cbiomes

Simons Collaboration on Computational Biogeochemical Modeling of Marine Ecosystems

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Article | Open access | Published: 27 August 2025

Parameterization of photoinhibition for phytoplankton

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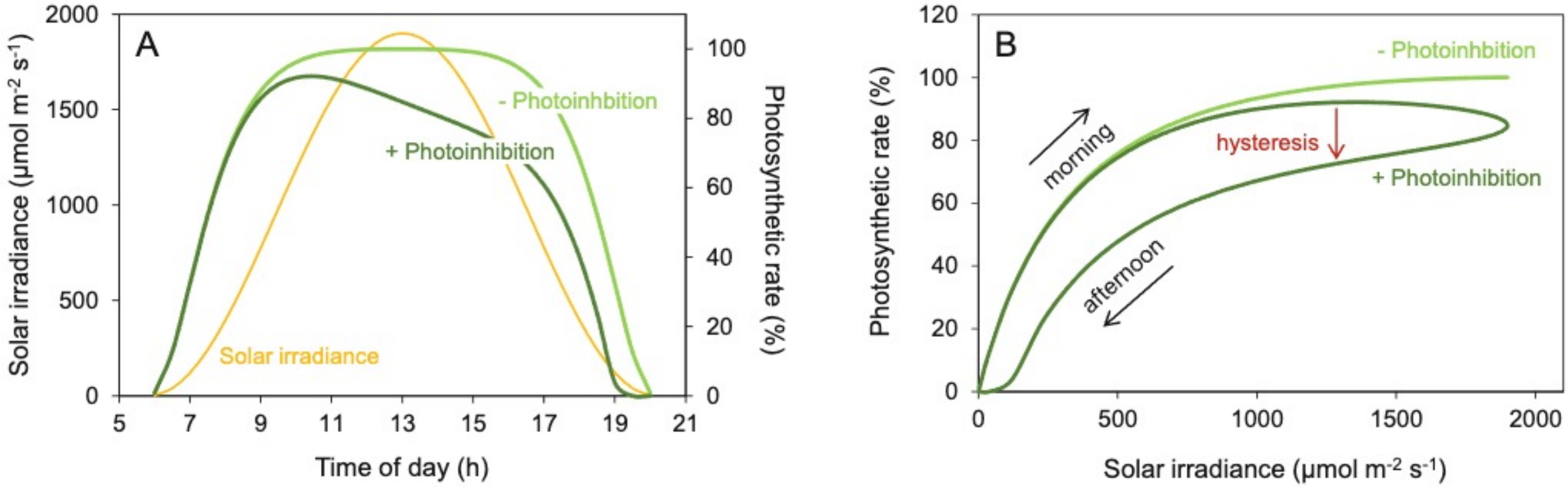
Oct 28, 2025

What is photoinhibition?

Light damage to photosynthetic machinery, resulting in decreases in photosynthetic rate.



Serôdio and Campbell (2021) 10.1007/978-3-319-71064-8_48-1

Does photoinhibition affect primary production?

- Mid-day reduction in photosynthetic energy conversion efficiency reduces quantum yield by up to 25%
- Water column integrated carbon fixation reduced by 5-20% depending on mixing rate

Long et al. (1994), fluorescence

- Depth-integrated productivity reduced 6-7% during the spring bloom in the Ross Sea Polynya on a clear day

Smyth et al (2017), model

- Photoinhibition occurred on 77% of 900 days between 10-14h (in lakes) and more photoinhibition was correlated with lower GPP

Staehr et al (2015)

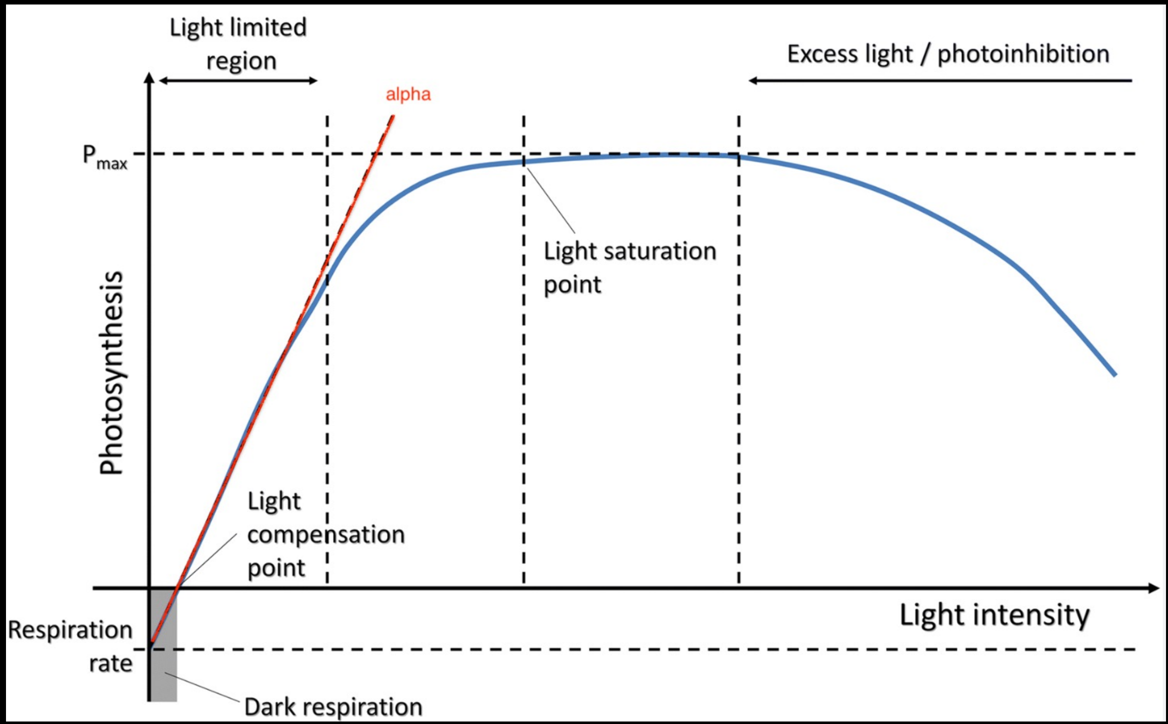
- Vertical Generalized Production Model (VGPM) with photoinhibition tends to overestimate primary production at higher values and underestimate at lower values

Lobanova et al (2018)

Components of the PI curve

The PI curve consists of 3 main regions

- Light-limited region
- Light-saturated region
- Photoinhibition region



The **PI curve** is a visualization of the biomass-normalized photosynthetic rate, P^B (mg C . [mg chl a]$^{-1}$. h^{-1}) against irradiance, I (Watts . m^{-2}).

PI curve formulations

1 $$P^B = \begin{cases} \alpha I, & I \le P_m^B/\alpha \\ P_m^B, & I > P_m^B/\alpha \end{cases}$$

2 $$P^B = P_m^B \alpha I / (P_m^B + \alpha I)$$

3 $$P^B = P_m^B \alpha I / [(P_m^B)^2 + (\alpha I)^2]^{\frac{1}{2}}$$

4 $$P^B = \alpha I \exp(-\alpha I / P_m^B e)$$

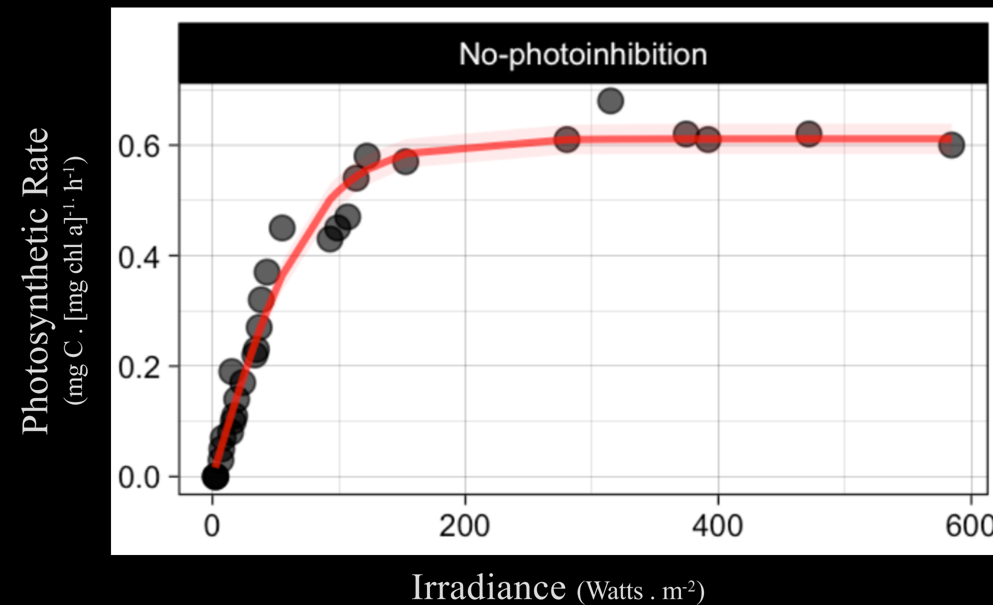
5 $$P^B = \begin{cases} \alpha I \exp(-\alpha I / P_m^B e), & I \le P_m^B e/\alpha \\ P_m^B, & I > P_m^B e/\alpha \end{cases}$$

6 $$P^B = P_m^B[1 - \exp(-\alpha I / P_m^B)]$$

7 $$P^B = \begin{cases} \alpha I - (\alpha I)^2 / 4P_m^B, & I \le 2P_m^B/\alpha \\ P_m^B, & I > 2P_m^B/\alpha \end{cases}$$

8 $$P^B = P_m^B \tanh(\alpha I / P_m^B)$$ Best model

Usual models: tanh (Eq. 8) and exp (Eq. 6)



P_{max} and α values vary by 5-40% when fit with Eq (6) model

Jassby and Platt, *L&O*, 21(4):540-547, 1976

PI curves with photoinhibition

$$P^B = P^B_m \alpha I/(P^B_m + \alpha I)$$

$$P^B = P^B_m \alpha I/[(P^B_m)^2 + (\alpha I)^2]^{\frac{1}{2}}$$

$$P^B = \alpha I \exp(-\alpha I/P^B_m e)$$

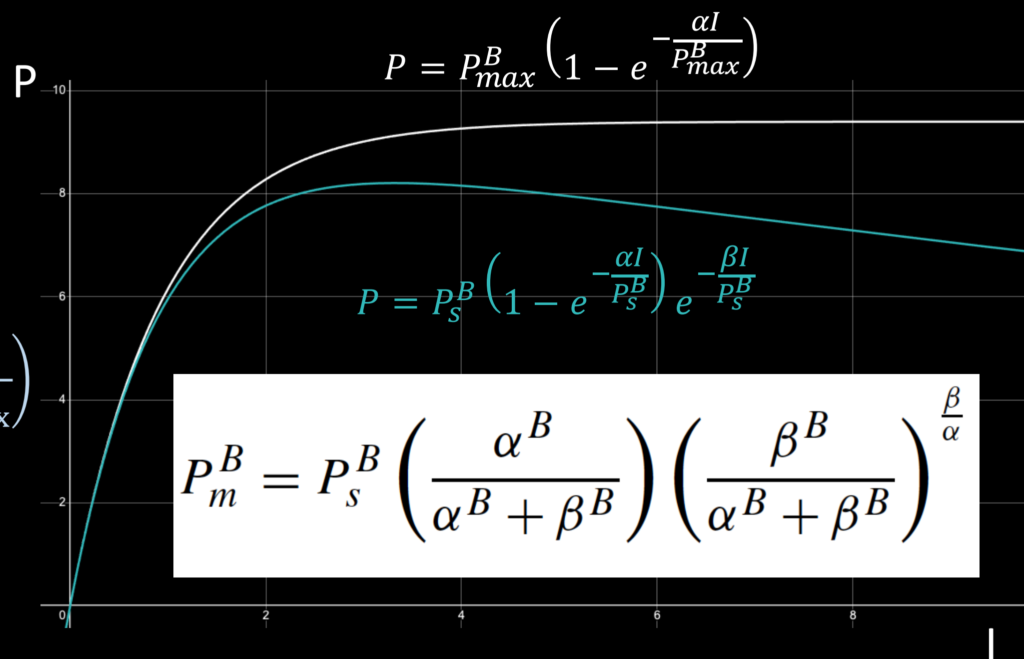
$$P^B = \begin{cases} \alpha I \exp(-\alpha I/P^B_m e), & I \leq P^B_m e/\alpha \\ P^B_m, & I > P^B_m e/\alpha \end{cases}$$

$$P^B = P^B_m[1-\exp(-\alpha I/P^B_m)]$$ Best model

$$P^B = \begin{cases} \alpha I - (\alpha I)^2/4P^B_m, & I \leq 2P^B_m/\alpha \\ P^B_m, & I > 2P^B_m/\alpha \end{cases}$$

$$P^B = P^B_m \tanh(\alpha I/P^B_m)$$

$$\times \exp\left(-\frac{\beta I}{\mathrm{P}^B_{\mathrm{max}}}\right)$$



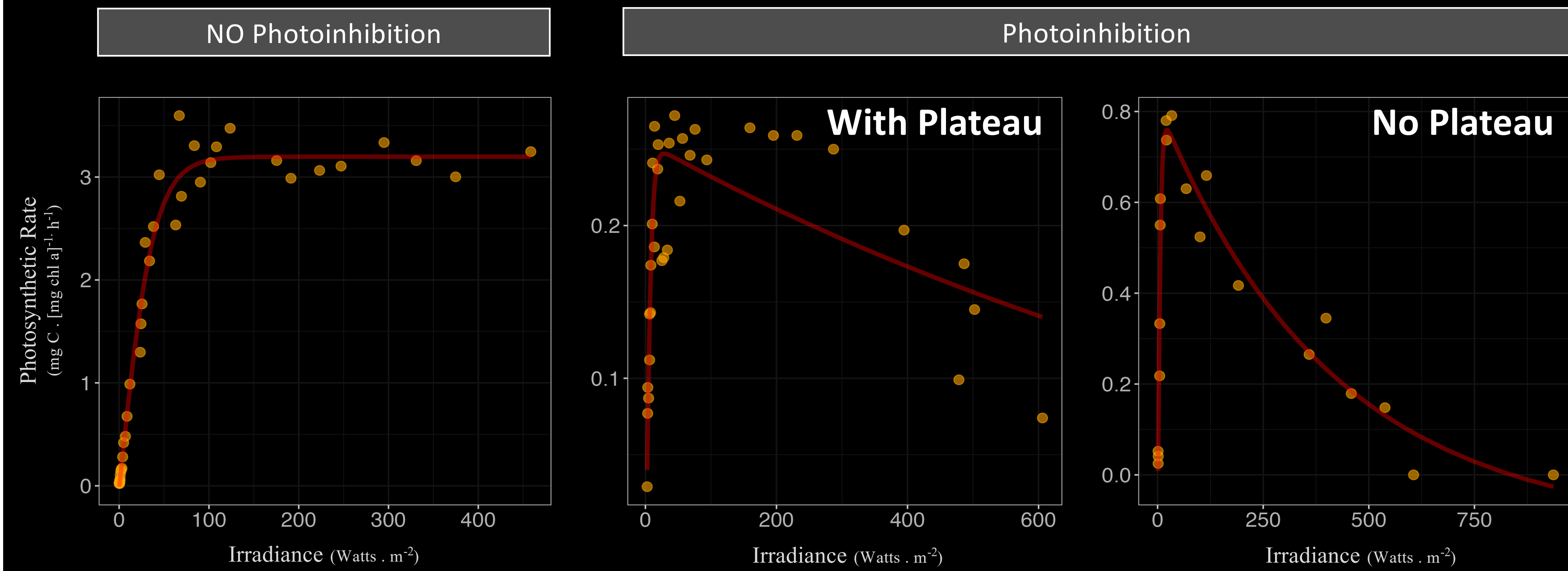
$$P^B_m = P^B_s\left(\frac{\alpha^B}{\alpha^B + \beta^B}\right)\left(\frac{\beta^B}{\alpha^B + \beta^B}\right)^{\frac{\beta}{\alpha}}$$

P_{max} and α values vary when fit with different models

Steele, *L&O*, 1962
Platt et al. *J. Mar. Sci*, 1980

Neale et al. *J. Plankton Res*, 1987
Bouman et al. *ESSD*, 2018

Models don’t describe a plateau in PI curve



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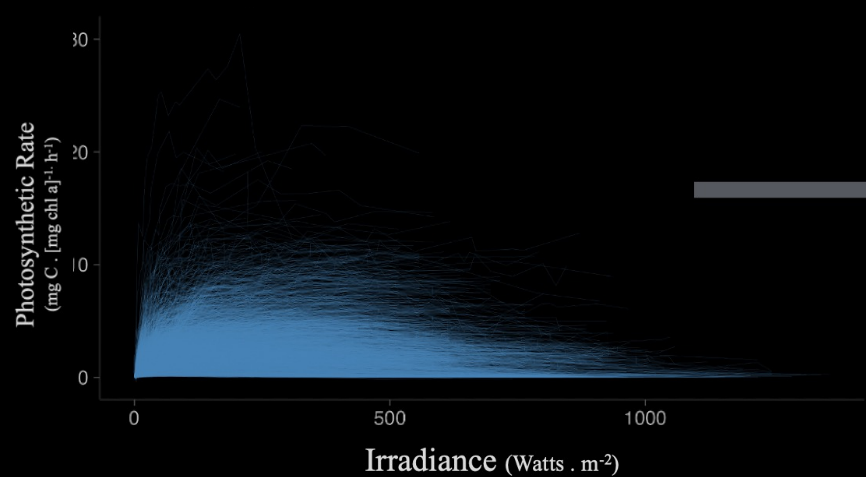
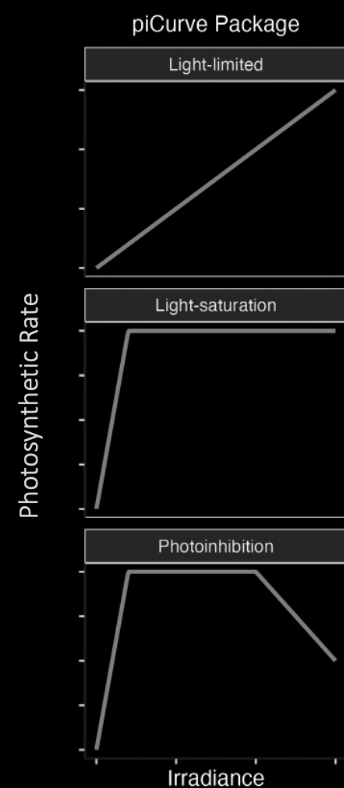
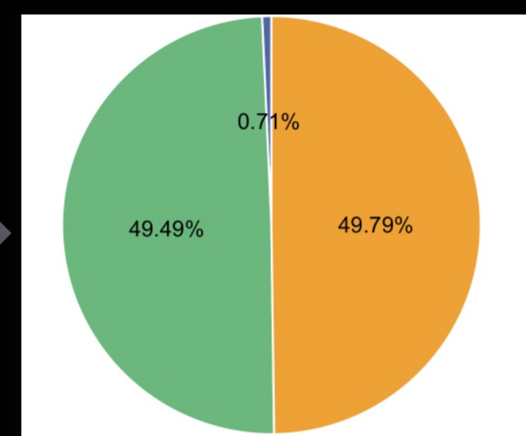
Photoinhibition is observed frequently

All PI curves





Light limited



Light saturated

Photoinhibited

75% have plateau

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Objective: develop a new PI curve for photoinhibition

- Capture plateau in photosynthetic rate
- Simplifies to other PI curve when no photoinhibition detected
- Photoinhibition does not change interpretation of other parameters
- Simple, geometric interpretation of photoinhibition parameter
- Parsimonious (as few parameters as possible)
- Parameters easy to estimate with data typically available

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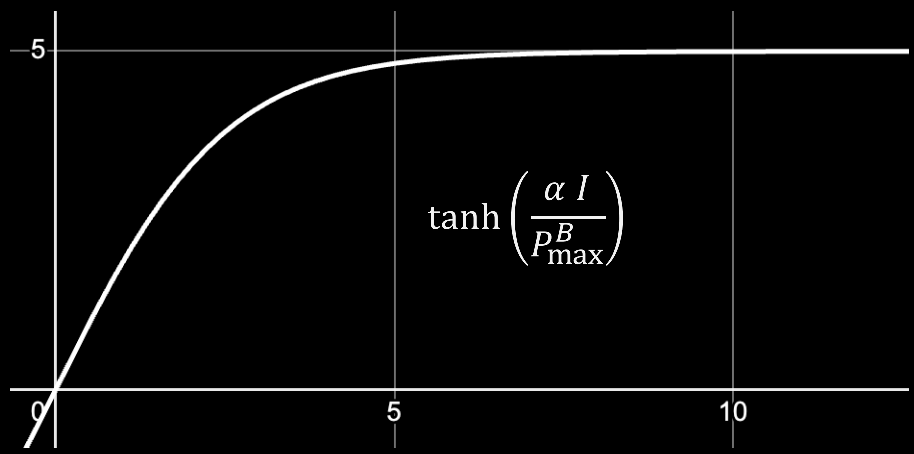
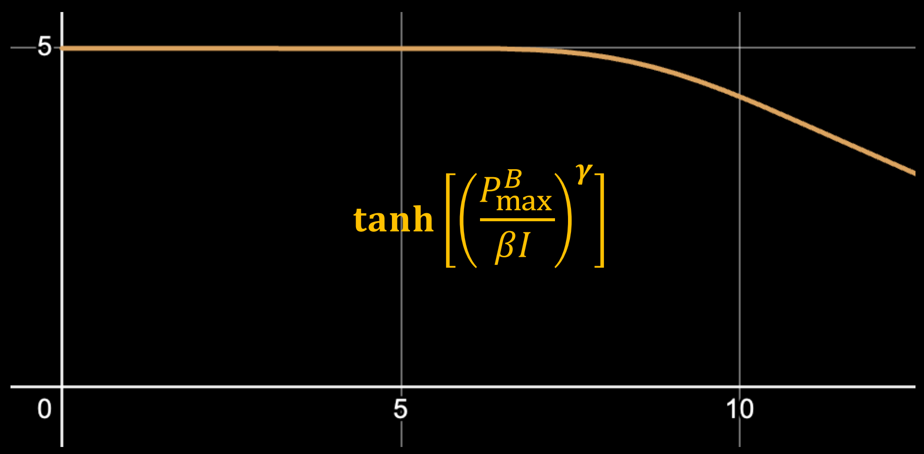
A New Parameterization of Photoinhibition

Use a saturating function of the **reciprocal of irradiance** to model photoinhibition:

$$P^B = P^B_{\max} \tanh\left(\frac{\alpha I}{P^B_{\max}}\right) . \mathbf{tanh}\left[\left(\frac{P^B_{\max}}{\beta I}\right)^{\gamma}\right], \quad \gamma = \cosh^2(1) \approx 2.38$$



$$\tanh\left(\frac{\alpha I}{P^B_{\max}}\right)$$



$$\mathbf{tanh}\left[\left(\frac{P^B_{\max}}{\beta I}\right)^{\gamma}\right]$$

Amirian et al. *Commun. Earth Environ*, 2025

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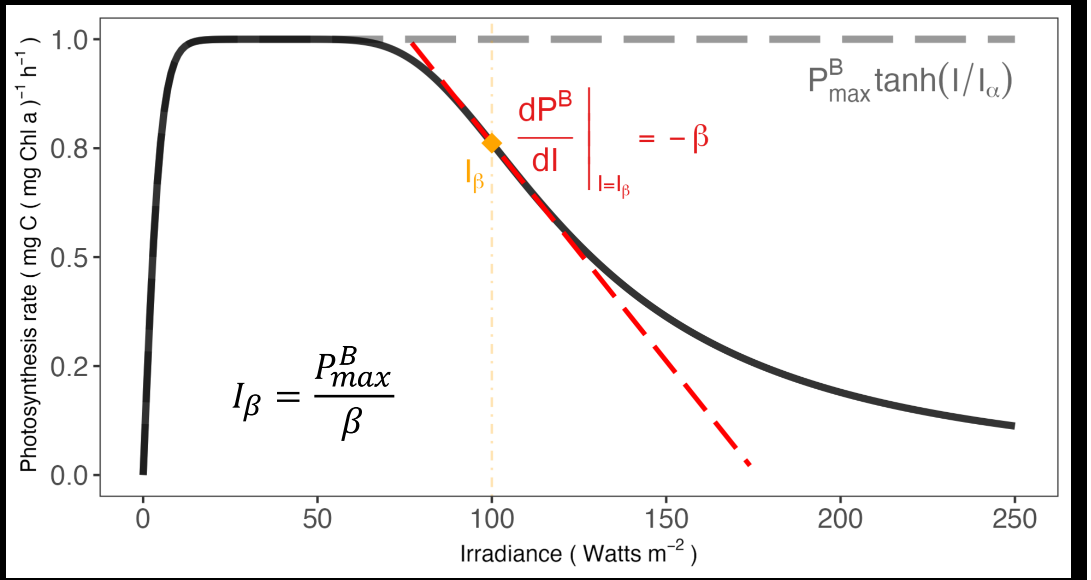
$$\left.\frac{dP}{dI}\right|_{I=0} = \alpha \qquad \left.\frac{dP}{dI}\right|_{I=\frac{P_{\max}}{\beta}} = -\beta$$

γ determined statistically from data agrees with our mathematical calculation, $\gamma = \cosh^2(1)$!



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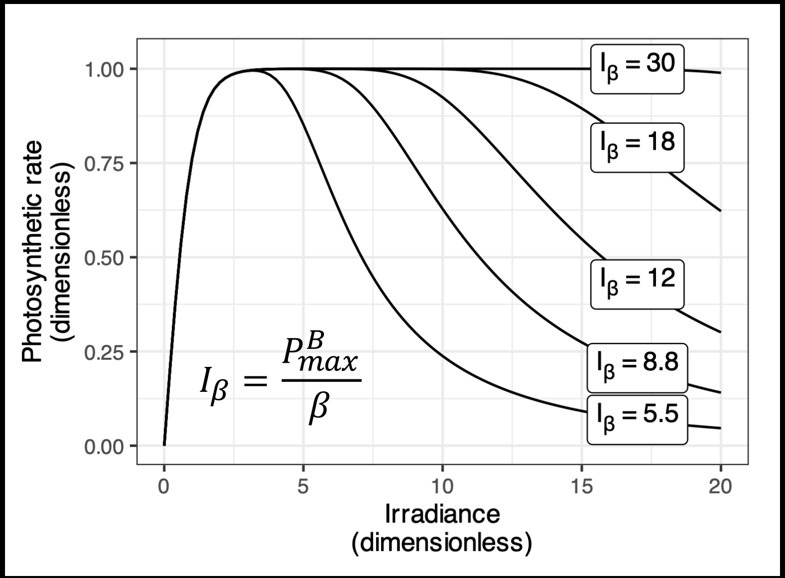

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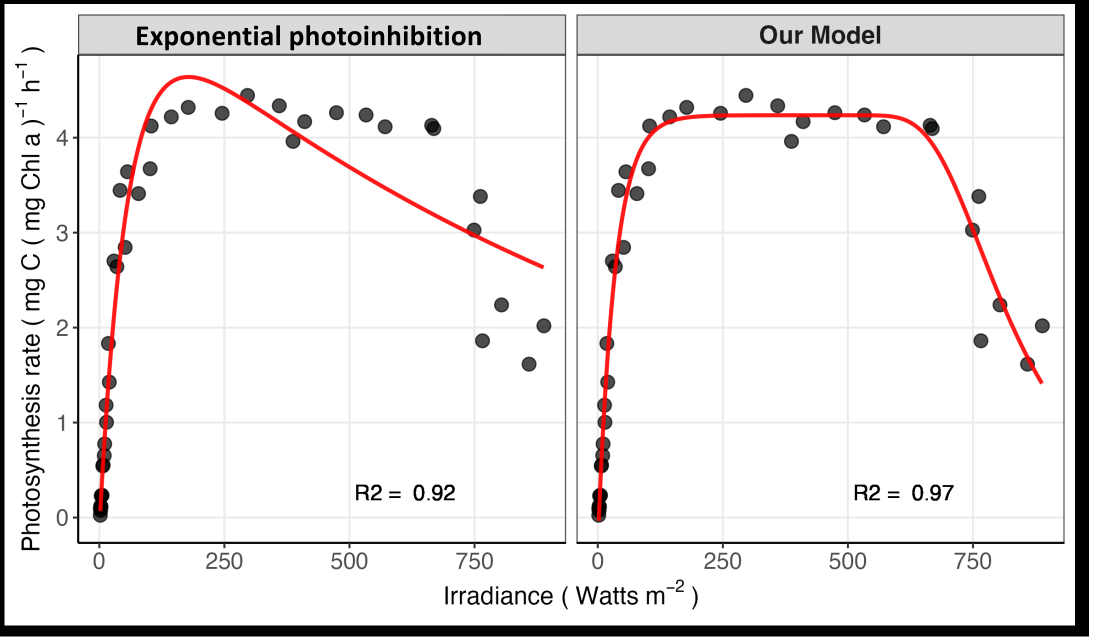

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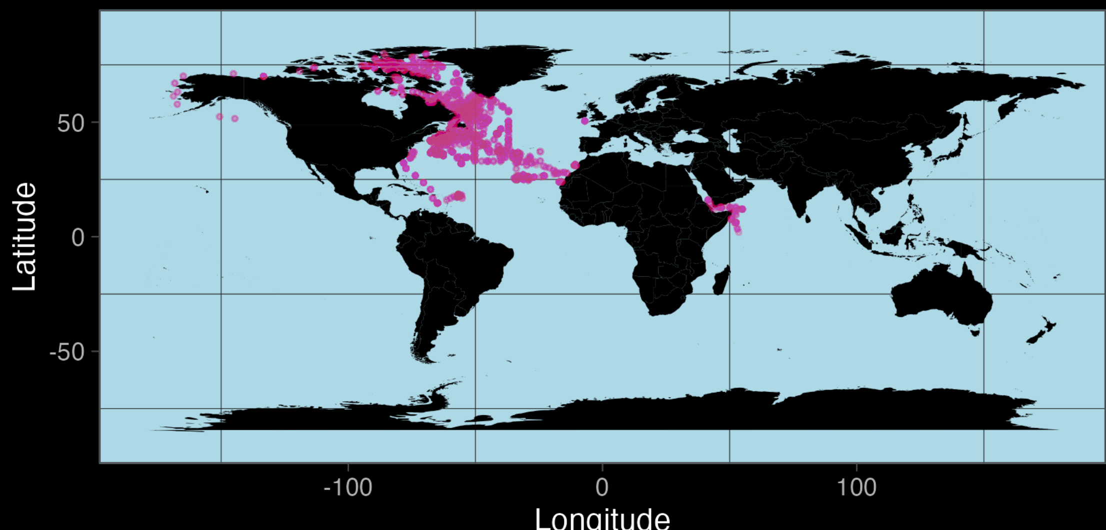
Testing models with a database of PI experiments

Global map of PI data samples collected between 1973 to 2022



Total plotted data samples: 3641

Experiments performed over many decades by scientists at Bedford Institute of Oceanography (B. Irwin, T. Platt, W. G. Harrison, P. Dickie, C. Caverhill, J. Anning, E. Devred, and many others).

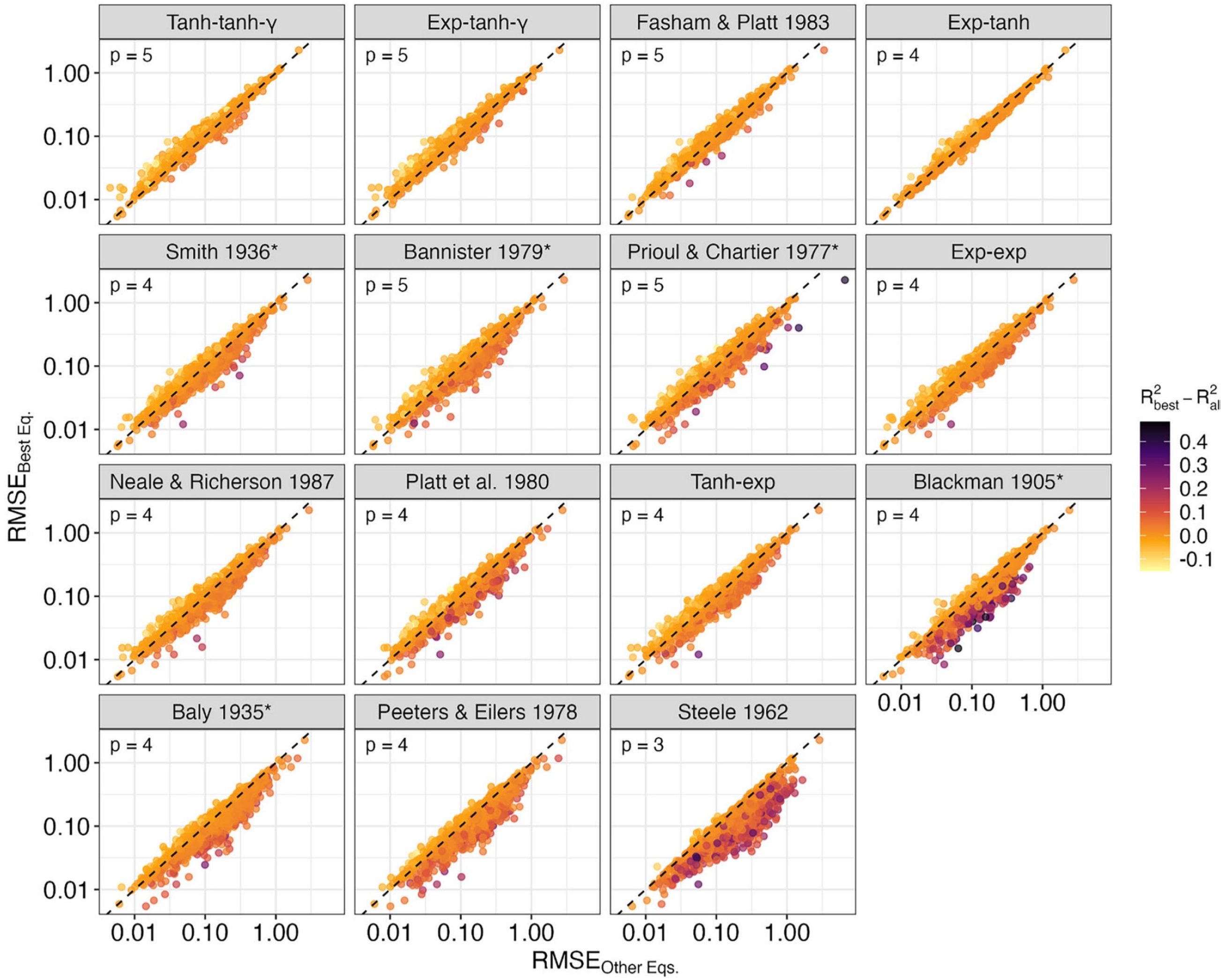
Compilation developed in collaboration with E. Devred.

Table 1. Number of observed values of key parameters.

number_datasets	number_datapoints	number_pi_curve	number_dates	number_locations
80	108826	3641	1346	1304

Statistical evaluation of photoinhibition models

- 10 models with traditional exp model of photoinhibition
- 6 variations on new idea using reciprocal irradiance we developed



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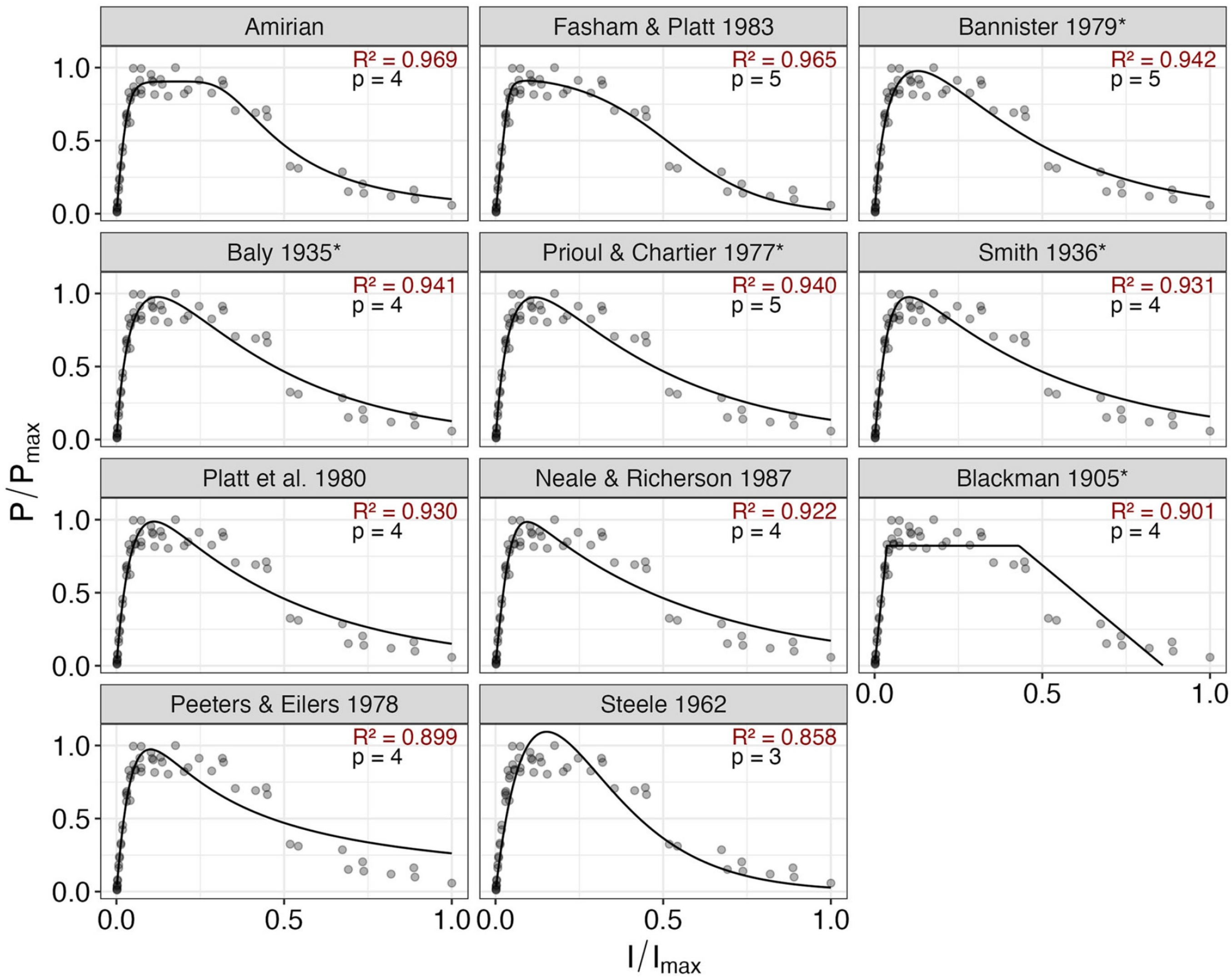

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Table 2 | Statistical summary of 1808 photoinhibition model fits, ordered by increasing mean root mean squared error (RMSE)

Model	*p*	All irradiance			Excluding $I < I_\alpha$		
		Median R^2_{adj} (%)	Mean RMSE	Mean rRMSE (%)	Median R^2_{adj} (%)	Mean RMSE	Mean rRMSE (%)
Tanh-tanh-γ	**5**	**96.5**	**0.144**	**−5.860**	**64.6**	**0.161**	**−8.080**
Exp-tanh-γ	5	96.4	0.146	−4.620	64.2	0.163	−7.360
Fasham & Platt[21]	5	96.3	0.148	−3.340	57.7	0.172	−1.590
Amirian	**4**	**96.1**	**0.151**	**0.000**	**59.0**	**0.175**	**0.000**
Exp−tanh	4	95.9	0.156	3.320	58.5	0.180	2.920
Smith[32a]	4	95.7	0.161	7.360	52.7	0.194	14.72
Bannister[26a]	5	95.4	0.161	8.780	50.8	0.193	15.98
Prioul & Chartier[25a]	5	95.4	0.166	9.250	47.4	0.198	16.06
Exp-exp	4	95.6	0.162	9.170	56.4	0.193	14.67
Neale & Richerson[20]	4	95.5	0.164	10.62	48.7	0.198	18.52
Platt et al.[16]	4	95.4	0.169	13.29	47.5	0.204	21.28
Tanh−exp	4	95.4	0.164	10.69	52.1	0.197	17.92
Blackman[33a]	4	94.6	0.180	27.96	40.1	0.212	33.46
Baly[9a]	4	94.3	0.186	25.80	44.1	0.228	36.50
Peeters & Eilers[28]	4	93.5	0.195	34.64	37.8	0.243	49.45
Steele[15]	**3**	**89.3**	**0.248**	**74.03**	**22.4**	**0.279**	**70.25**

Model	***p***	**Excluding $I < I_\alpha$**		
		Median R^2_{adj} (%)	**Mean RMSE**	**Mean rRMSE (%)**
Amirian	**4**	**59.0**	**0.175**	**0.000**
Exp–tanh	4	58.5	0.180	2.920
Smith[32a]	4	52.7	0.194	14.72
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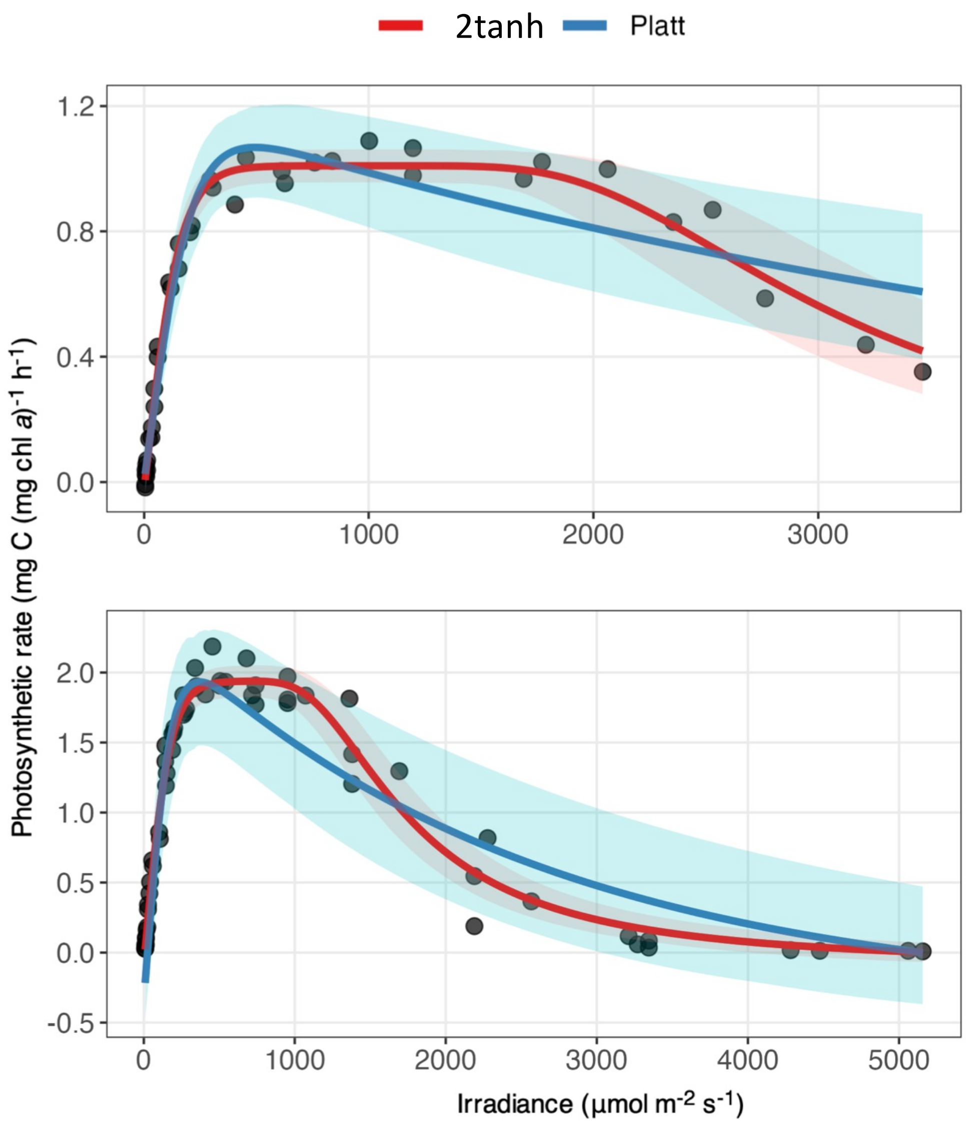
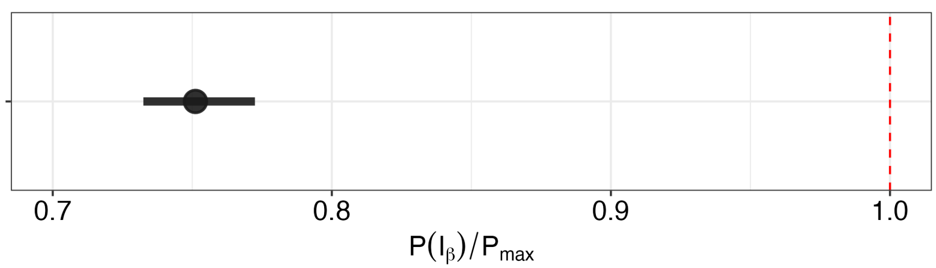
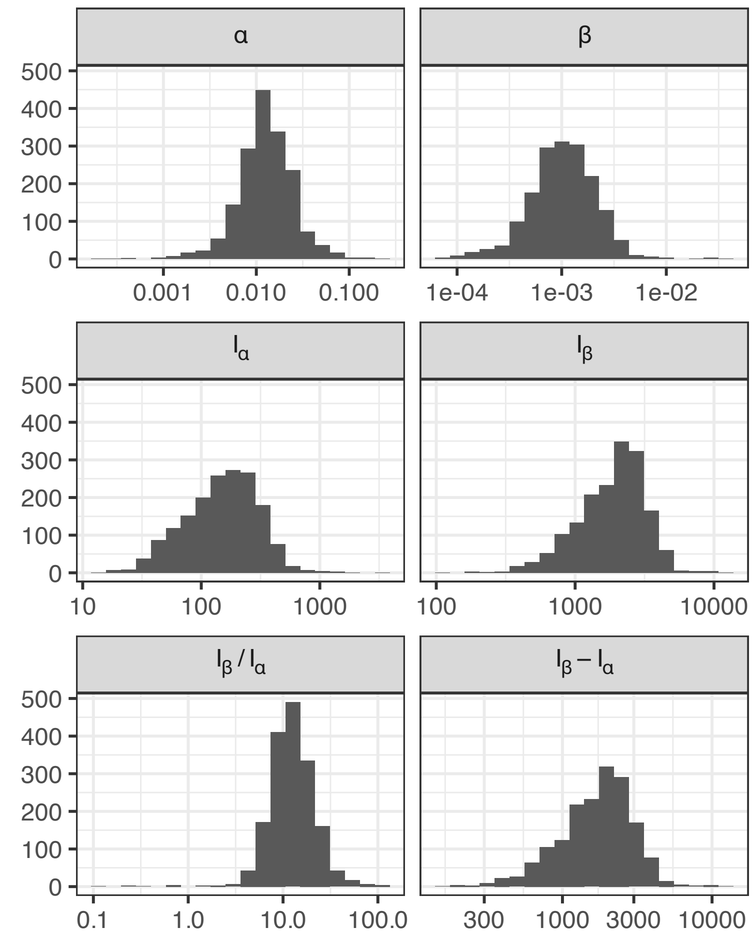


2tanh
Platt
Photosynthetic rate (mg C (mg chl a)-1 h-1)
1.2
0.8
0.4
0.0
0
1000
2000
3000
2.0
1.5
1.0
0.5
0.0
-0.5
0
1000
2000
3000
4000
5000
Irradiance (μmol m-2 s-1)

Photoinhibition generally requires high light

- Median I_β / I_α is about 13
- I_β < 1300 µmol m^{-2} s^{-1} for 25% of PI curves
- Photosynthesis rate reduced 25% at I_β





Irradiance measured in µmol m^{-2} s^{-1}

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Summary

- Our double-tanh model outperforms all the existing models on large scale, reducing RMSE by 3 to 70 %.
- It has potential to more accurately describe photosynthetic rate since it captures the PI curve plateau.
- We can estimate all the parameters directly from the date, more specifically Pmax and beta
- We the onset of photoinhibition from PI curves.
- Photosynthetic efficiency reduces by 25% at photoinhibition onset.

Acknowledgements

Marine Microbial Macroecology Lab Members

- Prof. Zoe V. Finkel
- Prof. Andrew J. Irwin
- Dr. Peyman Fahimi

Fisheries and Oceans Canada (DFO)

- Dr. Emmanuel Devred (DFO, Canada)
- Stephanie Clay (DFO, Canada)

We are indebted to many scientists at the Bedford Institute of Oceanography, Fisheries and Oceans Canada in Dartmouth, Nova Scotia, Canada, who over five decades have collected the data we analyzed.

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