Application of Grey System Theory on Biology: (2) Photosystem I Attributes More Than Photosystem II to Photosynthesis Rate in Higher Plants

Wen-Dar Huang[1*], Jr-Syu Yang[2], Ming-Huang Hsu[1], Zu-Wei Yang[1], Yang-Zenq Tsai[1], Shine-Shiang Chang[1] and Chi-Ming Yang[3*]

1. *Department of Agronomy, National Taiwan University, Daan, Taipei, Taiwan 101*
2. *Department of Mechanical and Electro-Mechanical Engineering, Tamkang University, Tamshui, Taipei County, Taiwan 251*
3. *Institute of Botany, Academia Sinica, Nankang, Taipei, Taiwan 115*

*Corresponding author.
Email: wendar@ntu.edu.tw (WDH); cmyang@gate.sinica.edu.tw (CMY).

Abstract

The grey relation analysis was applied to analyze the contribution degree of the antenna and peptides of photosystem I (PSI) and photosystem II (PSII) on the maximal photosynthetic rate (P_{max}) of *Arabidopsis thaliana* during their response to low and high growth irradiance. The original data was from Bailey *et al* (2001). For all growth irradiance (0-600 μmol $m^{-2}s^{-1}$) and for low (0-200 μmol $m^{-2}s^{-1}$) and high (400-600 μmol $m^{-2}s^{-1}$) growth irradiance, the antenna and peptides of PSI play more contribution to P_{max} than these of PSII. It is apparent that PSI is more important than PSII in photosynthesis.

Key word: grey relational analysis, contribution degree; antenna, PSI; PSII; maximal photosynthetic rate.

Introduction

It is well known that all chlorophylls are non-covalently bound to intrinsic polypeptides to form pigment- protein complexes in the thylakoid membrane of higher plants [1]. Light quanta captured by chlorophyll and carotenoid pigments are channeled into the specific reaction centers of PSI and PSII where the primary photochemical conversion occurs. PSI and PSII are connected in series and function to transport electron from H_2O to $NADP^+$ so that the proton gradient can be generated to produce ATP. Both PSI and PSII contain reaction center and light-harvesting complex (antenna), both of which are pigment-protein complexes.

Many external factors in nature such as light intensity and regime, photoperiod, temperature, and relative humidity apparently influence P_{max}. Internal factors such as the components of pigment-protein complexes, i.e. reaction centers and light-harvesting complexes, may also play an important role in P_{max}. However, no data explored the contribution degree of the polypeptides of PSI and PSII on P_{max}.

The maximal photosynthesis rate is a combined effect of all components in leaf, especially PSI and PSII in the chloroplast. It is very important to determine what part of the photosynthesis results from individual constituents of PSI and/or PSII. No solution can be found in the traditional theory of mathematics and statistics. However, the grey system theory can solve this problem [2,3]. Using grey relational analysis, it has been found that PSI plays more important in P_{max} than PSII [4]. Grey relational analysis was successfully employed to connect satellite remote sensing data monitored in space and chlorophyll biochemical data detected on earth. In this way, chlorophylls and their derivatives with less or non-polar chemical structures were found to contribute much more to the normalized difference vegetation index (NDVI) than those with more polarity. The former are located in the thylakoid membrane and the latter in the stroma, of higher plant chloroplast [5]. For the satellite remote sensing vegetation indices, normalized difference vegetation index and brightness index, in Mt. Huangzui area of Yangminshan National Park, light and temperature are more important determinant climate factors than precipitation and relative humidity [6,7].

In this paper, we therefore applied grey theory to analyze the contribution degree of four and six polypeptides in PSI and PSII, respectively, on P_{max}.

Materials and Methods

Data source

The original data used in this article were taken from a paper of Bailey et al [8]. The digital data in table 1 and 2 of this article were obtained by image processing of the figures 1-3 and 5, respectively. Lhca1、Lhca2、Lhca3 and Lhca4 belong to the light-harvesting complex of PSI, whereas Lhcb1、Lhcb2、Lhcb3、Lhcb4、Lhcb5 and Lhcb6 are polypeptide components of PSII light-harvesting complex.

Grey relational analysis

The photosystem content and total or individual antenna composition were used as a comparison or test series, and P_{max} was used as a reference series (Table 1). The basic principle and method of grey relational analysis are as follows [2,3].

(1) Normalization of original data series:

Mean value normalization method is applied in the data series treatment. For example:

If the original data is $x_0(k)$ = (x(1), x(2), x(3),…,x(k)), the mean value of the original data is $\overline{X}$, then the mean value normalization data series becomes x_0^* = $(\frac{x(1)}{\overline{X}},\frac{x(2)}{\overline{X}},\frac{x(3)}{\overline{X}},...,\frac{x(k)}{\overline{X}})$ where $\overline{X} = \frac{1}{n}\sum_{k=1}^{n} x(k)$.

(2) The grey relational coefficient γ is defined as follows :

$$\gamma(x_0(k), x_j(k)) = \frac{\min_j \min_k \left\| x_0(k) - x_j(k) \right\| + \zeta \max_j \max_k \left\| x_0(k) - x_j(k) \right\|}{\left\| x_0(k) - x_j(k) \right\| + \zeta \max_j \max_k \left\| x_0(k) - x_j(k) \right\|}$$

where

j = 1 , … , m; k = 1 , … , n

j is the identification coefficient; its value is taken as [0,1], usually, $\gamma = 0.5$.

x_0 is the reference data series.

x_j is the test data series.

$\left\| x_0(k) - x_j(k) \right\|$ is the absolute value (norm) of the difference between $x_0(k)$ and $x_j(k)$.

$\min_j \min_k \left\| x_0(k) - x_j(k) \right\|$ is called the secondary minimum difference which is selected in all j.

$\min_k \left\| x_0(k) - x_j(k) \right\|$ is called the first minimum difference which is selected in all k.

all the same as *max max*.

(3) The grey relational grade $\gamma^*(x_0(k), x_j(k))$ is

$$\gamma^*(x_0(k), x_j(k)) = \frac{1}{n}\sum_{k=1}^{n} \gamma(x_0(k), x_j(k)) .$$

(4) Rearrangement of grey relational grade from large value to little value in a series.

The grey relational grade has the following characteristics:

a. $0 \le \gamma^* \le 1$.

b. The more similar the test data $x_j(k)$ is to the reference data $x_0(k)$, the larger the grey relational grade value γ^*.

c. Only if the reference series $x_0(k)$ is exactly equal to the test series $x_j(k)$, does the grey relational grade value $\gamma^* = 1$.

Results and Discussion

It is apparent that the photosystems, PSI and PSII, contain various amounts of each polypeptide associated with chlorophyll and carotenoid to form pigment-protein complex, and also vary in the extent of their P_{max} during the change of growth irradiance (Table 1). In other words, the difference in polypeptide composition and/or in photosynthetic pigments of PSI and/or PSII may affect the P_{max} during the growth irradiance changes. For example, while Lhca1 of PSI increases then decreases its content, Lhcb1 of PSII always declines during as the growth irradiance intensifies.

Ten individual polypeptides were treated as a comparison or test series, and P_{max} was used as a reference series, under various growth irradiance condition, including 0-200, 200-400, 400-600, and 0-600 μmol $m^{-2}s^{-1}$. The grey relational analysis displayed consistent results under any growth irradiance (Table 2).

During the change of low irradiance between 0-200 μmol $m^{-2}s^{-1}$, the grey relational value and contribution degree of individual polypeptide is： Lhca1＞Lhca4＞Lhca2＞Lhcb4＞Lhca3＞Lhcb3＞Lhcb2＞Lhcb5＞Lhcb1＞Lhcb6. During the change of medium irradiance between 200-400 μmol $m^{-2}s^{-1}$, the grey relational value and contribution degree of individual polypeptide is： Lhcb6＞Lhcb5＞Lhcb3＞Lhcb4＞Lhca2＞Lhcb2＞Lhca4＞Lhca1＞Lhca3＞Lhcb1. During the change of high irradiance between 400-600 μmol $m^{-2}s^{-1}$, the grey relational value and contribution degree of individual polypeptide is： Lhca3＞Lhca2＞Lhca1＞Lhcb1＞Lhcb2＞Lhcb6＞Lhcb5＞Lhcb3＞Lhcb4＞Lhca10. If the entire process of irradiance, 0-600 μmol $m^{-2}s^{-1}$, was treated as one growth condition, the grey relational value and contribution degree of individual polypeptide becomes： Lhca2＞Lhca3＞Lhca1＞Lhcb6＞Lhcb5＞Lhcb3＞Lhcb4＞Lhca4＞Lhcb2＞Lhcb1. This data suggested an interesting phenomenon that the individual polypeptides of light-harvesting complexes in either PSI or PSII alter their influence ability to the photosynthesis rate as the growth irradiance change. The data further suggested that PSI made more contribution to P_{max} than PSII.

If total amount of ten individual polypeptides was treated as a comparison or test series, and P_{max} was used as a reference series, under various growth irradiance condition, including 0-200, 200-400, 400-600, and 0-600 μmol $m^{-2}s^{-1}$. The grey relational analysis displayed consistent results between individual and total amount of polypeptides of light-harvesting complexes under any growth irradiance (Table 2). In spite of any growth irradiance, the grey relational value and contribution degree always is: PSI＞PSII. This confirms the result mentioned above that PSI is more important than PSII. The total and/or individual amount of light-harvesting proteins was treated as experiment data series and the chlorophyll a/b ratio as reference data series. The contribution degree of total and individual amount of light-harvesting proteins in PSI to P_{max} was higher than those in PSII.

On the basis of evolution, PSI appeared much earlier than PSII on earth, i.e. the PSI is more intimate to photosynthesis than PSII. The PSI and PSII alter their light-harvesting proteins composition to adapt to the gradual increase of light intensity. During the adaptation process, the two photosystems manipulate the light-harvesting polypeptide composition and regulate their contribution degree to achieve the best adaptation for higher plants, so as to achieve the maximal photosynthesis rate under any environmental condition. The same mechanism can be applied to the adaptation of crops to light environment.

References

[1] Markwell, J. P., Thornber, J. P. and Boggs, R. T. 1979. Higher plant chloroplasts: evidence that all chlorophyll exists as chlorophyll-protein complexes. Proc. Natl. Acad. Sci. USA 76: 1233-1235.

[2] Deng, J. L. 1982. Control problems of grey systems. Systems and Control Lett. 5: 288-294.

[3] Deng, J. L. 1989. Introduction to grey system theory. J. Grey System 1: 1-24.

[4] Huang, W. D., Tsai, Y. Z., Chang, S. S., Yang, J. S. and Yang, C. M. 2003. The grey relational analysis of the effect of light-harvesting proteins on chlorophyll a/b ratio in higher plants. J. Agri. Assoc. China 4: 550-556

[5] Yang, Z. W. 2001. Satellite remote sensing and grey system theory applied for monitoring the vegetation stage of paddy rice. MS thesis. Graduate Institute of Agronomy, National Taiwan University.

[6] Huang, W. D., Chen, J. C., Hsu, M. H., Yang, Z. W., Chang, S. S. and Tsai, Y. Z., Huang, K. Y., Lu, L. C., Chen, C. C. and Yang, C. M. 2003. Grey relational analysis of the effect of climate factors on the satellite remote sensing brightness index of carpetgrass in Mt. Huangzui. Chinese Agron. J. 13: 59-66.

[7] Huang, W. D., Chen, J. C., Hsu, M. H., Yang, Z. W., Chang, S. S. and Tsai, Y. Z., Huang, K. Y., Lu, L. C., Chen, C. C. and Yang, C. M. 2004. Grey relational analysis of the effect of climate factors on the satellite remote sensing normalized difference vegetation index (NDVI) of vegetation in Mt. Huangzui. (submitted to Bot. Bull. Acad. Sin.).

[8] Bailey, S., R. G. Walters., S. Janson, and P. Horton. 2001. Acclimation of *Arabidosis thaliana* to the light environment: the existence of separate low light and high light responses. Planta 213: 794-801.

Table 1. The effect of growth irradiance on photosystem antenna composition and the maximal photosynthesis rate. The data were obtained by image processing of figure 4 of a paper by Bailey et al (2001). Number in parenthesis was obtained by grey theory. (A) PSI; (B) PSII.

(A) PSI

Irradiance (mol/ m^2s)	Pmax (mmol/mol Chl.s)	PSI (content per PSI)				
		Lhca1	Lhca2	Lhca3	Lhca4	Total
35	26.92	0.683	1.917	0.683	0.833	4.116
100	51.54	1.350	2.400	2.917	1.417	8.084
200	53.08	1.333	1.817	3.550	1.600	8.300
400	64.23	0.967	3.200	1.767	1.167	7.101
500	84.62	(0.892)	(3.884)	(2.267)	(0.759)	(7.801)
600	113.85	0.817	4.567	2.767	0.350	8.501

(B) PSII

Irradiance (mol/ m^2s)	Pmax (mmol/mol Chl.s)	PSII (content per PSII)						
		Lhcb1	Lhcb2	Lhcb3	Lhcb4	Lhcb5	Lhcb6	Total
35	26.92	6.700	2.557	0.843	0.629	1.557	1.671	13.957
100	51.54	2.629	1.600	0.814	0.757	0.757	0.629	7.186
200	53.08	2.200	0.771	0.643	0.643	0.557	0.543	5.357
400	64.23	0.671	0.586	0.586	0.586	0.614	0.600	3.643
500	84.62	(0.579)	(0.458)	(0.400)	(0.400)	(0.457)	(0.450)	(2.744)
600	113.85	0.49	0.33	0.21	0.21	0.30	0.49	1.844

Table. 2. Grey relational value and order of the effect of photosystem antenna, and polypeptides of *Arabidopsis thaliana* on the the maximal photosynthetic rate during their response to low and high growth irradiance.

	Growth irradiance (μmol $m^{-2}s^{-1}$)			
	0-200	200-400	400-600	0-600
Individual polypeptides				
Lhca1	0.97189(1)	0.63203(8)	0.68109(3)	0.77488(3)
Lhca2	0.76147(3)	0.72607(5)	0.94313(2)	0.92564(1)
Lhca3	0.74635(5)	0.48238(9)	1.00000(1)	0.78899(2)
Lhca4	0.92696(2)	0.63499(7)	0.39531(10)	0.70256(8)
Lhcb1	0.45135(9)	0.38132(10)	0.62156(4)	0.61763(10)
Lhcb2	0.52014(7)	0.65847(6)	0.53884(5)	0.64552(9)
Lhcb3	0.66323(6)	0.78858(3)	0.43193(8)	0.71120(6)
Lhcb4	0.75041(4)	0.78858(4)	0.43193(9)	0.71036(7)
Lhcb5	0.48097(8)	0.99669(2)	0.49929(7)	0.72997(5)
Lhcb6	0.44675(10)	1.00000(1)	0.50539(6)	0.74006(4)
Total polypeptides (antenna)				
PSI	0.99252(1)	1.00000(1)	1.00000(1)	0.81025(1)
PSII	0.45354(2)	0.73708(2)	0.53592(2)	0.60800(2)