

Revisiting Classical Photosynthesis–Irradiance Estimates with a Hierarchical Bayesian Model

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INTRODUCTION

Marine primary production is a key quantity for tracking ocean carbon fluxes and their response to a changing climate (Kulk et al., 2020). The light dependence of phytoplankton photosynthesis is captured by the photosynthesis–irradiance (P–I) relationship, summarised by the parameters α^B , P_m^B , R^B and β^B in the classical form of Platt et al. (1980). These parameters are usually obtained as single best-fit numbers, leaving their uncertainty largely unquantified. We instead estimate them within a hierarchical Bayesian model, which returns a complete posterior distribution for each parameter and borrows strength across surveys to constrain those with sparse or noisy data (Sivia and Skilling, 2006). Because the same dataset was analysed decades ago by classical least squares, it offers a natural benchmark: we place our posterior estimates side by side with the original published values.

P–I MODEL AND PARAMETERS

Production is described by the exponential photosynthesis–irradiance model of Platt et al. (1980) that combines light limitation, photoinhibition and dark respiration. Normalising to chlorophyll (superscript B) gives

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

The low-light efficiency is set by the initial slope α^B ; the light-saturated rate by the assimilation number P_m^B ; the loss at zero light by the respiration term R^B ; and the high-light decline by the photoinhibition parameter β^B .

METHODS

The data are replicated ¹⁴C incubations from Bedford Basin (Canada, 1975–76). Each sampling date contributes production measurements at several light levels from multiple replicate bottles; dates with incomplete records were dropped. We implement the full P–I model in PyMC, inferring per-survey values of α^B , P_m^B , R^B and β^B together with the group-level distributions from which they are drawn. A softplus transform keeps the physiological parameters positive, and β^B is given a log-normal hierarchy. The original analysis used a multi-step least-squares procedure, reporting one estimate and confidence interval per survey. We use these published numbers as the reference for our comparison.

RESULTS: PARAMETER POSTERIORIORS

Each parameter emerges as a probability distribution rather than a single number. The posteriors for α^B , P_m^B and R^B are sharp and fall in physically sensible ranges, and R^B stays clearly positive, on the same order as production at the lowest light levels. The photoinhibition parameter β^B , by contrast, piles up near zero, so high-light suppression is at most weak in these waters.

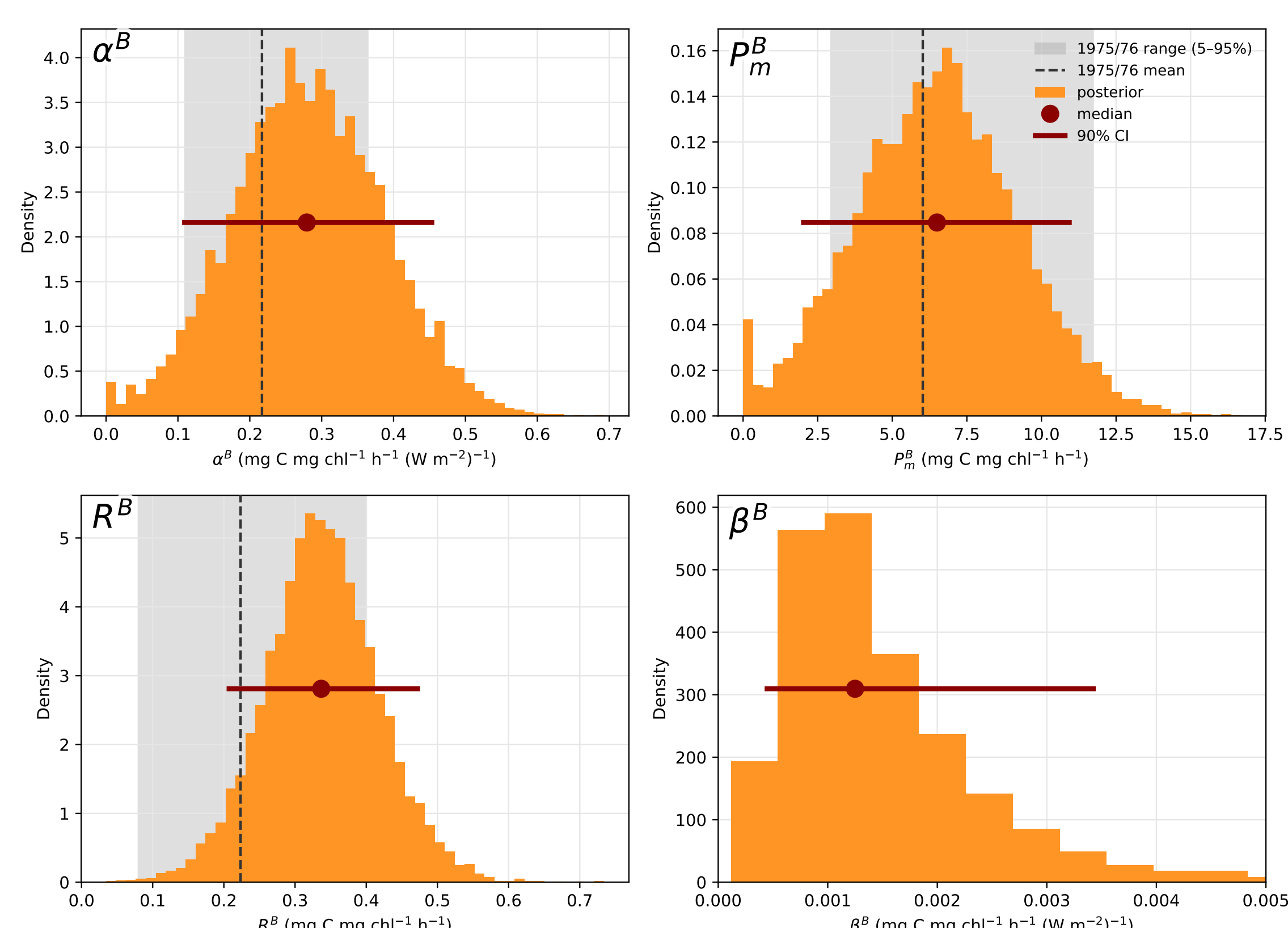


Figure 1: Group-level posterior distributions of the four P–I parameters α^B , P_m^B , R^B and β^B , representing the predicted value for a new survey. Bars give the posterior density; markers show the posterior median with its 90 % credible interval. Dashed lines and shaded bands mark the mean and 5–95 % range of the 1975/76 reference estimates across surveys, where reported.

RESULTS: MODEL VS. HISTORICAL ESTIMATES

Survey by survey, the initial slope α^B and assimilation number P_m^B fall along the 1:1 diagonal: the Bayesian fit recovers the same central values as the classical one, with the residual scatter reflecting partial pooling toward the group mean. The respiration term R^B sits slightly above the diagonal, not from error but from definition: the historical R^B is the intercept of a line through the low-light points of a tanh curve, while ours is fitted jointly across the full exponential curve.

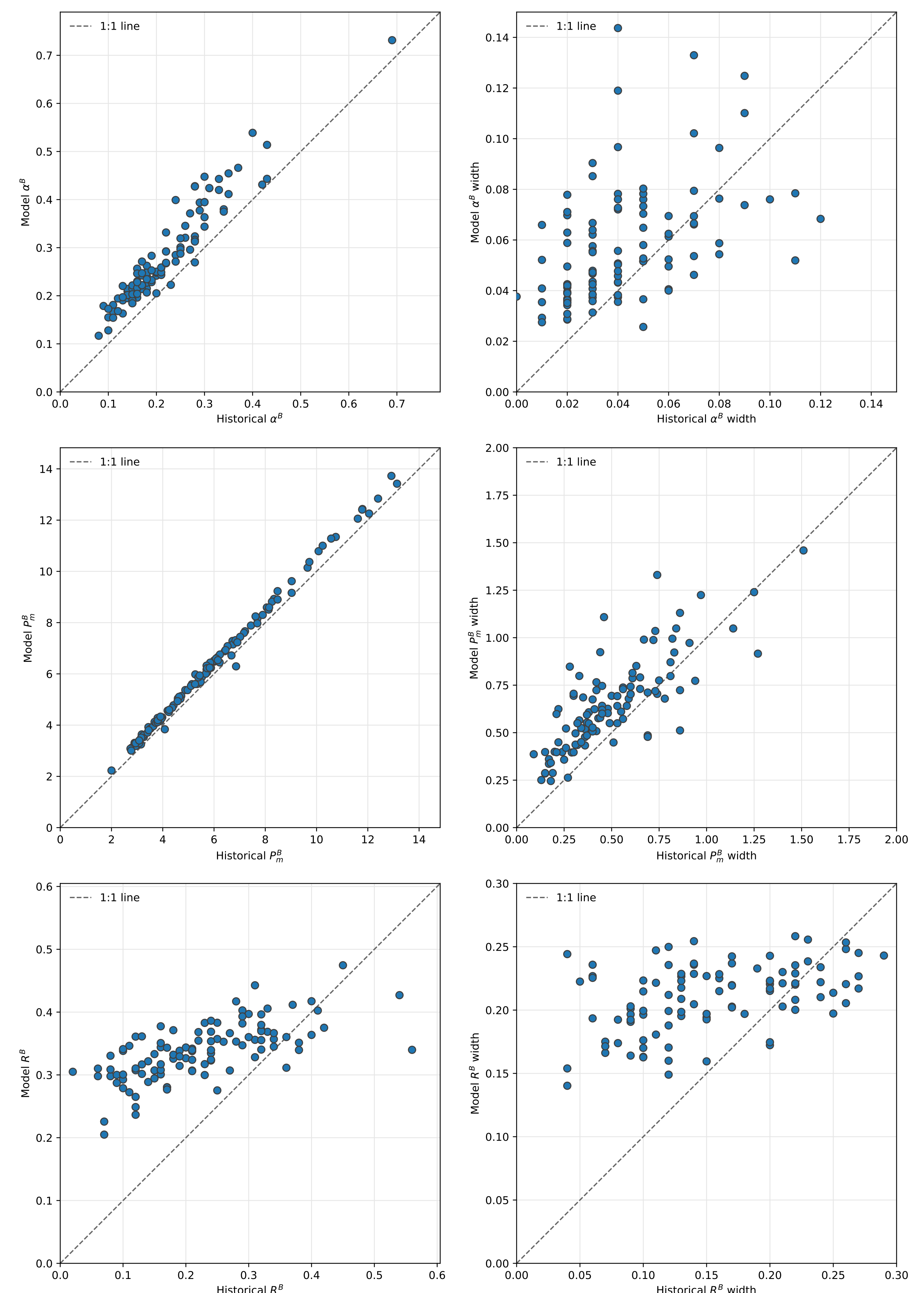


Figure 2: Bayesian estimates versus historical least-squares values, one point per survey, for α^B , P_m^B and R^B (rows). Left: posterior means; right: 90 % interval widths. Dashed lines mark exact agreement.

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