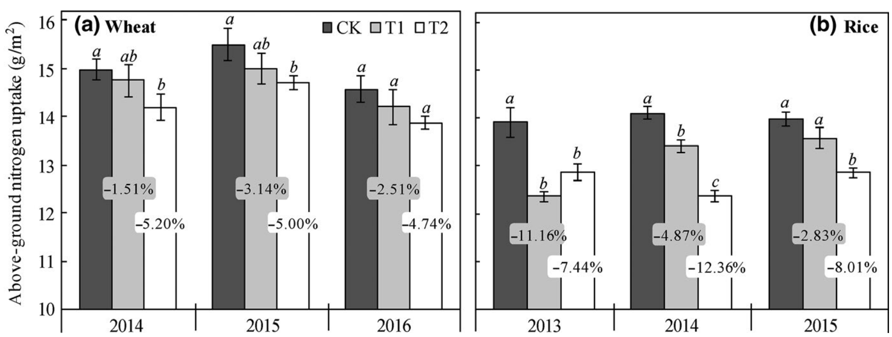

FIGURE 7 Above-ground nitrogen uptake of three treatments, and the changes of shading treatments (T1 and T2) relative to the CK treatment (the numbers inside columns), at wheat (a) and rice (b) harvest. CK treatments were under natural conditions. T1 and T2 treatments were covered by different layers and thickness of polyethylene films (see Table 1). Error bars represent standard errors of the means (n = 3). Different italic letters (*a*, *b*, *c*) on the column bars indicate significant differences (p < .05) among treatments within a year

However, $A_n - I_{inc}$ curves (examples shown in Figure 4) showed that, compared with the CK treatment, shading increased A_n. The leaf photosynthetic parameters of Equation (7) estimated from these curves, that is, $A_{g,max}$ (Figure 5) and ε (Figure 6), increased under shading at each growth stage, and the increases in ε were more noticeable than in $A_{g,max}$.

Plant nitrogen uptake (Figure 7) was decreased under shading. We noticed that the reduction in nitrogen uptake was lower than that in above-ground biomass (Figure 1), which lead to a lower carbon: nitrogen ratio in shaded crops. As a result, shading increased leaf nitrogen concentration relative to the control treatment (Figure 8). We found that $A_{g,max}$ and ε were both significantly correlated with leaf nitrogen concentration (Figure 8).

4 | DISCUSSION

4.1 | The reliability of statistical analysis versus experimental analysis

Our study, for the first time, attempted to quantify the global dimming impact on managed ecosystem productivity, crop yields, both by statistical analysis based on historical data and by field experimental

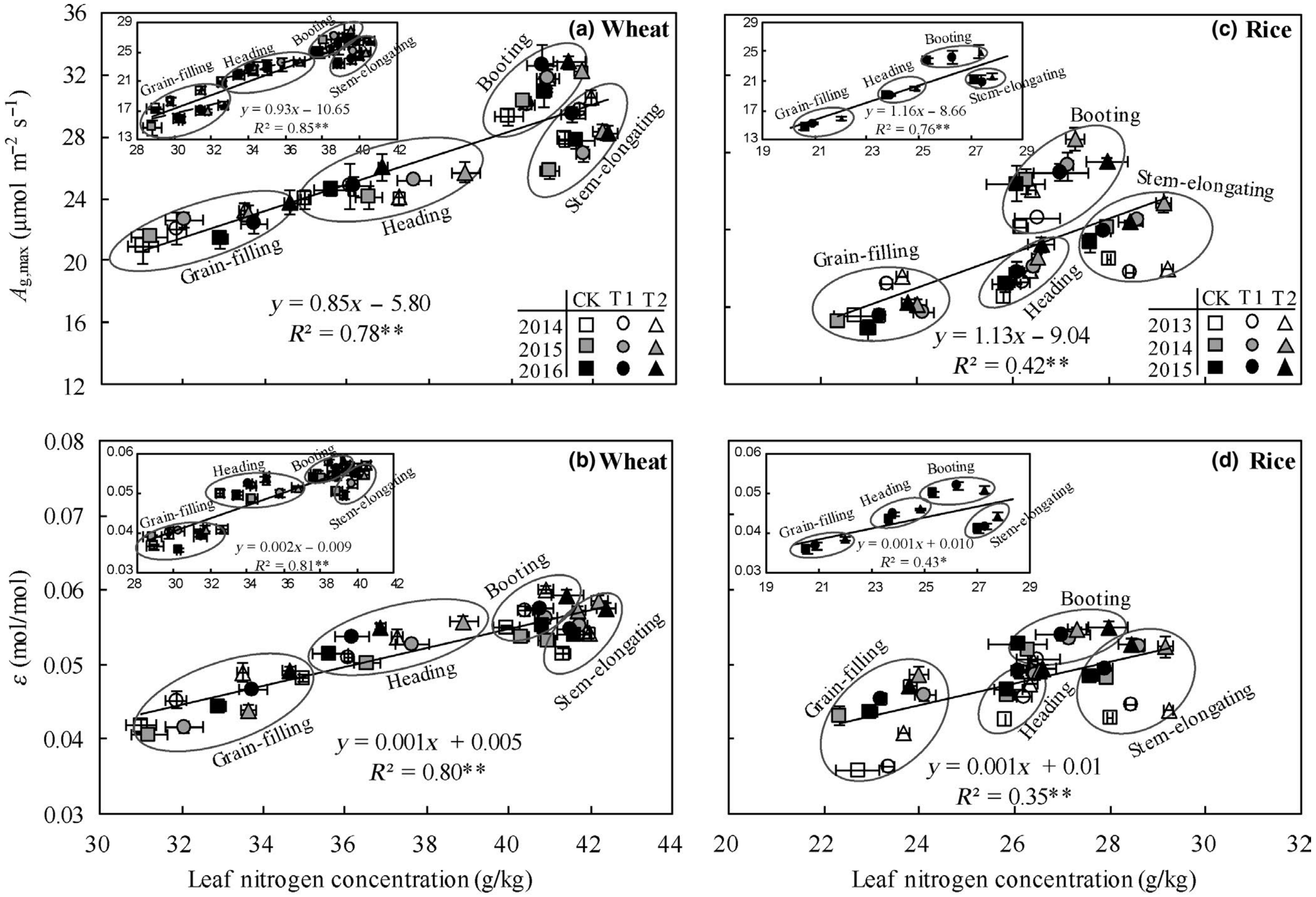

FIGURE 8 Relationships of light-saturated gross photosynthetic rate ($A_{g,max}$) (a, c) and initial light-use efficiency (ε) (b, d) versus leaf nitrogen concentration in wheat (a, b) and rice (c, d) growing seasons. The relationships for the first and third leaves are given in the main-panels and insets respectively. CK treatments were under natural conditions. T1 and T2 treatments were covered by different layers and thickness of polyethylene films (see Table 1). Horizontal error bars represent standard errors of the means (n = 3) for leaf nitrogen concentration. Vertical error bars represent standard errors of the means (n = 3) for $A_{g,max}$ and ε. There is no vertical error bar in the 2013 rice growing season as only one light response curve was measured for each treatment. The correlations marked '*' and '**' were significant at p < .05 and < .01 levels respectively

analysis. Statistical analyses of historical climate and crop data have been one of the main tools for studying the impacts of climate change (including global dimming) on crop yields (Lobell & Burke, 2010; Lobell et al., 2011; Schauberger, Gornott, & Wechsung, 2017; Tao et al., 2013). Our results, however, demonstrated that statistical analyses using historical data only cannot reliably assess the impact of global dimming on crop yields; in fact, it can generate the effect values that are often opposite to theoretical expectations in terms of the relative effects of R_{dir} versus R_{diff} and the effect of temperature (Table S2). This can be attributed to the significant correlation between temperature and global radiation (Figure S4) and the often dominant effects of the temporal trend and temperature on crop yields (Table S2), which may have overridden the effect of solar radiation. Another contributing factor is that part of the radiation data were not from the same station as crop data were collected and it is always a challenge to obtain a complete set of statistical data with a required quality due to the often lack of radiation observations. In contrast, temperature did not differ much among treatments as well as among years (Figure S2), and the same cultivars and agronomic management were adopted in our field experiments, and therefore, our field experimentation effectively eliminated these confounding effects.

However, shading slightly prolonged growth durations (Table 2), which is in line with previous reports that shading delays flowering and grain development (Cai, 2011; Cantagallo, Medan, & Hall, 2004). Given that air temperature did not differ much between the treatments (Figure S2), the slightly changed phenology was presumably because canopy surface energy balance changed due to the changes in received radiation, which might have led to changes in canopy temperature, and therefore, in phenology, among the treatments. In addition, shading reduced the carbon: nitrogen ratio in our experiments (see Section 4 later), which may indirectly cause a prolonged observed crop-maturity time as the carbon: nitrogen balance plays a role in regulating leaf senescence (Wingler, Purdy, Maclean, & Pourtau, 2005). Nevertheless, the observed phenology by shading was prolonged by only few days (Table 2), and the effects of shading on yield (or on biomass) in terms of their absolute values (Figure 1) were not much different from those in terms of the relative values per day (Figure S3), suggesting that the impact of changed phenology on our main results was very small.

Because of the different effectiveness in separating the effects of confounding climate variables, analyses of historical data and experimental data could result in very different conclusions. For example, based on historical data for similar regions in China, Chameides et al. (1999) reported a 1:1 relationship between a percentage decrease in R_{GR} and a percentage decrease in wheat and rice yields when F_{diff} was made constant. Our experiments demonstrated that, for wheat and rice, the percentage of yield loss (Figure 1) was lower than the percentage of R_{GR} reduction (Table 1). Previously, shading treatments have commonly been used to examine whether yield is limited by photosynthesis in agronomic or physiological contexts (e.g. Estrada-Campuzano, Miralles, & Slafer, 2008; Ishibashi et al., 2014; Wang, Deng, & Ren, 2015). Our shading experimental results for yield losses in the context of global dimming were in line with these previous shading experiments.

It is worthy to note that strictly speaking, the 'control' treatment of our experiments is not a true control because it had the background dimming under the current climate. However, true control is not possible to achieve under field conditions, and the background dimming also occurred in other treatments. As long as the effect of average radiation is roughly linear (Table 4), the background dimming had little influence on our experimental results for the relative impact of direct versus diffuse radiation.

4.2 | Diffuse radiation fertilization effect

Our experiments demonstrated a fertilization effect of the increased F_{diff} under global dimming (Table 4), but the effect was insufficient to completely offset above-ground biomass and yield losses caused by the declining R_{GR} for both crops. As a result, both wheat and rice above-ground biomass and yields still decreased under shading (Figure 1). This was consistent with some prior findings that the declining R_{GR} reduced the productivity of crops (Proctor et al., 2018), and GPP of some open-canopy forest (Alton, North, et al., 2007) and grassland (Niyogi et al., 2004), although part of the reduction was offset by diffuse radiation fertilization effect. In contrast, other studies on GPP or NPP of unmanaged ecosystems (Gu et al., 2003; Mercado et al., 2009; Rap et al., 2018; Urban et al., 2007) and of crop lands (Niyogi et al., 2004) tended to show that the diffuse radiation fertilization effect overcompensated for the effect of decreased R_{GR}. Such a difference in diffuse radiation fertilization effect probably reflects the confounding effect of other uncontrolled factors during observations or the efficiency of converting GPP or NPP to edible yield in agroecosystems (Proctor et al., 2018).

Differences in the response to global dimming between crop and other ecosystems should be considered. HI is an important trait that distinguishes crops from other ecosystems (Long et al., 2006; Tollenaar et al., 2017). Consistent with earlier studies (Gao et al., 2017; Li et al., 2010), a decreasing trend in HI under shading treatments was observed in our experiments (Table 6). In addition, the importance of HI in determining the fertilization effect on crops was also highlighted in our calculation of the required increments in F_{diff} in order to completely compensate for the losses in above-ground biomass and yields (Table 5). The required increment for yield was higher than that for the above-ground biomass, and this difference was much greater in rice than in wheat. The difference between the two crops can be explained by the comparatively more significant decrease in HI caused by shading in rice (Table 6). Overall, the required increment in F_{diff} to compensate for losses of yield or above-ground biomass was higher in rice than in wheat (Table 5), also in line with more days treated with shading in rice than in wheat experiments (Table 2).

Yields of wheat and rice can be analysed by the number of filled grains per ear, the number of ears per unit area and the individual grain mass. The product of the first two components makes the number of grains per unit area, which is most important for determining HI and yield (Estrada-Campuzano et al., 2008; Makino, 2011). Our field experiments showed that for both crops, especially for rice, yield loss under global dimming was mainly ascribed to the reduction in the number of filled grains per ear (Table 3). The small difference in the contribution of yield components to yield between the two crops may be because the thousand grain mass is relatively less affected by growth environment in rice than in wheat (Makino, 2011). The number of filled grains per ear is determined, to a large extent, by floret development which may be predominantly affected by nitrogen availability before heading (Cai et al., 2016; Sinclair & Jamieson, 2006). In our experiments, above-ground nitrogen uptake decreased under shading (Figure 7), and significant correlations between the number of filled grains per ear and nitrogen uptake before heading were observed (Figure S5). This indicated that global dimming during preheading phase had a predominant influence on the number of filled grains per ear, and thus, on HI.

4.3 | The fertilization effect was not due to an improved light interception, but due to an increased RUE

It has long been a common belief that, on overcast days (when diffuse radiation is dominant), canopy has a higher FIR than on clear days (when direct radiation is dominant) because all canopy layers can receive radiation effectively (Goward & Huemmrich, 1992; Li & Fang, 2015; Xin et al., 2016). This is probably because dimming and overcasting enhance scattering in the atmosphere, thereby, creating a more uniform light distribution in crop canopy (Mercado et al., 2009; Wang et al., 2018). Also, crops can enhance light interception efficiency by improving canopy size, such as increasing LAI, in order to capture more solar radiation to accommodate the declining global radiation conditions (Li et al., 2010; Ratjen & Kage, 2013). Our observations showed that although global dimming caused an increase in LAI (Figure 2), surprisingly it did not cause an obvious shift in FIR (Table 6) because FIR is affected not only by LAI but also by *k* (Hirose, 2004). Although diffuse radiation can penetrate deeper into the canopy (Rap et al., 2018; Williams et al., 2014), it also allows more light to leak under the crop canopy, which leads to a notable decrease in *k* (Figure 3). Due to the opposite changes in LAI and *k*, FIR hardly changed under global dimming (Table 6) and thereby had no significant effect on wheat and rice yields (Table S4). Therefore, our experimental study demonstrated that the fertilization effect did not arise from any improved canopy light interception but mainly from the enhanced RUE (Table S4).

It should be noted that the response of FIR to diffuse radiation depends on the canopy structure (Goward & Huemmrich, 1992). The FIR under diffuse radiation is higher than that under direct radiation for a closed canopy, but is opposite for an open canopy (Matsui et al., 2008; Thomas et al., 2006). Canopy structure differs among crop stages, among species and between managed and unmanaged ecosystems; so the effect of global dimming could depend on photosynthetically active plant-surface area (Niyogi et al., 2004; Wohlfahrt et al., 2008). This dependence may be another reason why the diffuse radiation fertilization effects were different in different ecosystems (see earlier Section 4).

In our experiments, shading treatments increased RUE (Table 6), in line with a model-simulated result that crop RUE increased with the increasing fraction of diffuse PAR under a given total PAR (Tubiello, Volk, & Bugbee, 1997). However, we were unable to establish an explicit relationship between RUE and F_{diff} from our data because the variation of RUE was confounded by the simultaneous change in R_{GR}. The enhancement of RUE by shading in our experiments was, on average, 2.5% for wheat and 2.7% for rice (Table 6), lower than those reported earlier (e.g. Choudhury, 2001; Cohan et al., 2002; Xin et al., 2016). One major cause is that, the increment in F_{diff} was much lower in our experiment than in the previous studies. The previous studies compared the RUE under perfectly clear and overcast days, thus overestimating the increases in RUE due to the high increases in F_{diff} (more than 70%). In contrast, in our study, shading was imposed during the main crop growing seasons rather than several days. The shading increased the seasonal F_{diff} by 7%–22% (see Table 1); thereby, the associated variation in RUE was closer to the commonly observed values under dimming.

4.4 | Causes for the increased RUE

An enhanced RUE under global dimming is expected from the photosynthetic light response curves as described by Equation (7), in which a diminishing return with increasing light intensity is commonly observed. When canopy is illuminated more by direct radiation, the upper leaves are easy to reach light saturation, while the leaves at the bottom may be shaded and not receive sufficient radiation for photosynthesis (Kanniah et al., 2013; Williams et al., 2014). In contrast, diffuse radiation allows the lower leaves to receive more radiation, and prevents the upper leaves from reaching light saturation (Gu et al., 2002; Mercado et al., 2009; Schiferl & Heald, 2018). This diminishing return light response shape in combination with differences in canopy light profile between CK and shading treatments contributed to our result that, for both crops, RUE increased under global dimming (Table 6). Such a general consideration presumes that the increased RUE was due to the lower light level received by plants under shading than those under control conditions, while these plants have the same light response curves.

Our experiments revealed an additional, novel mechanism. We found that $A_{g,max}$ (Figure 5) and ε (Figure 6) were increased by shading, which means that both the maximum value and the initial slope of photosynthetic light response curves were increased, that is, the curves were shifted up by shading (Figure 4). Increases in leaf nitrogen concentration and its significant positive effect on leaf photosynthetic parameters ($A_{g,max}$ and ε) were observed (Figure 8). This indicates that plants, when having grown under dimming, acclimate to growth environments as a result of initially decreased photosynthesis. An after-effect of the initially decreased photosynthesis led to a lower carbon: nitrogen ratio, that is, a higher nitrogen concentration in leaves (Figure 8). As many photosynthetic compounds require leaf nitrogen to constitute, leaf photosynthesis is strongly correlated with leaf nitrogen concentration (Evans, 1989; Jensen, 2000; Onoda, Hikosaka, & Hirose, 2004). Such a reasoning may directly explain our observed enhanced leaf photosynthetic rates under shading (Figure 4). Furthermore, we observed a significant increase in specific leaf area under shading (Figure S6), which would be expected to decrease leaf photosynthesis (Boote & Tollenaar, 1994; Cai, 2011). Our observed increases in leaf photosynthesis under shading suggest that shading-induced increases in leaf nitrogen concentration overcame the decreases in leaf thickness. The earlier discussed increase in the canopy LAI under shading (Figure 2) is associated with the increased specific leaf area. However, it is not clear if the increased LAI could be partly ascribed indirectly to an enhanced leaf photosynthetic rate. If it was, the acclimation effect initially occurred at the leaf level could further have prompted crop canopy to intercept more light and to produce more biomass. As such, the enhanced RUE can be additionally explained by plant acclimation to dimming via a feedback mechanism that gradually adjusted leaf nitrogen status and possibly canopy LAI.

4.5 | Implications for further studies

In summary, our study suggests that a statistical analysis of historical data only is not enough, and experimental data are essential, for reliable assessment of the global dimming impacts on crop productivity. Our experiments demonstrated that the diffuse radiation fertilization effect on crop yields was not arisen from the commonly believed improvement of light interception, but is mainly attributed to an increased RUE. More importantly, our experiments revealed that the increased RUE arose not only from a saturating shape of photosynthetic light response curve but additionally due to leaf photosynthetic acclimation to dimming light. Moreover, HI decreased under shading, which discounted the fertilization effect on agroecosystems. Current crop simulation models have not accounted for these new mechanisms. Our result may result in a paradigm shift in the understanding and modelling of global dimming impacts on crop-ecosystem productivity. Further studies are needed to elucidate the physiological mechanism of leaf photosynthetic acclimation to global dimming in relation to plant carbon: nitrogen ratio and leaf nitrogen content.

Our experimental study was conducted in Nanjing, China, on wheat and rice, both being C_3 crops. Changes in R_{GR} and F_{diff} vary among different regions, and their impacts on crops may depend on crop varieties and other climatic factors. In addition, earlier studies have suggested that global dimming might also have an effect on C_4 crops like maize (Proctor et al., 2018; Schiferl & Heald, 2018; Yue & Unger, 2017). Whether the mechanisms we found here for wheat and rice in our study area apply to other C_3 crops or varieties grown elsewhere, or to C_4 crops merits further investigations.

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