Bayesian Estimation of Photosynthesis–Irradiance Parameters for Marine Phytoplankton

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Introduction

Understanding marine primary production is central to evaluating oceanic carbon cycling and climate impacts, as demonstrated by Kulk et al. (2020). Phytoplankton photosynthesis is commonly described with a photosynthesis–irradiance (P–I) model whose key parameters (α^B, P_m^B, R^B, β^B) follow the classical formulation of Platt, Gallegos and Harrison (1980). Conventional analyses often report only point estimates with limited treatment of uncertainty. Here we use a Bayesian framework to infer full posterior distributions of P–I parameters from replicated *in situ* incubations. A hierarchical structure pools information across experiments while retaining survey-specific estimates, following the approach advocated by Sivia and Skilling (2006) for data-limited problems.

P–I model and parameters

We use a Platt-type P–I formulation with photoinhibition and dark respiration, written in chlorophyll-normalized units, with the superscript B indicating normalization by chlorophyll:

$$P^B(I) = P_m^B\left(1 - \exp\left(-\frac{\alpha^B I}{P_m^B}\right)\right)\exp\left(-\frac{\beta^B I}{P_m^B}\right) - R^B.$$

Here, α^B represents the initial slope at low irradiance, P_m^B is the light-saturated assimilation number, R^B denotes the dark respiration rate, and β^B controls photoinhibition at high irradiance.

Methods

We analyse replicated phytoplankton incubations from Bedford Basin (Canada, 1975), each providing irradiance levels across several light treatments and corresponding chlorophyll-normalized production from multiple replicates; surveys with missing data were excluded. We fit both the full P–I model (with β^B) and a reduced non-photoinhibiting version (with $\beta^B = 0$) using a hierarchical Bayesian framework in `PyMC`. For each survey we infer survey-specific α^B, P_m^B and R^B (and β^B where applicable) while estimating group-level distributions that share information across surveys. Parameter positivity is enforced with a softplus transform, and photoinhibition in the full model follows a log-normal hierarchy. Given irradiance I, the model predicts mean chlorophyll-normalized production, with observations treated as normally distributed around this mean with survey-specific noise. Posterior sampling uses the NUTS algorithm, and model performance is assessed with prior predictive checks, convergence diagnostics, and posterior predictive comparisons against observed production.

Results

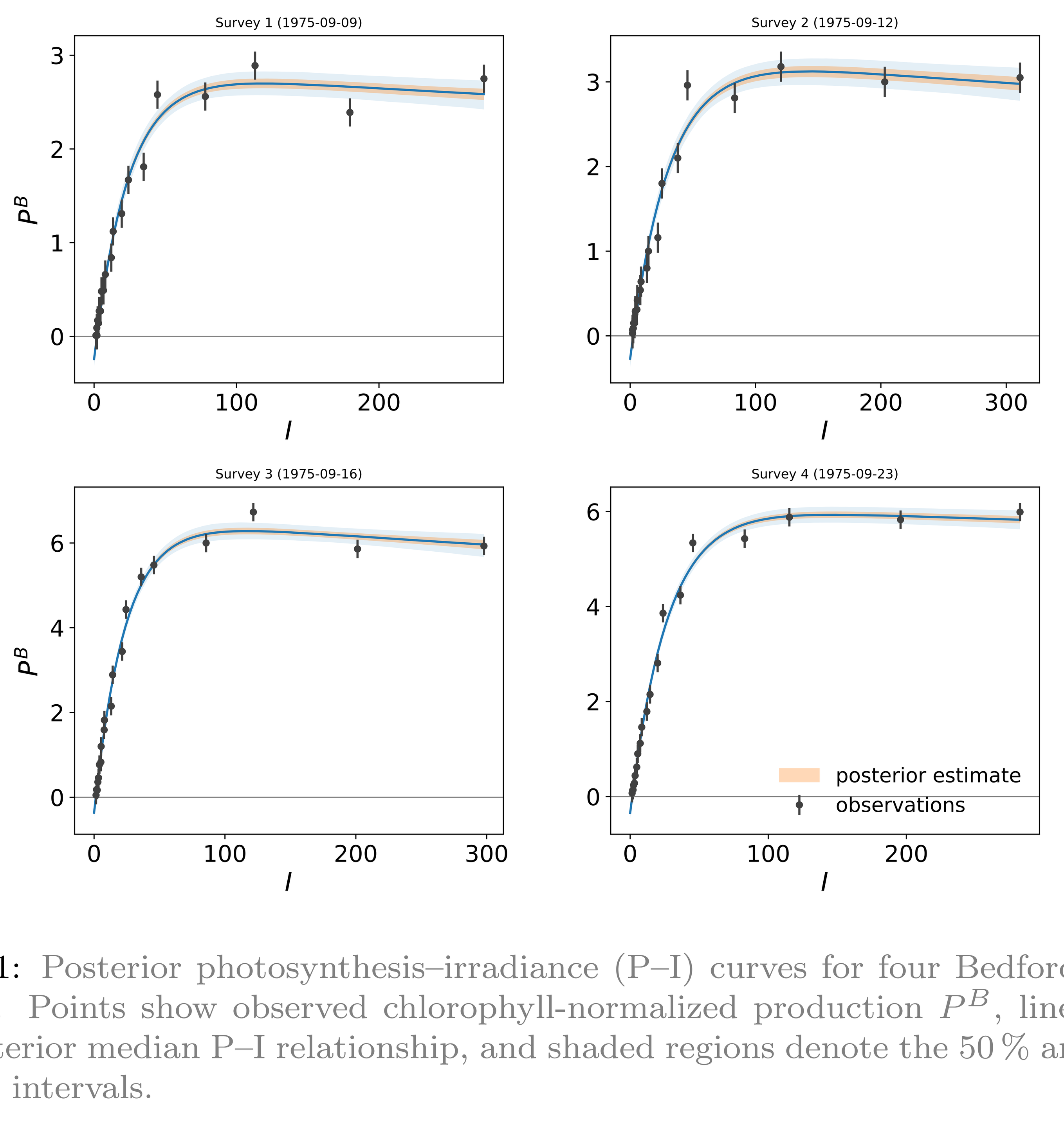

Figure 1: Posterior photosynthesis–irradiance (P–I) curves for four Bedford Basin surveys. Points show observed chlorophyll-normalized production P^B, lines show the posterior median P–I relationship, and shaded regions denote the 50 % and 90 % credible intervals.

For each survey, the Bayesian framework yields an ensemble of P–I curves whose medians track the observed normalized production, with credible bands capturing most data points. Partial pooling draws survey-level parameter estimates toward group-level values, reducing uncertainty while preserving meaningful differences. Posteriors for α^B and P_m^B are well constrained and physically plausible, and R^B remains positive and comparable to low-light production. In Bedford Basin, β^B is consistently near zero, and a reduced model without photoinhibition fits the data as closely as the full model, supporting the use of a simpler non-photoinhibiting P–I formulation.

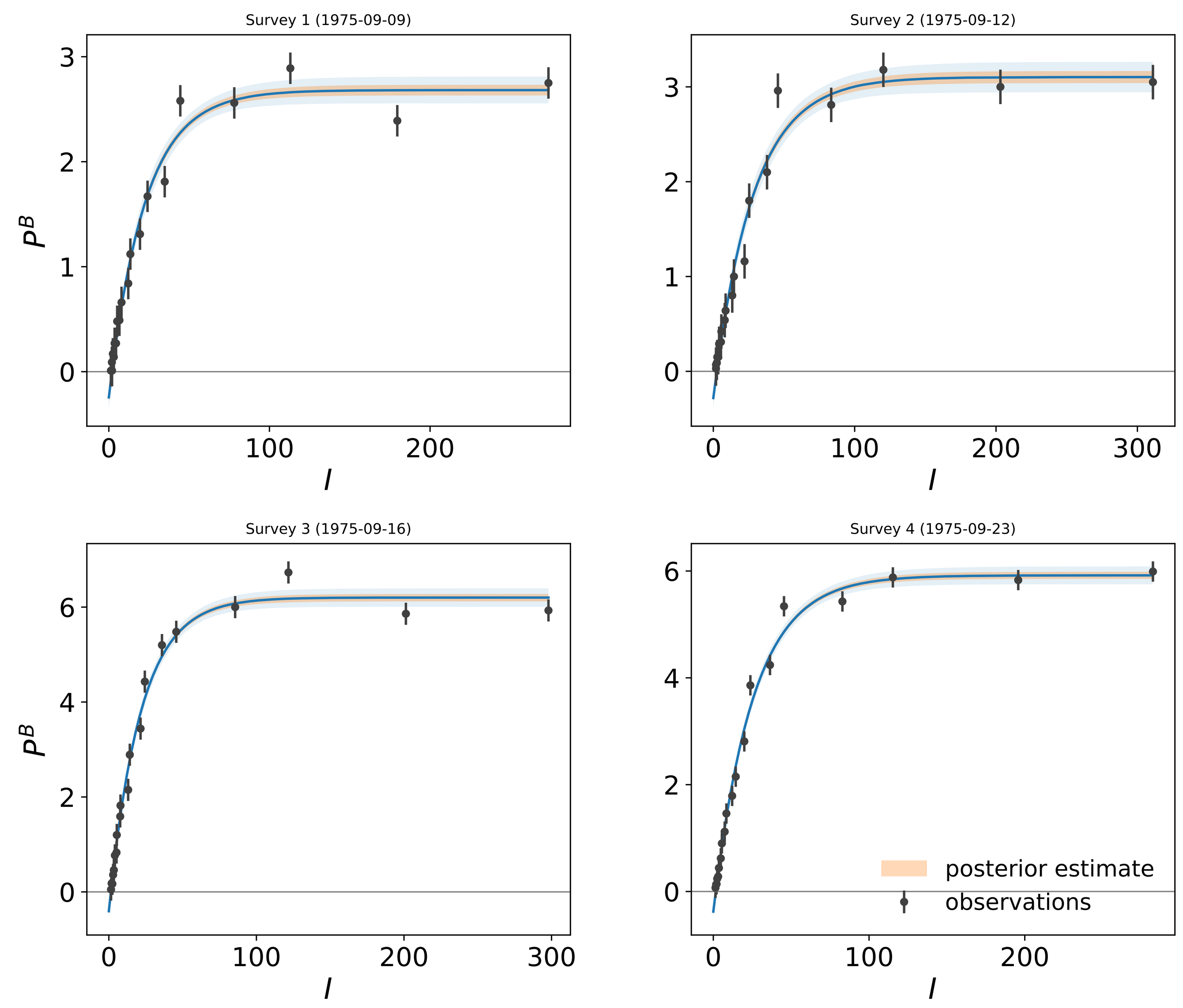

Figure 2: Posterior P–I curves from the reduced model without photoinhibition ($\beta^B = 0$). Fits are nearly identical to the full model, consistent with the very small posterior β^B values and indicating that photoinhibition is negligible in this dataset.

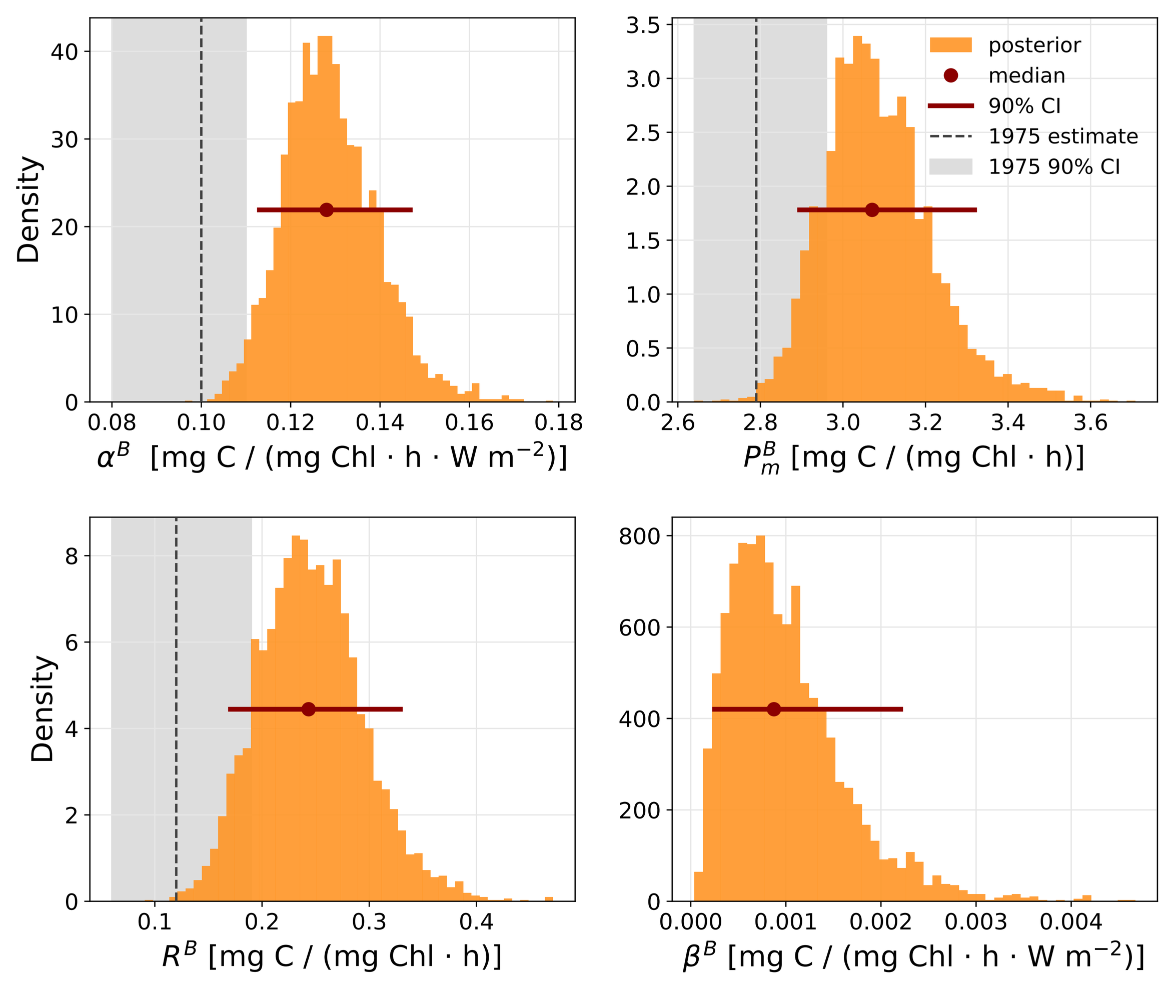

Figure 3: Posterior distributions of the photosynthesis–irradiance parameters α^B, P_m^B, R^B, and β^B for one Bedford Basin survey. Histograms show the posterior density, markers denote posterior medians with 90 % credible intervals, and dashed lines and shaded spans represent the 1975 reference estimates where available.

References

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