

Effects of high temperature on the chlorophyll *a* fluorescence of *Alhagi sparsifolia* at the southern Taklamakan Desert

Lei Li · Xiang-Yi Li · Xin-Wen Xu ·
Li-Sha Lin · Fan-Jiang Zeng

Received: 18 March 2013 / Revised: 1 July 2013 / Accepted: 7 October 2013
© Franciszek Górski Institute of Plant Physiology, Polish Academy of Sciences, Kraków 2013

Abstract Climate change is expected to result in an increase in the frequency and magnitude of extreme weather events. *Alhagi sparsifolia* is an important factor for wind prevention and sand fixation in the forelands of the Taklamakan Desert. The effects of high temperature on desert plants remain widely unknown. In this work, chlorophyll *a* fluorescence induction kinetics were investigated at different time stresses of 5, 20, 40, and 60 min at temperature gradients of 38–44 °C at 2 °C intervals. A pronounced K-step was found, and the values of the maximum quantum yield for primary photochemistry, the quantum yield of electron transport, the density of reaction centers and the performance index on absorption basis were lowest

after 60 min at 44 °C, thus indicating that the oxygen-evolving complex was damaged, the inactivated reaction centers increased, and the activity of the photosystem II (PSII) reaction center in leaves was seriously limited. Therefore, we suggest that under normal temperature (below 42 °C), the PSII of *A. sparsifolia* would be unaffected. When such temperature is maintained for 40 min, the activity of PSII would be limited, and when retained for 60 min, PSII may be severely damaged.

Keywords *Alhagi sparsifolia* · Chlorophyll *a* fluorescence transient · Extreme weather · Heat stress · Taklamakan Desert

Abbreviations

ABS	Absorbance
Chl	Chlorophyll
CS	Cross-section
DI _o	Dissipate
OEC	Oxygen-evolving complex
PAR	Photosynthetic active radiation
PEA	Plant efficiency analyser
PI	Performance index
PSII	Photosystem II
RC	Reaction center
TR	Energy trapping flux
φ_{D_0}	Quantum yield of energy dissipation (at $t = 0$)
φ_{E_0}	Quantum yield of electron transport (at $t = 0$)
Ψ_0	Efficiency with which a trapped exciton can move an electron into the electron transport chain beyond Q_A (at $t = 0$)
φ_{P_0}	Maximum quantum yield for primary photochemistry (at $t = 0$)
W_k	Ratio of variable fluorescence at K-step to the amplitude $F_j - F_0$

Communicated by M. Garstka.

L. Li · X.-Y. Li (✉) · L.-S. Lin · F.-J. Zeng
State Key Laboratory of Desert and Oasis Ecology, Xinjiang
Institute of Ecology and Geography, Chinese Academy of
Sciences, Urumqi 830011, China
e-mail: lixy@ms.xjb.ac.cn

L. Li
e-mail: lleipaper@sina.com

L. Li
University of Chinese Academy of Sciences, Beijing 100049,
China

L. Li · X.-Y. Li · L.-S. Lin · F.-J. Zeng
Cele National Station of Observation & Research for Desert-
Grassland Ecosystem in Xinjiang, Cele, Xinjiang 848300, China

X.-W. Xu
Xinjiang Institute of Ecology and Geography, Chinese Academy
of Sciences, Urumqi 830011, China

Introduction

The frequency of extreme weather events is expected to increase because of the ongoing global climate change [IPCC (2007)]. The average global temperature is recorded to have increased by approximately 0.6 °C over the past 100 years and is projected to continue to rise rapidly, which can be ascribed to the ecological responses of both flora and fauna to climate change (Walther et al. 2002). The IPCC (2007) reported that climate warming would affect the structure and function of the ecological system, particularly those in cold and arid regions. Moreover, the rate of temperature increase in Xinjiang Uighur Autonomous Region has significantly exceeded the average temperature over the past 100 years (Shi and Shen 2003).

Climate change affects organism habitats through direct temperature warming and increased frequency of extreme weather events (Cardoso et al. 2008). For example, in Mondego, Portugal, the mean air temperature has increased by 0.15 °C per decade from 1931 to 2005, and a higher frequency of heat waves was observed over the last decade (Cardoso et al. 2008). The harsh weather can have devastating effects on the survival and breeding of both animals and plants (Romero et al. 2000; Cardoso et al. 2008; Piessens et al. 2009).

High temperature modifies the structure and damages the photosystem II (PSII). Temperatures higher than the optimal level for plant growth result in the deterioration of the structure and function of photosynthetic proteins, consequently leading to a decrease in photosynthetic efficiency (Briantais et al. 1996; Srivastava et al. 1997; Crafts-Brandner and Salvucci 2002; Sharkey 2005; Lu and Zhang 1999; Allakhverdiev et al. 2008; Kreslavski et al. 2009; Mohanty et al. 2012). PSII, with its oxygen-evolving complex (OEC), is one of the three major stress-sensitive sites in the photosynthetic machinery (Aro et al. 1993; Bukhov and Carpentier 2000; Nishiyama et al. 2005, 2006; Murata et al. 2007; Mohanty et al. 2007). Chlorophyll *a* fluorescence (OJIP) kinetics are an informative tool for studying the effects of different environmental stresses on photosynthesis and can thus be employed as the main method in the investigation of the function of PSII and its reactions to changes in the environment and growth conditions. PSII contains a number of sensitive proteins. In photosynthetic organs, the thermostability of PSII is weak (Čajánek et al. 1998; Tang et al. 2007). High temperature decreases the electron transport capacity in the acceptor side of PSII as well as the activity of the OEC.

Alhagi sparsifolia is the primary vegetation in the forelands of the Taklamakan Desert. This species is an important factor for wind prevention and sand fixation in the transition zone (Zeng et al. 2006). For many photosynthetic processes, down-regulation typically occurs

above 40 °C (Kaňa et al. 2008). However, the air temperature at midday goes beyond 42 °C during summer in this desert. Mild experimental climate warming has been reported to induce metabolic impairment and massive mortalities in succulent plants in South Africa (Musil et al. 2009).

In this study, we set a series of temperature and time gradients to investigate how PSII in *A. sparsifolia*, a species known to adapt to severe environments, tolerates different temperatures at different durations. This study aims (a) to confirm the changes in the PSII activity in the leaves of *A. sparsifolia* under different time stresses with elevated temperatures and (b) to predict the effects of extreme weather (high temperature) on plant growth. Findings of this study would be useful for estimating the general consequences of climate change on photosynthetic activity and plant productivity in the Taklamakan Desert.

Methods

Study site

This study was conducted on the extended observation plot of Xinjiang Cele National Field Scientific Observation and Research Station of Desertification and Grassland Ecosystem. This area is situated at the desert edge of the transition zone, near Qira (Cele) oasis, which is located at the southern fringe of Taklamakan Desert with coordinates 80°42'59" to 80°43'29"E and 37°01'00" to 37°01'30"N at an elevation of 1,360 m. We selected an isolated and enclosed study site to avoid disturbance factors. The flora in the area has been described by Thomas et al. (2000) and Li et al. (2002). The mean annual precipitation is less than 40 mm, whereas evaporation can be as high as 2,600 mm annually. The mean summer temperature is 26.1 °C, the maximum temperature is 42 °C, and the surface maximum temperature is 70.3 °C. Tributaries and ephemeral rivers, fed by snow melt from the mountains during the summer months, enabled the establishment of river oases along the desert margins.

Experiment material selection and treatment

The desert plant *A. sparsifolia* is the main floristic element of the oasis–desert transition zone in the southern fringe of the Taklamakan Desert. Samples of *A. sparsifolia* from the same plot were collected randomly on a sunny morning at 10:00 a.m. with low winds in the early August 2011. The average plant height was 43–62 cm and the crown diameter was 56–72 cm.

Well-growing shoots of the plant were randomly selected. Dust on the surfaces of the leaves was washed lightly

with distilled water. The branches were cut away, inserted into moist absorbent cotton, immediately placed in an incubator with 60 % relative humidity, and then taken back to the laboratory, enclosed in damp filter paper. The absorbent cotton was placed in a culture dish filled with distilled water and then transferred into a tissue culture incubator enclosed in damp filter paper. The viewport was covered with black plastic bags, and the entire experiment was carried out in darkness. The heat stress was timed at 5, 20, 40, and 60 min at temperature gradients of 38 to 44 ± 0.1 °C at 2 °C intervals to determine the effect of time stress on *A. sparsifolia*. Temperatures from 38 to 42 °C are considered real temperatures, whereas 44 °C is considered as extreme weather temperature. Eight intact mature leaves and assimilative branches were used to measure OJIP after each temperature treatment. Eight repetitions of each temperature gradient were measured.

Measurement of chlorophyll *a* fluorescence transient

The polyphasic OJIP transient was measured using a plant efficiency analyzer (Hansatech Instruments Limited, Norfolk, UK). The OJIP transient was induced by a saturation photon flux density at $3,500 \mu\text{mol photons m}^{-2} \text{s}^{-1}$ provided by an array of three light-emitting diodes (peak at 650 nm) to generate fluorescence curves expanding from minimal fluorescence (F_o) to maximal fluorescence (F_m) for all treatments (in this research, $F_m = F_p$). Data were initially sampled at 10 μs intervals for the first 300 μs to achieve an excellent time resolution of dark-adapted F_o as well as the initial rise kinetics. The time resolution of digitization was then switched to slower acquisition rates. The PSII parameters and OJIP transient were analyzed according to Strasser et al. (2000, 2004).

Statistical analysis

Descriptive statistics was used to calculate averages and standard deviations of the data from each set of replicates, and the results were expressed as mean \pm SE (standard error). Student's *t* test was used for statistical analysis of experimental data. The results were presented as standard error, and statistical significance was accepted when $P \leq 0.05$. The graphs were produced using Origin 8.0 (Origin Lab Inc., Hampton, USA) and Adobe Photoshop (Adobe Inc., San Jose, USA).

Results

Both the shape and the intensity of OJIP transients were altered based on timing heat stress and different temperature levels in *A. sparsifolia* in darkness (Fig. 1). OJIP

transients were only slightly changed at 5 and 20 min (Fig. 1a, b), but decreased with increasing temperature at 40 min with no apparent K-step, and indicate that they have recovery of activity of PSII with 5, 20 and 40 min heat stress (Allakhverdiev et al. 2008; Kreslavski et al. 2009) (Fig. 1c). An evident K-step was found at 44 °C for 60 min (Fig. 1d). For the timing levels, the OJIP transients did not significantly change at 38, 40, and 42 °C (Fig. 1a–c). However, the OJIP transients were limited by increasing timing stress, with a pronounced K-step at 44 °C for 60 min (Fig. 1d).

Changes in quantum efficiencies are depicted in Fig. 2. The maximum quantum yield for primary photochemistry (ϕ_{P_0}) and the quantum yield of electron transport (ϕ_{E_0}) were significantly decreased by increasing the temperature for 60 min in darkness (Fig. 2a, c). Treatments with increasing temperature resulted in an increase in the probability that a trapped exciton moves an electron into the electron transport chain beyond Q_A (ψ_o) as well as a quantum yield of energy dissipation (ϕ_{D_0}), except for a decrease 60 min from 38 to 42 °C (Fig. 2b, d).

Figure 3 shows the reaction center parameters of the leaves of *A. sparsifolia* under different time treatments. Treatment resulted in a decrease in the density of reaction centers (RC/CS_o), but an increase in absorption flux per reaction center (ABS/RC), trapping flux per reaction center (TR_o/RC), and dissipated energy flux per reaction center (DI_o/RC).

The ratio of variable fluorescence at the K-step to the amplitude $F_j - F_o$ (W_k) increased by 123.1 % with increasing temperature from 38 to 44 °C at 60 min (Fig. 4).

The fluorescence parameters $(F_j - F_o)/(F_p - F_o)$ of the leaves of *A. sparsifolia* under different time treatments of 5, 20, 40, and 60 min did not exhibit a uniform change (Fig. 5). At 20 and 40 min, $(F_j - F_o)/(F_p - F_o)$ decreased with the increasing temperature, whereas at 60 min, $(F_j - F_o)/(F_p - F_o)$ increased at 38–42 °C and decreased significantly at 44 °C.

With increasing temperature, the performance index on absorption basis (PI_{ABS}) decreased by 482.2 % at 44 °C compared to that at 38 °C for 60 min (Fig. 6).

Discussion

Threats of global warming and climate change have resulted in heat stress and drought, two major stresses for plants. Most previous investigations on high-temperature stress have focused on the regulation of PSII in a single leaf (Briantais et al. 1996; Čajánek et al. 1998; Crafts-Brandner and Salvucci 2002; Musil et al. 2009). The fluorescence transient test, reflecting energy fluxes, and transportation of

Fig. 1 OJIP transient of the leaves of *A. sparsifolia* (38, 40, 42, and 44 °C, in the dark) under different time treatments of 5 (a), 20 (b), 40 (c), and 60 min (d). Data are mean \pm SE of eight independent measurements

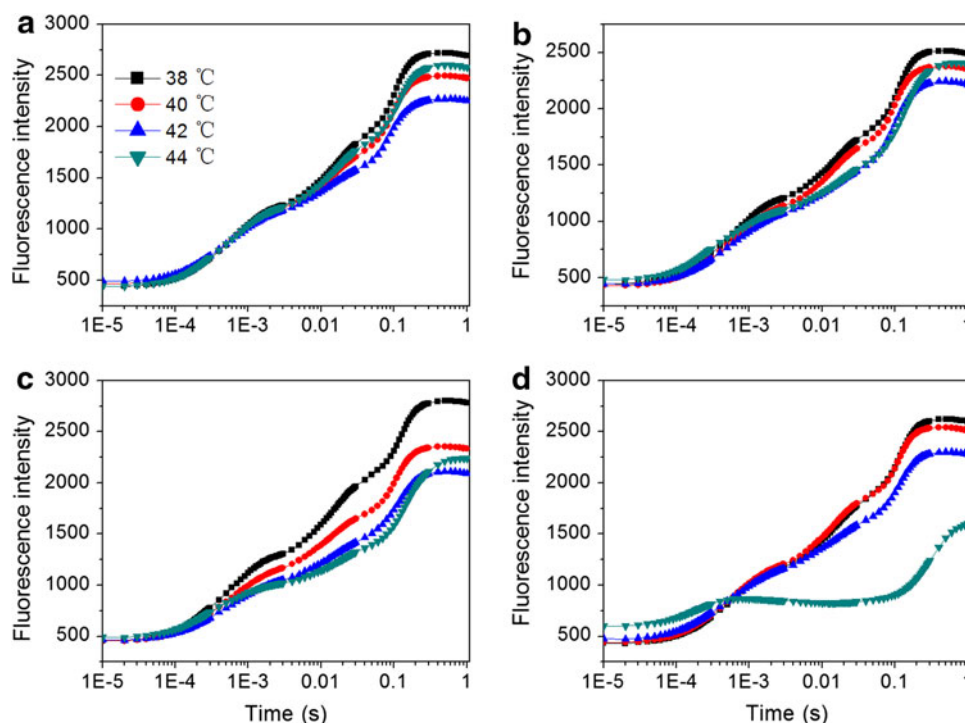
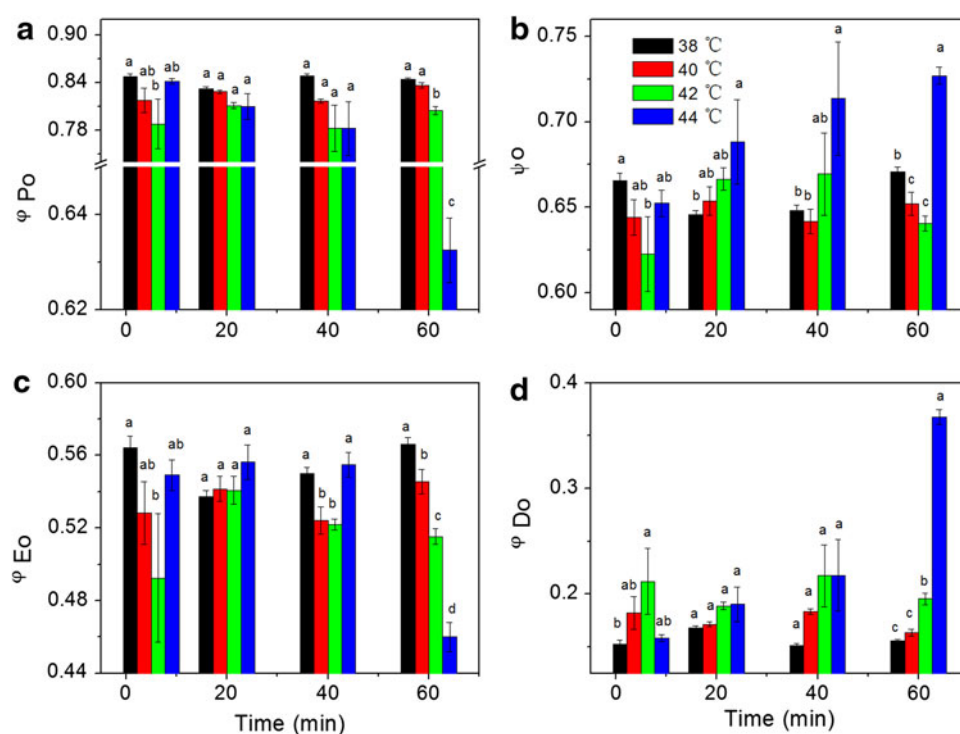


Fig. 2 Quantum efficiencies of the leaves of *A. sparsifolia* (38, 40, 42, and 44 °C, in the dark) under different time treatments of 5, 20, 40, and 60 min. φ_{Po} (a) denotes the maximum quantum yield for primary photochemistry (at $t = 0$), ψ_o (b) is the efficiency at which a trapped exciton can move an electron into the electron transport chain beyond Q_A (at $t = 0$); φ_{Eo} (c) denotes the quantum yield of electron transport (at $t = 0$); and φ_{Do} (d) is the quantum yield of energy dissipation (at $t = 0$). The same letters indicate no significant difference between same stress time and different temperature levels, whereas different letters indicate a significant difference ($P < 0.05$). Data are mean \pm SE of eight independent measurements



electron in PSII can be used as indicators of plant damage (Strasser et al. 2000, 2004).

The rise in chlorophyll fluorescence induction reveals a characteristic O-J-I-P polyphasic transient at room temperature (Strasser et al. 2000, 2004). Fluorescence transient rises from the origin point O to the fluorescence peak P

faster when the reoxidation of Q_A^- is inhibited by any stress, thus resulting in a characteristic O-K-J-I-P polyphasic transient when plotted on a logarithmic scale.

In our study, a marked K-step was found at 44 °C for 60 min in darkness (Fig. 1). Phase K results from an inhibition of the electron donor to the secondary electron donor of PSII,

Fig. 3 Reaction center parameters of the leaves of *A. sparsifolia* (38, 40, 42, and 44 °C, in the dark) under different time treatments of 5, 20, 40, and 60 min RC/CS_o. (a) denotes the density of reaction centers; ABS/RC (b) stands for the absorption flux per reaction center; TR_o/RC (c) is the trapping flux per reaction center; and DI_o/RC (d) is the dissipated energy flux per reaction center. The same letters indicate no significant difference between same stress time and different temperature levels, whereas different letters indicate a significant difference ($P < 0.05$). Data are mean \pm SE of eight independent measurements

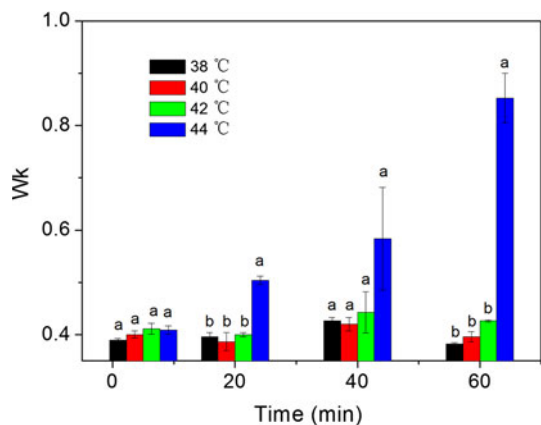
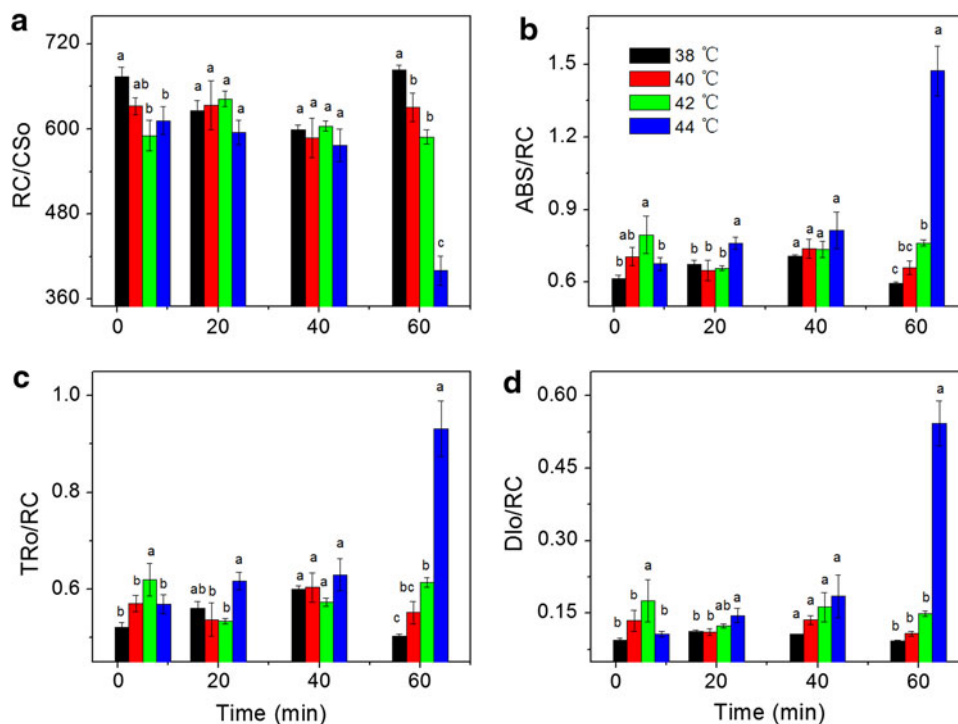


Fig. 4 Ratio of variable fluorescence at the K-step to the amplitude $F_j - F_o$ (W_k) of the leaves of *A. sparsifolia* (38, 40, 42, and 44 °C, in the dark) under different time treatments of 5, 20, 40, and 60 min. The same letters indicate no significant difference between same stress time and different temperature levels, whereas different letters indicate a significant difference ($P < 0.05$). Data are mean \pm SE of eight independent measurements

which can be attributed to a damaged OEC. Thus, phase K can be used as a specific indicator of OEC damage. The results reveal that the donor side of PSII might be damaged (Allakhverdiev et al. 2008; Kreslavski et al. 2009).

From the JIP test, the maximum quantum yield for primary photochemistry ($\phi_{P_0} = F_v/F_m$), the quantum yield of electron transport (ϕ_{E_0}), the motion of a trapped exciton into the electron transport chain beyond Q_A (ψ_0), and the quantum yield of energy dissipation (ϕ_{D_0}) could be estimated (Fig. 2). The ϕ_{P_0} and ϕ_{E_0} values are slightly

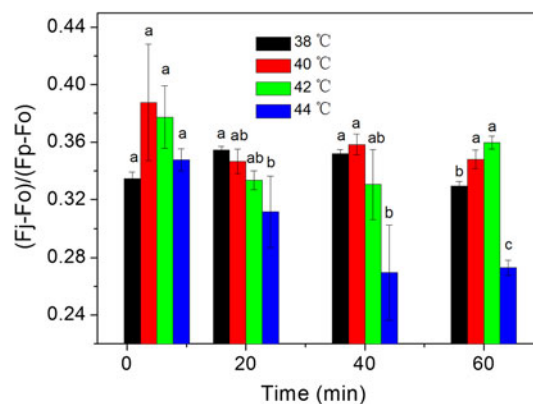


Fig. 5 Fluorescence parameters $(F_j - F_o)/(F_p - F_o)$ of the leaves of *A. sparsifolia* (38, 40, 42, and 44 °C, in the dark) under different time treatments of 5, 20, 40, and 60 min. The same letters indicate no significant difference between same stress time and different temperature levels, whereas different letters indicate a significant difference ($P < 0.05$). Data are mean \pm SE of eight independent measurements

changed from 5 to 40 min and are seriously affected by the temperature treatment at 60 min, which indicates that the increase of ψ_0 at 5–40 min is attributed to the enhanced electron flow from Q_A^- to Q_B or Q_B^- , which facilitates normal photosynthesis. The activity of PSII RC in leaves was also damaged seriously by high temperature in darkness. The results are shown in Fig. 1.

Excess excitation energy was converted into thermal dissipation, thus maintaining the energy balance between absorption and utilization to protect the cell growth under

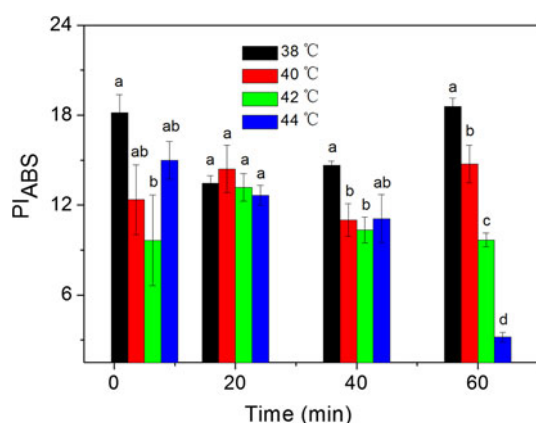


Fig. 6 Performance index on absorption basis PI_{ABS} of the leaves of *A. sparsifolia* (38, 40, 42, and 44 °C, in the dark) under different time treatments of 5, 20, 40, and 60 min. The same letters indicate no significant difference between same stress time and different temperature levels, whereas different letters indicate a significant difference ($P < 0.05$). Data are mean \pm SE of eight independent measurements

various environment stresses (Hagemeyer 1999; Perales-Vela et al. 2007). In general, with the increasing stress, RC/CS_o is inhibited and the number of RC/CS_o is reduced. Consequently, the decrease in the number of RC/CS_o resulted in increased ABS/RC , TR_o/RC , and DI_o/RC (Ali et al. 2006). In our study, among the reaction center parameters of the leaves of *A. sparsifolia*, RC/CS_o decreased, whereas ABS/RC , TR_o/RC and DI_o/RC increased in darkness. This finding implies that energy was dissipated to maintain the energy balance to certain extent. Otherwise, a blockage in electron transfer on the acceptor side of PSII would occur (Zhang et al. 2010; Chen et al. 2008).

W_K was increased at 44 °C compared with other temperature gradients, and a pronounced K-step was found at 44 °C for 60 min in darkness (Figs. 1, 4). This result indicates that the high temperature (44 °C) has limited the acceptor side of the electron transport chain. The ratio of $(F_j - F_o)$ to $(F_p - F_o)$ declined at 44 °C at 60 min compared to that at 5–40 min. The K-step was found at 44 °C in 60 min (Figs. 1d, 5), indicating that the fraction of inactivated reaction centers that cannot transport electrons from Q_A to Q_B increased (Dai et al. 2004). The results are shown in Fig. 3a. The above changes resulted in a drastic decrease in the overall photosynthesis performance index (PI_{ABS}), which is a parameter that is sensitive to environment stress (Wang et al. 2012).

In conclusion, normal temperature (below 42 °C) would not affect the PSII of *A. sparsifolia* in darkness with respect to the different time gradient stresses in this area. An elevation in air temperature to 44 °C under extreme weather in ambient environment would limit the activity of

PSII when retained for 40 min and would result in severe damage when retained for 60 min. Such conditions may result in the photoinhibition and metabolic impairment of *A. sparsifolia* at the southern Taklamakan Desert before its adaption to 44 °C which is transient elevation in air temperature under extreme weather conditions.

Author contribution Lei Li is responsible for conception and design, analysis and interpretation, data collection and critical revision of the article. Xin-wen Xu, Lisha Lin, Fan-jiang Zeng performed research and analyzed data. Xiang-yi Li obtained funding and took the overall responsibility.

Acknowledgments This study was supported jointly by the key Project in the National Science and Technology Pillar Program (2009BAC54B03), the National Basic Research Program of China (2009CB421303) and the key program for Science and Technology Development of Xinjiang (200933125). We would like to thank Feng-Li Chen, Wei-Cheng Luo and Cong Song for their helpful during manuscript preparation. We also would like to thank the reviewers for their valuable comments on the version of the manuscript.

References

- Ali NA, Dewez D, Didur O, Popovic R (2006) Inhibition of photosystem II photochemistry by Cr is caused by the alteration of both D_1 protein and oxygen evolving complex. *Photosynth Res* 89:81–87
- Allakhverdiev SI, Kreslavski VD, Klimov VV, Los DA, Carpentier R, Mohanty P (2008) Heat stress: an overview of molecular responses in photosynthesis. *Photosynth Res* 98:541–550
- Aro E-M, Virgin I, Andersson B (1993) Photo inhibition of photosystem II: inactivation, protein damage and turnover. *Biochim Biophys Acta* 1143:113–134
- Briantais J-M, Dacosta J, Goulas Y, Ducruet J-M, Moya I (1996) Heat stress induces in leaves an increase of the minimum level of chlorophyll fluorescence F_o : a time-resolved analysis. *Photosynth Res* 48:189–196
- Bukhov NG, Carpentier R (2000) Heterogeneity of photosystem II reaction centers as influenced by heat treatment of barley leaves. *Physiol Plantarum* 110:279–285
- Čajánek M, Štroch M, Lachetová I, Kalina J, Spunda V (1998) Characterization of the photosystem II inactivation of heat-stressed barley leaves as monitored by the various parameters of chlorophyll a fluorescence and delayed fluorescence. *J Photochem Photobiol B* 47:39–45
- Cardoso PG, Raffaelli D, Pardal MA (2008) The impact of extreme weather events on the seagrass *Zostera noltii* and related hydrobia ulvae population. *Mar Pollut Bull* 56:483–492
- Chen S, Yin C, Dai X, Qiang S, Xu X (2008) Action of tenuazonic acid, a natural phytotoxin, on photosystem II of spinach. *Environ Exp Bot* 62:279–289
- Crafts-Brandner SJ, Salvucci ME (2002) Sensitivity of photosynthesis in a C_4 plant, maize, to heat stress. *Plant Physiol* 129:1773–1780
- Dai J, Gao H, Zou Q (2004) Changes in activity of energy dissipating mechanisms in wheat flag leaves during senescence. *Plant Biol* 6:171–177
- Hagemeyer J (1999) Ecophysiology of plant growth under heavy metal stress. In: Prasad J, Hagemeyer J (eds) Heavy metal stress in plants. Springer, Berlin, pp 157–181

- IPCC (Intergovernmental Panel on Climate Change) (2007) Climate change: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge
- Kaňa R, Vass I (2008) Thermo imaging as a tool for studying light-induced heating of leaves: correlation of heat dissipation with the efficiency of photosystem II photochemistry and non-photochemical quenching. *Environ Exp Bot* 64:90–96
- Kreslavski VD, Lubimov VY, Shabnova NI, Balakhnina TI, Kosobryukhov AA (2009) Heat-induced impairments and recovery of photosynthetic machinery in wheat seedlings: role of light and prooxidant-antioxidant balance. *Physiol Mol Biol Plant* 15(2):115–122
- Li XY, Zhang XM, Zeng FJ, Foetzki A, Thomas FM, Li XM, Runge M, He XY (2002) Water relations on *Alhagi sparsifolia* in the southern fringe of Taklamakan Desert. *Acta Bot Sin* 44:1219–1224
- Lu CM, Zhang JH (1999) Heat-induced multiple effects on PSII in wheat plants. *J Plant Physiol* 156:259–265
- Mohanty P, Allakhverdiev SI, Murata N (2007) Application of low temperatures during photo inhibition allows characterization of individual steps in photo damage and repair of photosystem II. *Photosynth Res* 94:217–234
- Mohanty P, Kreslavski VD, Los DA, Klimov VV, Carpentier R, Allakhverdiev SI (2012) Heat stress: susceptibility, recovery and regulation. In: Eaton-Rye JJ, Tripathy BC (eds) *Photosynthesis. Plastid biology, energy conversion and carbon assimilation*, chapter 12. Springer, Dordrecht, pp 251–274
- Murata N, Takahashi S, Nishiyama Y, Allakhverdiev SI (2007) Photo inhibition of photosystem II under environmental stress. *Biochim Biophys Acta* 1767:414–421
- Musil CF, Van Heerden PDR, Cilliers CD, Schmiedel U (2009) Mild experimental climate warming induces metabolic impairment and massive mortalities in southern African quartz field succulents. *Environ Exp Bot* 66:79–87
- Nishiyama Y, Allakhverdiev SI, Murata N (2005) Inhibition of the repair of photosystem II by oxidative stress in cyanobacteria. *Photosynth Res* 84:1–7
- Nishiyama Y, Allakhverdiev SI, Murata N (2006) A new paradigm for the action of reactive oxygen species in the photo inhibition of photosystem II. *Biochim Biophys Acta* 1757:742–749
- Perales-Vela HV, Gonzalez-Moreno S, Montes-Horcasitas C, Canizares-Villanueva RO (2007) Growth, photosynthetic and respiratory responses to sub-lethal copper concentrations in *Scenedesmus incrassatulus* (Chlorophyceae). *Chemosphere* 67:2274–2281
- Piessens K, Adriaens D, Jacquemyn H, Honnay O (2009) Synergistic effects of an extreme weather event and habitat fragmentation on a specialised insect herbivore. *Oecologia* 159:117–126
- Romero LM, Reed JM, Wingfield JC (2000) Effects of weather on corticosterone responses in wild free-living passerine birds. *Gen Comp Endocr* 118:113–122
- Sharkey TD (2005) Effects of moderate heat stress on photosynthesis: importance of thylakoid reactions, rubisco deactivation, reactive oxygen species, and thermotolerance provided by isoprene. *Plant, Cell Environ* 28:269–277
- Shi YF, Shen YP (2003) Signa, impact and outlook of climatic shift from warm-dry to warm-humid in Northwest China. *Sci Tech Rev* 2:54–57
- Srivastava A, Guissé B, Greppin H, Strasser RJ (1997) Regulation of antenna structure and electron transport in photosystem II of *Pisum sativum* under elevated temperature probed by the fast polyphasic chlorophyll a fluorescence transient: OKJIP. *Biochim Biophys Acta* 1320:95–106
- Strasser RJ, Srivastava A, Tsimilli-Michael M (2000) The fluorescence transient as a tool to characterize and screen photosynthetic samples. In: Yunus M, Pathre U, Mohanty P (eds) *Probing photosynthesis: mechanisms, regulation and adaptation*. Taylor & Francis, London, pp 445–483
- Strasser RJ, Srivastava A, Tsimilli-Michael M (2004) Analysis of the chlorophyll a fluorescence transient. In: Papageorgiou G, Govindjee (eds) *Chlorophyll Fluorescence a Signature of Photosynthesis*, *Advances in Photosynthesis and Respiration*. Springer, the Netherlands, vol 19, pp 321–362
- Tang Y, Chen M, Xu Y, Kuang T (2007) Changes in thermostability of photosystem II and leaf lipid composition of rice mutant with deficiency of light-harvesting chlorophyll a/b protein complexes. *J Integr Plant Biol* 49:515–522
- Thomas FM, Arndt SK, Bruelheide H, Foetzki A, Gries D, Huang J, Popp M, Wang G, Zhang XM, Runge M (2000) Ecological basis for a sustainable management of the indigenous vegetation in a Central-Asian desert: presentation and first results. *J Appl Bot* 74:212–219
- Walther G-R, Post E, Convey P, Menzel A, Parmesan C, Beebee TJC, Fromentin J-M, Hoegh-Guldberg O, Bairlein F (2002) Ecological responses to recent climate change. *Nature* 416:389–395
- Wang SZ, Zhang DY, Pan XL (2012) Effects of arsenic on growth and photosystem II (PSII) activity of *Microcystis aeruginosa*. *Ecotox Environ Safe* 84:104–111
- Zeng FJ, Bleby TM, Landman PA, Adams MA, Arndt SK (2006) Water and nutrient dynamics in surface roots and soils are not modified by short-term flooding of phreatophytic plants in a hyperarid desert. *Plant Soil* 279:129–139
- Zhang DY, Pan XL, Mu GJ, Wang JL (2010) Toxic effects of antimony on photosystem II of *Synechocystis* sp. as probed by in vivo chlorophyll fluorescence. *J Appl Phycol* 22:479–488