草甘膦对抗草甘膦大豆光合特性日变化的影响

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摘 要:在大田条件下,采用随机区组设计,研究了不同用量草甘膦对抗草甘膦大豆(RR1)光合特性日变化的影响。结果表明:(1)在未喷施草甘膦情况下,抗草甘膦大豆(RR1)的净光合速率(*Pn*)、蒸腾速率(*Tr*)和气孔导度(*Gs*)日变化均呈单峰曲线,峰值分别出现在10:00、12:00和10:00。RR1叶片叶绿素含量指数(*CCI*)的日变化呈先降低后升高趋势,14:00左右最低。水分利用效率(*WUE*)和胞间CO_2浓度(*Ci*)随着时间的推移均呈波浪式变化,*WUE*在6:00、10:00和16:00有3个小峰,而*Ci*在6:00最高。(2)喷施草甘膦后,RR1光合特性的日变化趋势总体与未喷药前相似。*Pn*和*CCI*随草甘膦用量的增加呈降低趋势;但当草甘膦用量大于4.48 L·hm^{-2}时,*CCI*和*Pn*显著下降。12:00以前(包含12:00),除低用量(1.12 L·hm^{-2})的草甘膦促进RR1的*Gs*外,各用量抑制了RR1的*Tr*和*Gs*;而12:00以后,草甘膦却促进了RR1的*Tr*和*Gs*。草甘膦增加了RR1的*Ci*,而大于2.24 L·hm^{-2}的草甘膦却降低了RR1的*WUE*。表明光强和草甘膦会影响大豆的光合特性和叶绿素含量。

关键词:草甘膦;抗草甘膦大豆;光合特性;日变化

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Effect of Glyphosate on Photosynthesis Diurnal Variation of Glyphosate-resistant Soybean [*Glycine max* (L.) Merr.]

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Abstract: Random complete block design was used to research the different dosages of glyphosate on diurnal variation of photosynthetic characteristics in leaves of glyphosate-resistant soybean (RR1) in the field. The results showed that: (1) The trend of diurnal variation of net photosynthetic rate (*Pn*), transpiration rate (*Tr*) and stomatal conductance (*Gs*) in RR1 leaves showed a single peak curve, the peak appeared at about 10:00, 12:00 and 10:00, respectively. Chlorophyll content index (*CCI*) declined until 14:00, then increased. The water use efficiency (*WUE*) and intercellular CO_2 concentration (*Ci*) of RR1 changed like wave as time went on, *WUE* appeared three peaks at 6:00, 10:00 and 16:00, respectively, while the highest *Ci* was appeared at 6:00. (2) The trend of diurnal variation of photosynthetic characteristics in RR1 leaves treated with glyphosate was similar with the control. *Pn* and *CCI* decreased with increasing of glyphosate dosage, but only dropped significantly when glyphosate dose > 4.48 L·hm^{-2}. Glyphosate dose at 1.12 L·hm^{-2} promoted *Gs* of RR1, while the others inhibited *Tr* and *Gs* before 12:00 (including 12:00). Glyphosate increased *Tr* and *Gs* of RR1 after 12:00. *Ci* of RR1 increased with increasing of glyphosate dosage, and glyphosate > 2.24 L·hm^{-2} reduced *WUE* of RR1. Results suggest photosynthetic characteristics and chlorophyll content of RR1 leaves are affected by photosynthetic active radiation and glyphosate.

Key words: Glyphosate; Glyphosate-resistant soybean; Photosynthetic characteristics; Diurnal variation

光合作用与作物的产量关系密切,光合作用日变化是作物1 d光合生产过程中物质积累的主要生理过程,也是分析各因素影响作物生长和代谢的重要手段。抗草甘膦大豆(RR大豆)在许多大豆主产国已经成为主导品种[1]。研究草甘膦对抗草甘膦大豆光合日变化的影响具有重要的理论和现实意义。有研究表明[2-5],推荐剂量的草甘膦对RR大豆没有负面影响;也有研究表明[6-7],用草甘膦处理RR大豆可使其叶片发黄、皱缩。在温室和大田的试验中,RR大豆的氮固定或同化效率很少受推荐剂量草甘膦的影响,特别是在大豆早期生育阶段;但是高剂量的草甘膦会抑制RR大豆氮的固定或吸

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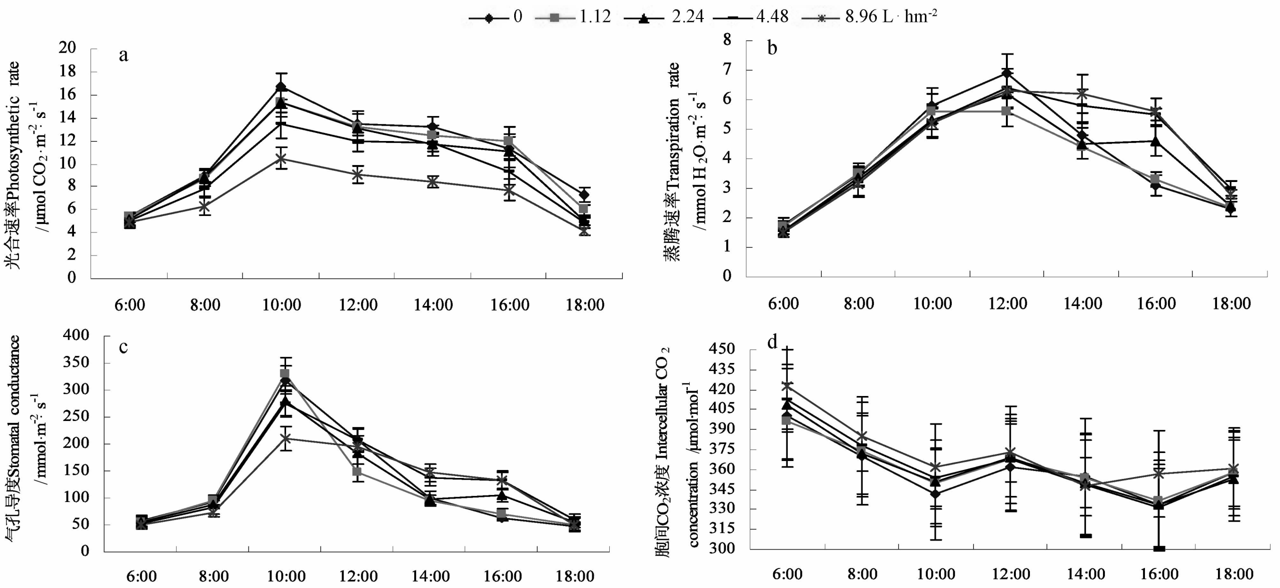

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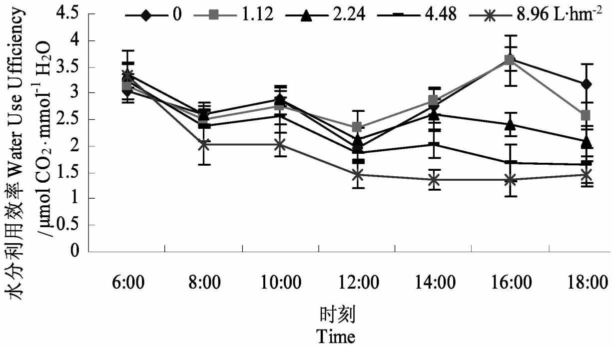

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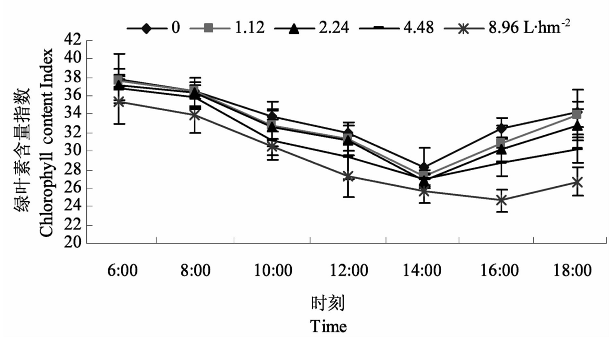

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降幅度较大。12：00 以前，除低用量（1.12 L·hm^{-2}）的农达 41% 水剂促进 RR1 的 *Gs* 外，各用量抑制了 RR1 的 *Tr* 和 *Gs*；14：00 以后，草甘膦处理却促进了 RR1 的 *Tr* 和 *Gs*。

表 1 光合特性各指标间的相关系数

Table 1 Correlative coefficient between photosynthetic characteristics in leaves of RR1 and other factors

变量	净光合速率 *Pn*	蒸腾速率 *Tr*	气孔导度 *Gs*	胞间 CO_2浓度 *Ci*	水分利用率 *WUE*	叶绿素含量指数 *CCI*
净光合速率 *Pn*	–					
蒸腾速率 *Tr*	0.87547 * *	–				
气孔导度 *Gs*	0.83241 *	0.81752 *	–			
胞间 CO_2浓度 *Ci*	–0.69993	–0.40307	–0.34353	–		
水分利用率 *WUE*	–0.30585	–0.70521	–0.46185	–0.27333	–	
叶绿素含量指数 CCI	–0.641435	–0.56038	–0.17964	0.61555	0.13515	–
光合有效辐射 PAR	0.90582 * *	0.81207 *	0.57229	–0.71823	–0.23750	–0.86747 *
草甘膦用量 Glyphosate Dosage	–0.99971 * *	0.80517	0.09326	0.97254 * *	–0.98001 * *	–0.99947 * *

表中 * 表示显著相关，* * 表示极显著相关。

* and * * indicate significant correlation at the 0.05 level or extremely significant correlation at the 0.01 level, respectively.

相关研究表明[13-14,16]，大豆光合日变化并不遵循一种固定不变的模式，概括起来有单峰型、双峰型、波动型和平缓型 4 种不同类型。气孔是植物与外界交换 CO_2和水分的通道，*Gs* 的大小直接影响植物 *Pn* 和 *Tr*，间接影响 *WUE*。叶片 *Pn* 降低如果是气孔因素所致，则 *Gs* 降低，气孔限制值升高，光能转化和碳同化速率仍然较高，致使 *Ci* 降低；如果是非气孔因素，则 *Gs* 不降低，气孔限制值不升高，光抑制现象加剧，并造成 *Ci* 升高[18-20]。RR1 在中午前后 *Gs* 下降，但 *Ci* 却没有下降，说明 *Gs* 下降的同时，叶肉同化 CO_2的能力也在下降，由此得出，*Pn* 的降低是气孔因素和非气孔因素共同作用所致。草甘膦增加了 RR1 的 *Ci*，表明草甘膦影响了 RR 大豆的光能转换。

叶绿素是捕获光能，进行光能转换的基本色素。研究表明[21-22]，在长期弱光条件下，植物叶片会发生一系列生理变化来适应环境，如通过增加叶绿素含量来增强捕光能力；而在强光条件下，植物通过加厚叶片，降低叶绿素含量，提高类胡萝卜素含量等，增加热耗散，保护其不受强光危害。该研究中，RR1 叶片的叶绿素含量在早晨和傍晚光强较弱时值较大，而在中午前后 *CCI* 值明显降低，说明即使在 1 d 之中，植物也会通过改变自身叶片的叶绿素代谢来适应环境变化，以达到较高的光能利用率。高于 4.48 L·hm^{-2}的草甘膦显著降低 RR1 的 *CCI* 值，与该课题组前期研究结果一致[4-5]。

较高用量的草甘膦抑制 RR1 的 *WUE*。*WUE* 的高低是 *Pn* 和 *Tr* 竞争的结果，当 *Pn* 大于 *Tr* 时，*WUE* 高，反之则低。

综上所述，草甘膦和外界环境如光照、温度等均影响抗草甘膦大豆叶片的叶绿素含量、气孔状态或光能转化。在草害较严重的 RR 大豆田，不超过 4.48 L·hm^{-2}农达 41% 水剂用量前提下，可适当提高其用量。

参考文献

[1] Reddy K N. Glyphosate-resistant soybean as a weed management tool: Opportunities and challenges[J]. Weed Biology and Management, 2002, 1(4): 193-202.

[2] Nelson K A, Renner K A. Cost-effective weed management in wide and narrow-row glyphosate resistant soybean[J]. Journal of Production Agriculture, 1999, 12: 460-465.

[3] Nelson K A, Renner K A. Soybean growth and development as affected by glyphosate and post emergence herbicide tank mixtures [J]. Agronomy Journal, 2001, 93(2): 428-434.

[4] 原向阳，郭平毅，张丽光，等. 不同时期喷施草甘膦对大豆生理指标的影响[J]. 中山大学学报(自然科学版), 2009, 48(2): 90-94. (Yuan X Y, Guo P Y, Zhang L G, et al. Impact of spraying glyphosate on physiological index of soybean at different growth stages[J]. Acta Scientiarum Naturalium Universitatis Sunyatseni(Natural Science Edition), 2009, 48(2): 90-94.)

[5] 原向阳，张丽光，郭平毅，等. 第一复叶期喷施农达 41% 水剂对大豆生理指标的影响[J]. 中国生态农业学报, 2008, 16(2): 401-404. (Yuan X Y, Zhang L G, Guo P Y, et al. Impact of Roundup 41% aqua on physiological index of soybean at one-trifoliolate leaf stage [J]. Chinese Journal of Eco-Agriculture, 2008, 16(2): 401-404.)

[6] Weber M L, Kapusta G. Control of tall weeds in soybean with glyphosate[J]. Research Report of the North Central Weed Sci-

ence Society,1998,55:371-373.

[7] Young B G, Young J M. Influence of late season post-emergence herbicides on soybean growth and development [J]. Research Report of the North Central Weed Science Society, 2000, 57: 263-264.

[8] Zablotowicz R M, Krishna N R. Impact of glyphosate on the *Bradyrhizobium japonicum* symbiosis with glyphosate-resistant transgenic soybean: A mini-review[J]. Journal of Environmental Quality,2004,33:825-831.

[9] Zablotowicza R M, Krishna N R. Nitrogenase activity, nitrogen content and yield responses to glyphosate in glyphosate-resistant soybean[J]. Crop Protection,2007,26(3):370-376.

[10] King C A, Purcell L C, Earl D V. Plant growth and nitrogenase activity of glyphosate-tolerant soybean in response to foliar glyphosate applications[J]. Agronomy Journal,2001,93:179-186.

[11] 原向阳,郭平毅,张丽光,等. 干旱胁迫下草甘膦对抗草甘膦大豆幼苗保护酶活性及脂质过氧化作用的影响[J]. 中国农业科学, 2010,43(4): 698-705. (Yuan X Y, Guo P Y, Zhang L G, et al. Glyphosate and post-drought rewatering on protective enzyme activities and membrane lipid peroxidation in leaves of glyphosate-resistant soybean [*Glycine max* (L.) Merr.] seedlings [J]. Scientia Agricultura Sinica, 2010,43(4):698-705.)

[12] 原向阳,毕耀宇,王鑫,等. 除草剂对抗草甘膦大豆光合作用和蒸腾作用的影响[J]. 农业现代化研究, 2006,27(4):311-313. (Yuan X Y, Bi Y Y, Wang X, et al. Effect of herbicides on photosynthesis and transpiration of glyphosate-resistant soybean [J]. Research of Agricultural Modernization,2006,27(4):311-313.)

[13] 高辉远,邹琦,程炳嵩. 大豆光合日变化的不同类型及其影响因素[J]. 大豆科学,1992,11(3):219-225. (Gao H Y, Zou Q, Cheng B S. The different types of diurnal course of photosynthesis of soybean [*Glycine max* (L). Merr.] leaves and related factors [J]. Soybean Science,1992,11(3):219-225.)

[14] 高辉远,邹琦,程炳嵩. 大豆光合日变化与内生节奏的关系(简报)[J]. 植物生理学通讯, 1992,28(4):262-264. (Gao H Y, Zou Q, Cheng B S. Relationship between diurnal variation of photosynthesis and circadian rhythm in soybean leave [J]. Plant Physiology Communication,1992,28(4):262-264.)

[15] 邹冬生,郑丕尧,王瑞舫. 大豆叶片光合、蒸腾的日变化及其与生态因子的相关性研究[J]. 植物生态学与植物学学报, 1990,14(4):350-357. (Zou D S, Zheng P Y, Wang R F. Studies on the diurnal variation of the photosynthesis and transpiration of soybean leaf and its correlation with ecological factors in field conditions [J]. Acta Phytoecologica Geobotanica Sinica,1990,14(4): 350-357.)

[16] 郑国生,邹琦. 不同天气条件下田间大豆光合作用日变化的研究[J]. 中国农业科学,1993,26(1):44-50. (Zheng G S, Zou Q. A study on the diurnal variation of photosynthesis of field-grown soybean in different weather conditions [J]. Scientia Agricultura Sinica, 1993,26(1):44-50.)

[17] 原向阳,郭平毅,张丽光,等. 草甘膦对大豆光合特性日变化的影响[J]. 山西农业大学学报(自然科学版),2010,30(6): 500-504. (Yuan X Y, Guo P Y, Zhang L G, et al. Effect of glyphosate on diurnal variation of photosynthesis in leaves of glyphosate-resistant soybean [*Glycine max* (L.) Merr.] [J]. Journal of Shanxi Agricultural University (Natural Science Edition),2010,30(6):500-504.)

[18] 高辉远,邹琦,程炳嵩. 大豆光合日变化过程中气孔限制和非气孔限制的研究[J]. 西北植物学报,1993,13(2):96-102. (Gao H Y, Zou Q, Cheng B S. Study on the stomatal and nonstomatal limitation during the diurnal course of photosynthesis in soybean leaves [J]. Acta Botanica Boreali-Occidentalla Sinica, 1993,13(2):96-102.)

[19] 张瑞朋,杨德忠,傅连舜,等. 不同来源大豆品种光合速率日变化及其影响因子的研究[J]. 大豆科学,2007,26(4):490-495. (Zhang R Y, Yang D Z, Fu L S, et al. Research of photosynthesis diurnal variation and its affecting factors for different source soybeans [J]. Soybean Science,2007,26(4):490-495.)

[20] 郑国生,王焘. 田间冬小麦叶片光合午休过程中的非气孔限制[J]. 应用生态学报,2001,12(5):799-800. (Zheng G S, Wang T. Nonstomatic limitations in midday depression of photosynthesis in winter wheat leaves[J]. Chinese Journal of Applied Ecology, 2001,12(5):799-800.)

[21] 何春霞,李吉跃,张燕香,等. 五种绿化树种叶片比叶重、光合色素含量和 $\delta^{13}C$ 的开度与方位差异[J]. 植物生态学报, 2010,34(2):134-143. (He C X, Li J Y, Zhang Y X, et al. Differences in leaf mass per area, photosynthetic pigments and $\delta^{13}C$ by orientation and crown position in five greening tree species [J]. Chinese Journal of Plant Ecology,2010,34(2):134-143.)

[22] 周忆堂,马红群,梁丽娇,等. 不同光照条件下长春花的光合作用和叶绿素荧光动力学特征[J]. 中国农业科学, 2008, 41(11): 3589-3595. (Zhou Y T, Ma H Q, Liang L J, et al. Photosynthetic characteristics and chlorophyll fluorescence in leaves of *Catharanthus roseus* grown under different light intensities[J]. Scientia Agricultura Sinica, 2008,41(11):3589-3595.)