The impact of floating dust on net photosynthetic rate of *Populus euphratica* in early spring, at Zepu, northwestern China

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Floating dust weather is an annual natural phenomenon in early spring in south of Xinjiang UygurAutonomous Region, northwestern China. Floating dust in air can influence human health and plant growth. *Populus euphratica* is a rare tree species which can grow in hot and dry conditions. Some investigations have evaluated the effect of floating dust on plants by means of artificial dust to which simulates the natural sand and dust, but the mechanism by which plants respond to sand is poorly understood. The investigation presented in this paper focused on a comparison of the variation in net photosynthetic rate (P_n) before and during floating dust weather, to elucidate the mechanisms involved. Stomatal conductance (g_s) and P_n appeared to increase during floating dust weather;in contrast, stomatal limitation (L_s) and non-stomatal limitation (L_{ns}) decreased with photosynthetic active radiation in the range 500 to 2000 μmol $m^{-2}s^{-1}$,which is optimum for plant growth. Aerosol ions, including potassium, dissolved in water collected by foliar structures or tender stems, may come into contact with intercellular stroma and improve chloroplast activity or ribulose-1,5-bisphosphate carboxylase/ oxygenase (Rubisco) levels, such as potassium, thereby influencing L_s and L_{ns}. Moreover, potassium, phosphorus, nitrogen and sodium in aerosols appeared to increase P_n, and this may be due to nutrient compounds in aerosols, which may have a similar effect to spraying fertilizer on leaves. In addition, the high relative humidity and carbon dioxide concentration in air during floating dust weather may facilitate an increase in P_n.

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Abstract

Floating dust weather is an annual natural phenomenon in early spring in south of Xinjiang Uygur Autonomous Region, northwestern China. Floating dust in air can influence human health and plant growth. *Populus euphratica* is a rare tree species which can grow in hot and dry conditions. Some investigations have evaluated the effect of floating dust on plants by means of artificial dust to which simulates the natural sand and dust, but the mechanism by which plants respond to sand is poorly understood. The investigation presented in this paper focused on a comparison of the variation in net photosynthetic rate (P_n) before and during floating dust weather, to elucidate the mechanisms involved. Stomatal conductance (g_s) and P_n appeared to increase during floating dust weather; in contrast, stomatal limitation (L_s) and non-stomatal limitation (L_{ns}) decreased with photosynthetic active radiation in the range 500 to 2000 μmol $m^{-2}s^{-1}$,which is optimum for plant growth. Aerosol ions, including potassium, dissolved in water collected by foliar structures or tender stems, may come into contact with intercellular stroma and improve chloroplast activity or ribulose-1,5-bisphosphate carboxylase/ oxygenase (Rubisco) levels, such as potassium, thereby influencing L_s and L_{ns}. Moreover, potassium, phosphorus, nitrogen and sodium in aerosols appeared to increase P_n, and this may be due to nutrient compounds in aerosols, which may have a similar effect to spraying fertilizer on leaves. In

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addition, the high relative humidity and carbon dioxide concentration in air during floating dust weather may facilitate an increase in P_n.

Keyword: *Populus euphratica, Photosynthesis, Floating dust,* Stomatal limitation, Non-stomatal limitation

Introduction

Leaf responses to dust have been studied for a long time. Both the chemical and physical characteristics of dust can influence photosynthesis and leaf physiology (Hirano et al., 1995). Vardaka et al. (1995) reported that the average rate of leaf photosynthesis decreased exponentially with increasing levels of dust on leaf surfaces. Dust coatings on leaves can block stomata, which leads to a decrease in photosynthesis and respiration (Vardaka et al., 1995; Xi and Sokolik, 2012), photosynthetic active radiation (PAR) and water use efficiency (Maletsika et al., 2015). Moreover, increasing dust deposition may lead to a decrease in chlorophyll content and an increase in ascorbic acid content (Squires, 2016). Similarly, Simon et al. (2016) found that metal content in dust on leaves correlated with the leaf tissue content. Toxic metals, phytotoxic gaseous pollution (Farmer, 1993) and calcium hydroxide (Czaja, 1962) in dust may penetrate leaf tissue, cause cell plasmolysis and may lead to death.

The size distribution of dust particles can cause different effects in plants. The dust of smaller particles caused a shading effect (Squires, 2016) which decreased photosynthetic rate by shading the leaf surface, but increased leaf temperature and transpiration (Armbrust, 1986; Hirano et al., 1995). All these factors can impact on photosynthesis. However, the shading effect of dust layers may be different among different plants. Manning (1971) found that leaves of *Vitis vinifera* were a much darker green when exposed to limestone dust, but the leaves of *Populus euphratica* did not suffer seriously from a shading effect (Vardaka et al., 1995). An investigation into the effect of iron ore dust on mangroves provided no evidence of cell damage caused by these particles (Paling et al., 2001).

Floating dust in southern Xinjiang almost always occurs in spring, and it may affect plant photosynthesis. *P. euphratica* is a native relic plant of the Taklimakan desert, but there have been few studies on the effect of floating dust on photosynthesis of *P. euphratica*. Human health effects, due to particle size distribution and particulate content, have received much attention, but there is a lack of information about the effect on plants. The aim of this research was to determine the effects of floating dust on P_n changes in *P. euphratica*. Because Wang et al. (2016) showed that aerosol ions dissolved in water collected by foliar structures or tender stems moves into intercellular stroma and improves the activity of chloroplasts or Rubisco levels such as potassium(Erel et al., 2015), this survey also investigated the relationship between P_n and the ions in aerosols. This study may increase our understanding of the survival strategies of *P. euphratica* in response to floating dust weather in early spring.

Materials and methods

Site description

The research area was located in a natural forest on the southern edge of Taklimakan desert in Zepu County, Xinjiang Uygur Autonomous Region, northwestern China. *P. euphratica* and *Elaeagnus angustifolia* are the dominant species in these forest communities, with an average height of about 11 m and 3 m, respectively. The forest lies at the border between desert and oasis, and it is approximately 12km from the Yarkant river. The monthly mean temperature in April is 15.7℃, and the monthly mean rainfall is 9.6 mm.

Experimental design

Leaf responses to light were measured in *P. euphratica* using a portable infrared gas analyzer (LI-COR 6400, Lincoln, NE, USA) on April 16 (sunny) and April 19, 2017 (floating dust), respectively. At the same time, the leaf chlorophyll content was measured using portable chlorophyll meter (SPAD-502Plus, Minolta, Osaka, Japan). Particulate size distributions were measured using an Anderson particle sizing sampler at the top of a bungalow on sunny days and floating dust days. The particle sizing sampling site was approximately 1.2 km away from the experimental natural woodland. Composition of ions in dust was determined by chromatography (Dionex Integrion Hpic, Thermo Scientific, USA). The ion experiment was carried out using the method of Shen et al. (2014).

Results

Leaf g_s characteristics of P. euphratica

Figure 1 shows an unexpected result: there were higher levels of P_n and g_s in floating dust weather than in sunny weather. Normally, g_s is positively correlated with P_n across a certain range for many plants, but g_s would be expected to decrease while P_n is above a certain threshold (Gao et al., 2016). On a sunny day, P_n increases, followed by an increase in g_s when PAR is below 2000 μmol $m^{-2}s^{-1}$; thereafter, P_n begins to decrease followed by a g_s increase, as shown in Fig. 1 (a and b). During floating dust weather, the g_s response curves indicated there were some obvious fluctuations during low and high levels of PAR; the P_n response curves were similar with g_s except for low and high levels of PAR (Fig. 1). The measurements were carried out on the same tree, which had a height of 1.5 m, and the dates were adjacent, so we deduced the differences may have been caused by environmental factors.

Fig. 1 Comparison of sunny and floating dust weather for P_n and g_s. April 16 was sunny weather, while April 19 was floating dust weather.

Stomatal limitation and non-stomatal limitation

Photosynthesis is influenced by various environmental factors. These environmental factors interact with each other, so it can be difficult to confirm which factor leads to a photosynthetic change. The main factors can be summarized as those influencing L_s and L_{ns}. L_s can be calculated by Formula 1, which indicates the photosynthetic rate change caused by stomata (Berry and Downton, 1982). In contrast, the ratio of C_i/g_s has been used as a parameter to describe the L_{ns} of photosynthesis (Ramanjulu et al., 1998), which indicates the activities of chloroplasts and Rubisco (Yang et al., 2015).

$$L_s=1-C_i/C_a \qquad \text{(Formula 1)}$$

Fig. 2 The comparison of L_s and L_{ns} influenced by PAR in sunny and floating dust weather.

By comparison, there were consistently higher values of L_{ns} in sunny weather than in floating dust weather; however, L_s was complex. During floating dust weather L_s was slightly higher than in sunny weather when PAR was under 250 μmol $m^{-2}s^{-1}$, which can be possibly ascribed to stomatal blockage caused by aerosols. Meanwhile, L_s in sunny weather was higher when PAR was 500 to 2000μmol $m^{-2}s^{-1}$ (Fig. 2), which is an optimum range for plant growth, and may be attributable to ion absorption in aerosols; it is abnormal. One possible explanation is that some substances promote the activities of chloroplasts or the Rubisco; another explanation is an increase in photosynthetic necessities, such as chloroplasts, CO_2 and H_2O. Indeed, chloroplast content (sunny weather is 30.8 SPAD, floating dust weather is 33.7 SPAD), CO_2 and H_2O were increased according to the measurements shown in figure 3. Nevertheless, it should not be ignored that L_{ns} had low values in floating dust weather, which may imply the existence of substances which promote the activity of chloroplasts or the Rubisco. Furthermore, recent research has shown that aerosol ions may be dissolved in water collected by foliar structures or tender stems (Wang et al., 2016), and may move into the intercellular stroma and improve the activity of chloroplasts or the Rubisco, such as potassium (Erel et al., 2015).

Fig.3 Comparison of CO_2 and H_2O air content, and relative humidity (RH_R) in sunny and floating dust weathers.

Characteristics of plant macronutrients in aerosols

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Nitrogen, phosphorus and potassium are important plant macronutrients. There are two pathways for nutrient intake; one is through root absorption, and the other is by foliar uptake. Wang et al. (2016) have reported that some plants living in extremely arid habitats can extract water from the air through their foliar structures or tender stems. Water-soluble ions in air particles will be dissolved in water concentrated from the air by stomata or water-absorbing scales, and thus move into foliar structures, especially tender stems. Potassium is an essential macronutrient which plays an important role in photosynthetic processes; furthermore, sodium can partially substitute for potassium in some plants (Erel et al., 2015).To investigate the effects of macronutrients on plant photosynthesis, we measured the concentration of some macronutrients in air particles using ion chromatography and the photosynthesis-light response, such as concentrations of K^+, Na^+, PO_4^{3-}, NH_4^+ and NO_3^- in air particles collected by an Anderson particle sizing sampler.

The sampling was carried out from April 16 to 20, 2017; the weather was sunny from April 16 to18, and April 19 to 20 was floating dust weather. The aerosols in floating dust weather had more mass concentration than in sunny weather (Fig. 4). The concentrations of ammonium and nitrate were low, shown in Table 1. The concentration of sodium and phosphate were relatively high in all samples (Fig. 4). All five ion concentrations indicate that floating dust days had higher levels than sunny days, but the potassium content of aerosols is relatively low (Fig. 4).

Table 1 Distribution of NH_4^+ and NO_3^- in different particle sizes in aerosols.

Fig. 4 Ion concentration distribution in different particle sizes.

Discussion

Modelling of stomatal conductance

Stomatal conductance (g_s) of leaves respond differently to environmental stimuli due to different leaf age, species and acclimation to the environment (Baldocchi, 1989). There are two classical models for modeling vegetative stomatal conductance, namely the Jarvis model (Jarvis,

1976) and the BWB model (Ball et al., 1987). The Jarvis model was widely used for surficial processes and biogeochemical (Guyot et al., 2017; Whitley et al., 2009; Ye and Yu, 2009; Yu et al., 2017). Both models are used to investigate the impact of different environmental conditions on plant photosynthesis caused by different environment status (Hongpakdee and Ruamrungsri, 2015; Hoshika et al., 2017; Ma et al., 2011). However, both of them are based on empirical or semi-empirical formulae; moreover, some aspects of the formulae have ambiguous biological meaning. Ye et al. (2013) established a mechanistic model (Formula 1) for the light response of photosynthetic electron transport rates based on light harvesting properties of photosynthetic pigment molecules (Ye et al., 2013).

The P_n measurements were conducted on 17 April to 19 April. The mechanistic model for stomatal conductance is based on photosynthetic electron transport, described by Ye et al. (2013, 2014), and the meanings of symbols in the mechanistic model referred to in Ye et al. (2013). Figure 5 shows the comparison between modeled and observed P_n in response to PAR in sand and non-sand weather. There were no significant differences between fitted and measured values for sunny days and floating dust weather by means of two independent sample tests (p_{sunny} =0.94, $p_{floating\ dust}$=0.97), which verified the applicability of the Ye et al. model. The paired-sample T test for the measured P_n values were carried out, and the results indicated significant differences between sunny and floating dust weather (r=0.988, p<0.001, n=16). The higher P_n values in floating dust weather than in sunny weather was unexpected, although both of P_n have the same trends. We deduced the results of σ_{ik}/σ_0 and N_k/N_0 from Formula 2 and Formula 3 (Fig. 6).

$$P_n = \frac{\alpha'\beta' N_0 \sigma_{ik} \varphi\theta}{S} \cdot \frac{1-\frac{(1-g_i/g_k)\sigma_{ik}\tau}{\xi_3+(\xi_1 k_P+\xi_2 k_D)\tau} I}{1+\frac{(1+g_i/g_k)\sigma_{ik}\tau}{\xi_3+(\xi_1 k_P+\xi_2 k_D)\tau} I} I - R_{light}, \quad \text{(Formula 2)}$$

Given that $\alpha_p = \frac{\alpha'\beta' N_0 \sigma_{ik} \varphi\theta}{S}$ (μmol CO_2 (μmol photons)$^{-1}$), $\beta_p = \frac{(1-g_i/g_k)\sigma_{ik}\tau}{\xi_3+(\xi_1 R_1+\xi_2 R_2)\tau}$ (m^2 s (μmol photons)$^{-1}$) and $\gamma_p = \frac{(1+g_i/g_k)\sigma_{ik}\tau}{\xi_3+(\xi_1 R_1+\xi_2 R_2)\tau}$ (m^2 s (μmol photons)$^{-1}$) , then Formula 1 can be simplified as :

$$P_n = \alpha_p \frac{1-\beta_p I}{1+\gamma_p I} I - R_d,$$ (Formula 3)

Fig. 5 Comparison of the measured and fitted values for P_n in sunny weather and floating dust weather.

The non-linear decreases of σ_{ik}/σ_0 with increases of PAR indicate that the capacity of light absorption by photosynthetic pigment molecules decreased with increased PAR in both sunny and floating dust weather, and the high values in floating dust weather indicated that the plant's photosynthetic pigment molecules had strong optical absorption capacities. The non-linear increases of N_k/N_0 with the increases of PAR indicate that the decrease in the capacity for light absorption, and the lower values of N_k/N_0 in floating dust weather, were due to more ground state photosynthetic pigment molecules which can facilitate photosynthesis. So, the floating dust weather had a better P_n according to both σ_{ik}/σ_0 and N_k/N_0.

Fig. 6 Light-response curves of both the ratio of the effective light absorption cross-section and Eigen-absorption cross-section (σ_{ik}/σ_0) and the ratio of the numbers of excited state photosynthetic pigment molecules and the ground state photosynthetic pigment molecules (N_k/N_0) versus photosynthetic active radiations (PAR) in floating dust and sunny weathers.

Variations in micro-environmental factors

In order to investigate the causes of variations in P_n, we conducted a Pearson correlation analysis of the micro-environment factors on the leaves. No significant correlation for P_n with the micro-environment factors was seen (Table 2). However, P_n had a significant correlation with Ci, Ci_{Pa} and Ci/Ca (Table 3). Consequently, it is possible that the factors causing the decrease of P_n were not micro-environment factors, but due to the intercellular material or the physiological parameters of leaves, instead. This conclusion is consistent with the results reached by the comparison between L_s and L_{ns}. Aerosols contain some macronutrients, which can enter into intercellular tissue and facilitate photosynthesis. In addition, the increase in CO_2 concentration and H_2O can facilitate the photosynthesis assumed with rich radiation (Fig.3). For the temperature per hour at Zepu County (China Meteorological Administration) all-day is above the dew point temperature with 4.05℃ on April 19, 10.7℃ on April 16, respectively, the leaves absorbed water just by means of its gaseous state, and the dew point temperatures were calculated from the formula of Goff-Gratch (John, 1957) and the correctional empirical calculation formula of the dew point temperature (Bu and Wang, 2001). Although research on water absorption of *P. euphratica* leaves or tender stems is very limited, it is known that many other xerophytes and halophytes have the ability to use atmospheric water vapor by absorption through aerial plant parts, such as *Reaumuria soongorica* (Wang et al., 2016) and *Stipagrostis sabulicola* (Ebner et al., 2011).The water soluble ions in fine particles of aerosols, mainly consisting of hydrophilic substances, may be absorbed via stomata or the cuticle pathway (Burkhardt, 2010). In addition, a proportion of fine particles can induce air water vapor to change to liquid water, which may be absorbed by stomata and cuticles (Burkhardt, 2010).

Table 2 Pearson Correlation analyses on the micro-environment factors of leaves

Table 3 Pearson Correlation analyses on photosynthetic parameters of leaves

Conclusion

This investigation discovered that tender leaves of *P. euphratica* have high values of P_n given sufficient radiation of floating dust weather than in sunny weather at Zepu County, Northwestern China. The growth processes of plants will increase the chlorophyll content thus improve P_n, which is not considered because there are just two days intervals between the two time measurements. Nevertheless, the low level of L_{ns} in floating dust weather implies lower chlorophyll and Rubisco activity, which seems to be the effect of the nutrients in aerosols, such as potassium (Wu and Berkowitz, 1992). It should be noted that the high level of air humidity in floating dust weather is an important factor, which can accelerate the dissolution of aerosols. The nutrients in aerosols may be absorbed by the leaves through stomata or cuticles (Wang et al., 2016), similar to the effect of spraying leaves with nutrients. It is important to note that further studies should be conducted on the permeation of aerosol nutrients into leaves. The increase in the concentration of CO_2 and water vapor were due to the lower temperature caused by floating dust shade effects, both of which are necessary for photosynthesis. This study increased our understanding of the growth strategy of *P. euphratica* when suffering from floating dust weather in early spring.

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Figure 1

Comparisons of sunny and floating dust weather for Pn and gs; April 16 is sunny weather while April 19 is floating dust weather

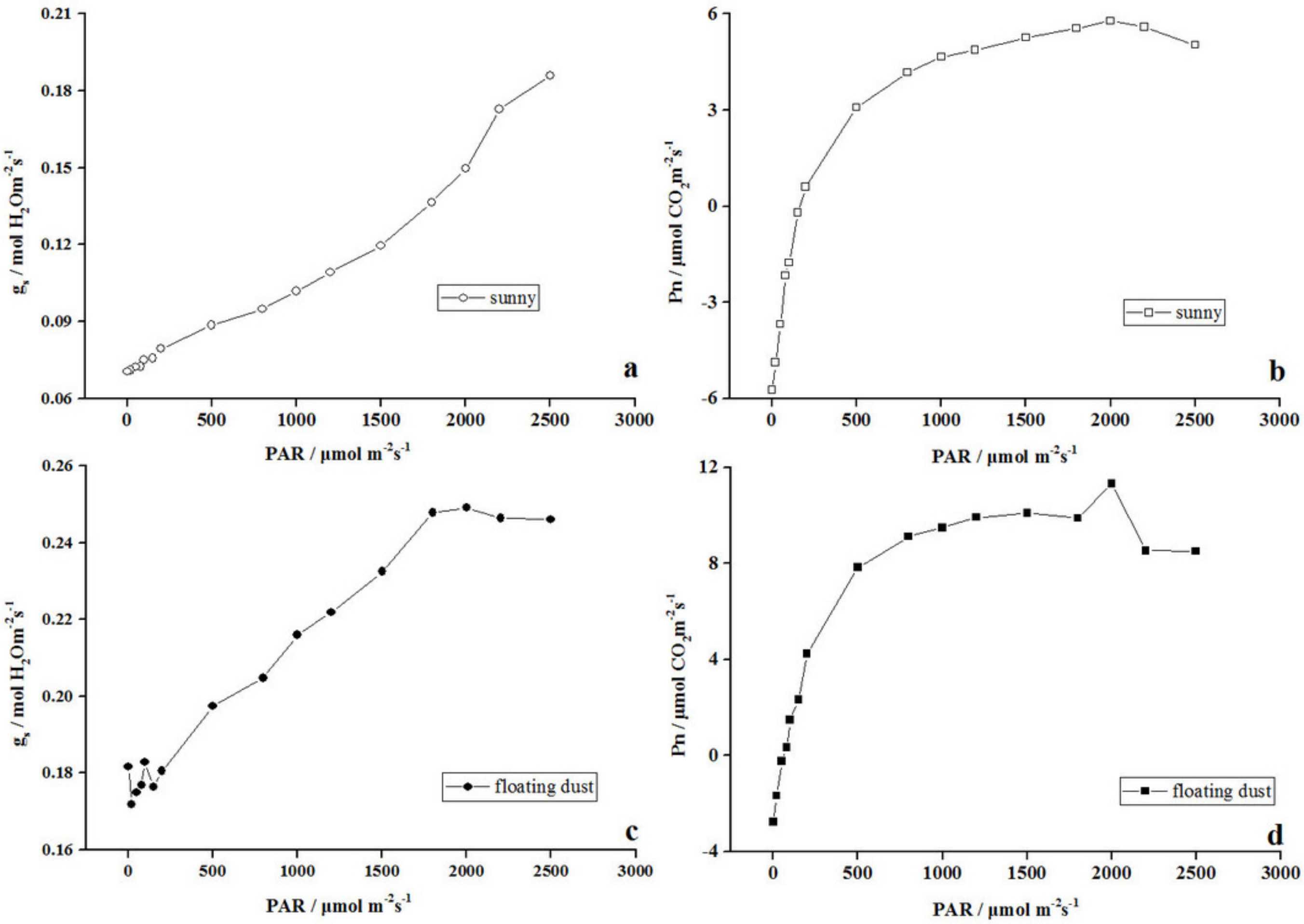

Figure 2

The comparison of L_s and L_{ns} influenced by PAR in sunny and floating dust weather.

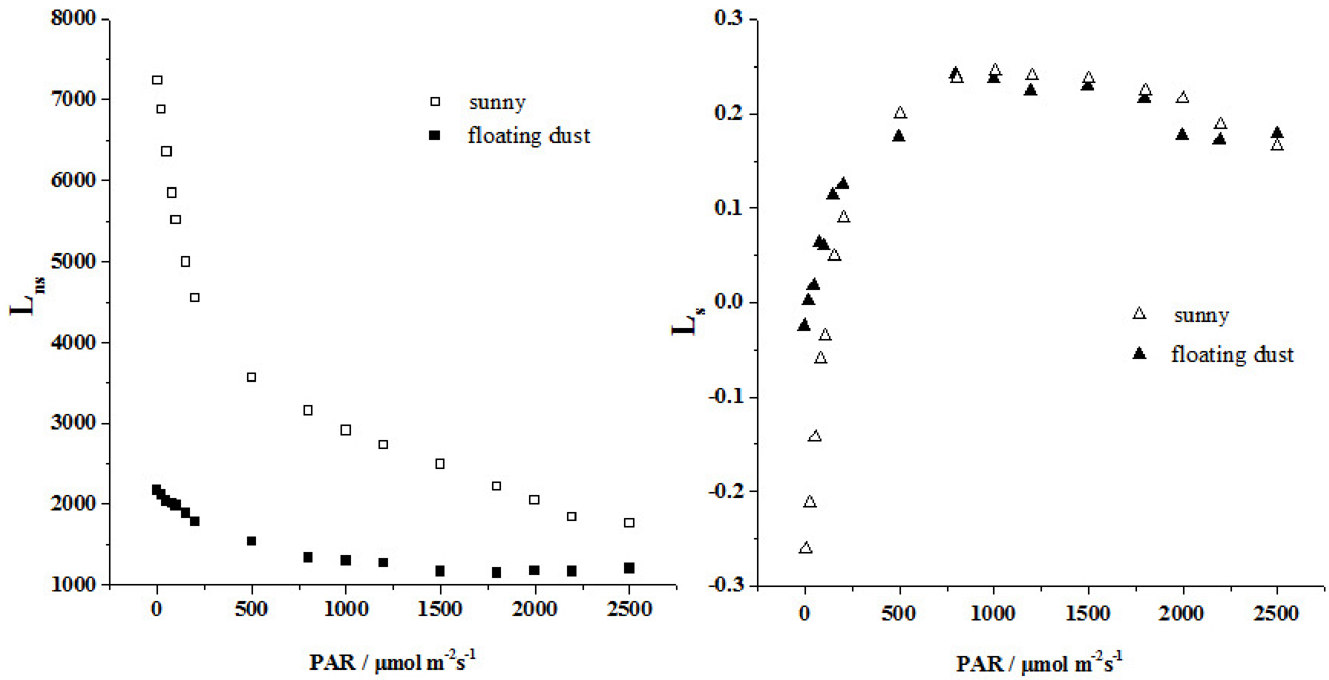

Figure 3

Comparison of CO_2 and H_2O air content, and relative humidity (RH_R) in sunny and floating dust weathers.

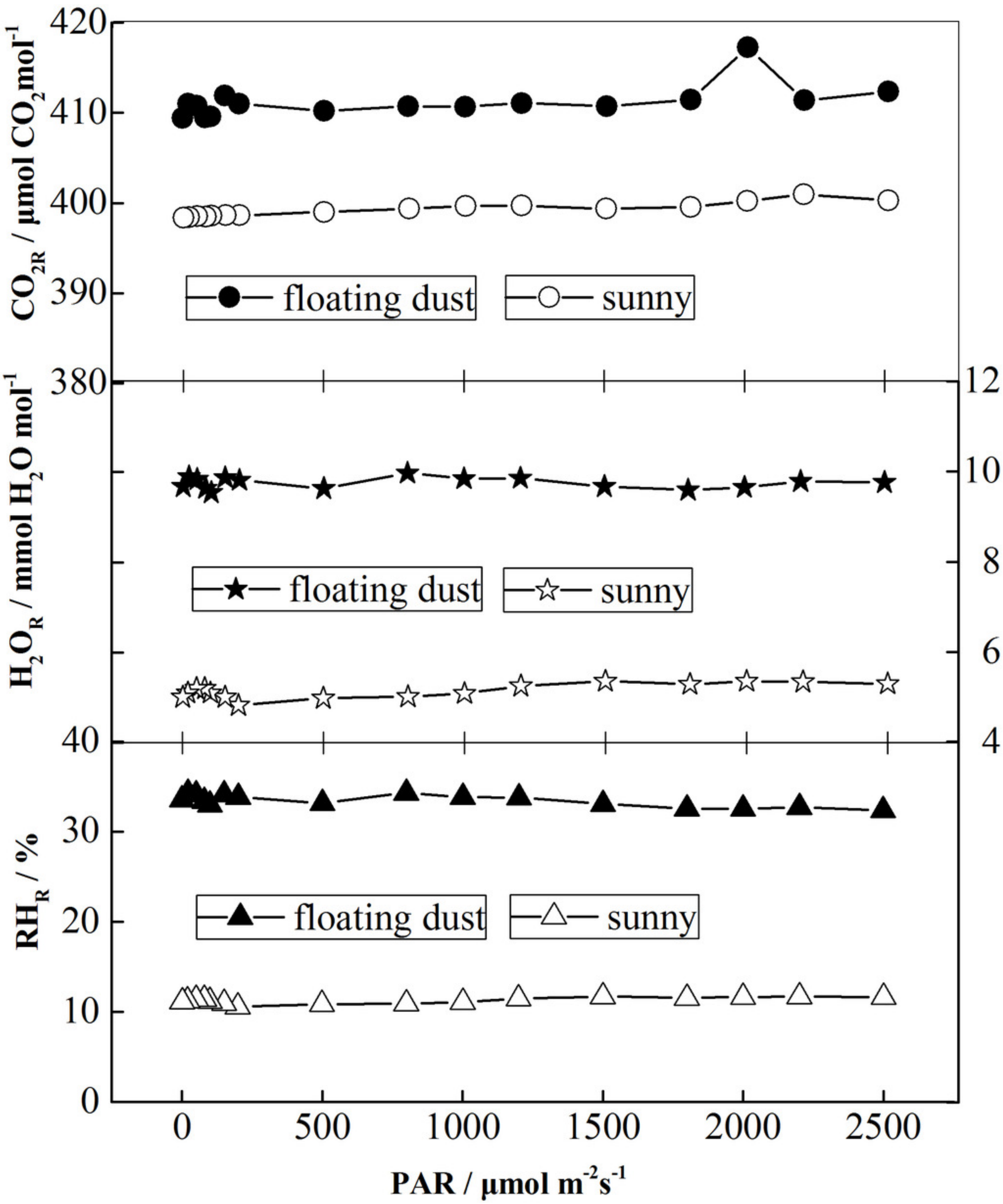
420
410
400
390
380
CO_{2R} / µmol CO_2 mol^{-1}
floating dust
sunny
12
10
8
6
4
H_2O_R / mmol H_2O mol^{-1}
floating dust
sunny
40
30
20
10
0
RH_R / %
floating dust
sunny
0
500
1000
1500
2000
2500
PAR / µmol m^{-2}s^{-1}

Figure 4

Ion concentration distribution in different particle sizes.

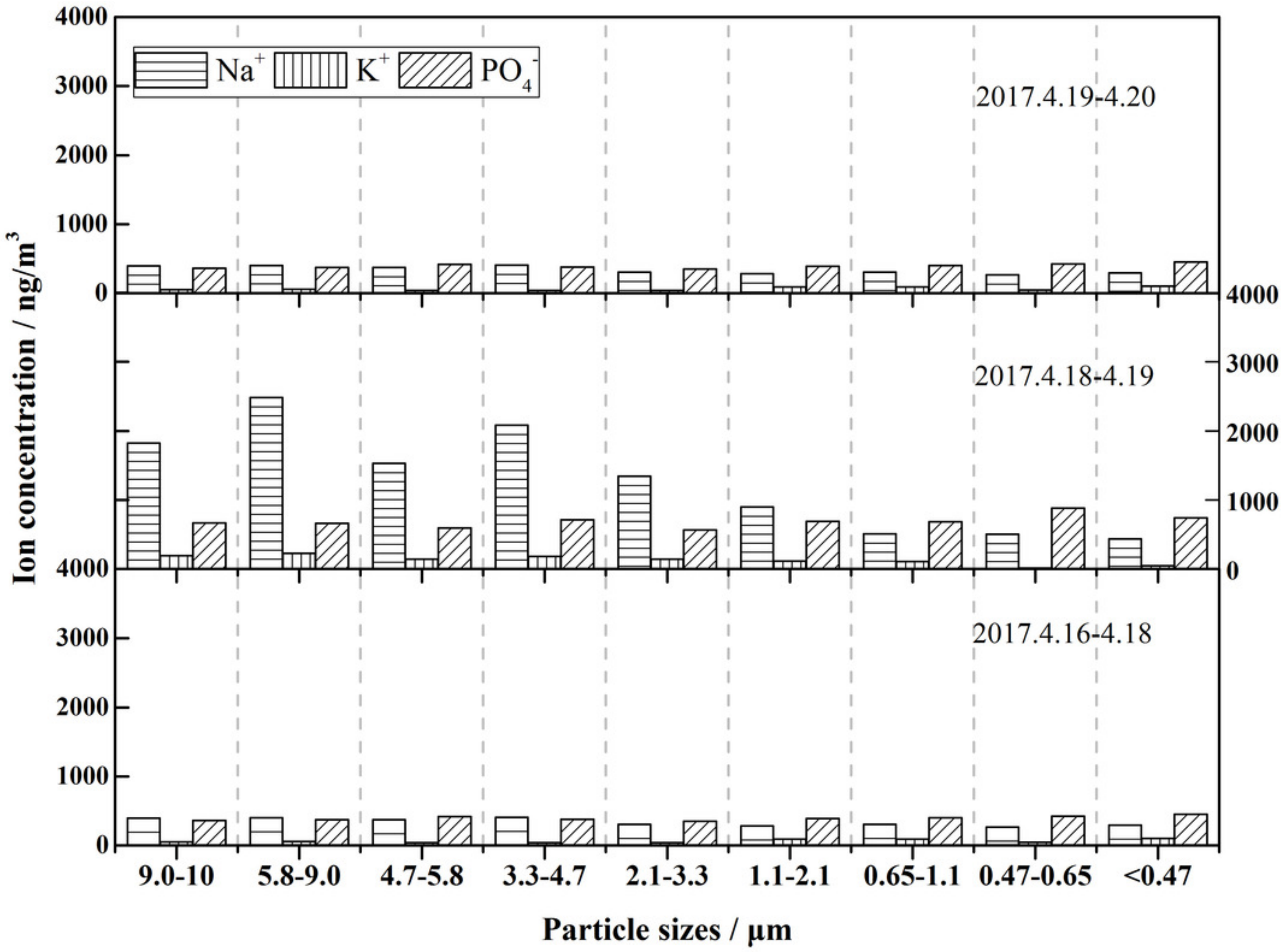

Figure 5

Comparison of the measured and fitted values for P_n in sunny weather and floating dust weather

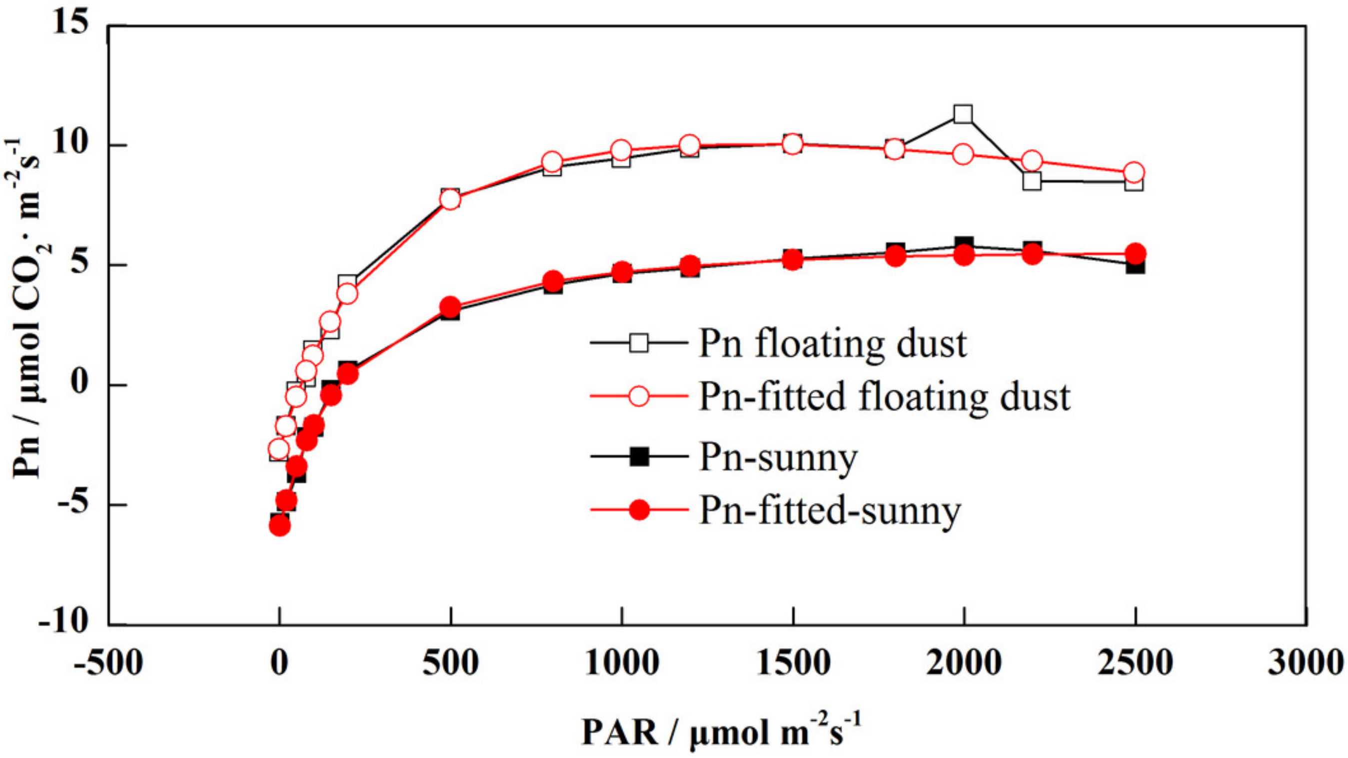

Figure 6

Light-response curves of both the ratio of the effective light absorption cross-section and Eigen-absorption cross-section (σ_{ik}/σ_0) and the ratio of the numbers of excited state photosynthetic pigment molecules and the ground state pho

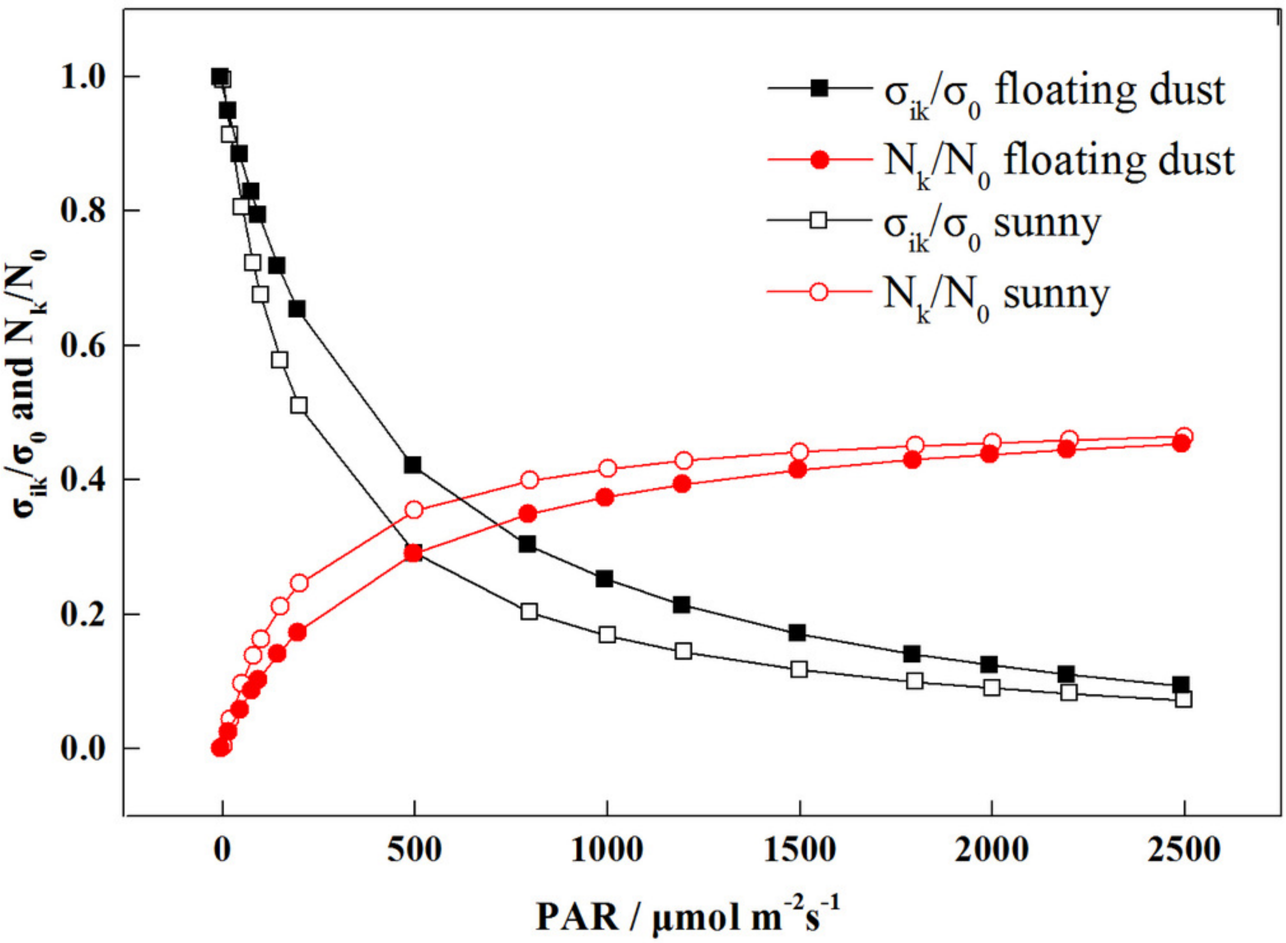

Table 1 (on next page)

Distribution of NH_4^+ and NO_3^- in different particle sizes in aerosols

Table 1 Distribution of NH_4^+ and NO_3^- in different particle sizes in aerosols.

	2017.4.16-4.18		2017.4.18-4.19		2017.4.19-4.20	
Particle sizes(μm)	Ammonium concentration(ng/m^3)	Nitrate concentration(ng/m^3)	Ammonium concentration(ng/m^3)	Nitrate concentration(ng/m^3)	Ammonium concentration(ng/m^3)	Nitrate concentration(ng/m^3)
9.0-10	0	0	0	0	0	0
5.8-9.0	0	0	0	0	0	0
4.7-5.8	0	0	29.13	4.47	0	0
3.3-4.7	0	0	0	0	0	0
2.1-3.3	0	0	0	0	0	0
1.1-2.1	0	0	0	0	0	0
0.65-1.1	0	0	0	0	0	0
0.47-0.65	0	0	0	0	59.58	0
<0.47	22.17	0	37.97	0	0	0
Sum	22.17	0	67.09	4.47	59.58	0

Table 2 (on next page)

Pearson Correlation analyses on the micro-environment factors of leaves

Table 2 Pearson Correlation analyses on the micro-environment factors of leaves

	Pn	Trmmol	Tleaf	CO_2R	H_2OR	RH_R	PARo	Press	VpdL	VpdA
Pn	1	-0.256	-0.211	0.294	-0.134	-0.127	0.13	-0.395	-0.254	0.086
Trmmol		1	-.818**	-0.175	0.487	.749**	-0.234	.935**	.980**	-.961**
Tleaf			1	0.103	-0.451	-.716**	-0.067	-.616*	-.813**	.920**
CO_2R				1	-0.12	-0.157	0.052	-0.226	-0.18	0.153
H_2OR					1	.926**	-0.133	0.428	.651**	-.617*
RH_R						1	-0.154	.666**	.862**	-.852**
PARo							1	-0.439	-0.234	0.118
Press								1	.911**	-.835**
VpdL									1	-.975**
VpdA										1

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

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Table 3(on next page)

Pearson Correlation analyses on photosynthetic parameters of leaves

Table 3 Pearson Correlation analyses on photosynthetic parameters of leaves

	Pn	gs	Ci	CndTotal	VpdL	VpdA	CndCO2	Ci_Pa	Ci/Ca
Pn	1	0.364	.584*	0.276	-0.254	0.086	0.288	.585*	.601*
gs		1	-0.094	.993**	.661**	-.766**	.995**	-0.093	-0.071
Ci			1	-0.18	-.562*	0.404	-0.169	1.000**	.999**
CndTotal				1	.744**	-.834**	1.000**	-0.18	-0.158
VpdL					1	-.975**	.734**	-.562*	-.552*
VpdA						1	-.825**	0.404	0.392
$CndCO_2$							1	-0.169	-0.147
Ci_Pa								1	.999**
Ci/Ca									1

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).