A new dynamic model for analyzing coupled nitrate-nitrite dynamics in phytoplankton communities

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INTRODUCTION:

Many phytoplankton species have been observed to take up and release significant amounts of nitrite, but both the dynamics and overall extent of this process are still mainly unknown. Failing to adequately account for the dynamics of nitrite uptake and release in ocean systems may bias predictions of total assimilated nitrogen and primary production. Also, excess nitrite build-up in aquaculture systems requires costly wastewater treatments and decrease the total productivity.

AIM: Design a nitrite-nitrate-biomass model that could be calibrated from time-series of readily measurable state variables.

MODEL:

The model was designed with sufficiently few parameters to allow calibration from relatively short time-series of phytoplankton biomass (*B*) and extracellular concentrations of nitrate (NO_3) and nitrite (NO_2). To achieve this, we extended the 'quota' modeling approach by Legovic and Cruzado (1997, Ecol. Model., 99) to incorporate both the release and uptake of nitrite. By using contemporary approaches for fitting multivariate autoregressive models, we estimated best-fit parameter estimates accounting for whether the deviations between observed and predicted values are dominated by process error (i.e., differences due to stochasticity in the culture dynamics itself; arrows in Fig.1), or by observation error (i.e., differences between observed and predicted values due to measurement error; solid line in Fig.1).

$$\frac{dN0_3(t)}{dt} = \left(a_{in} \times N0_{3,in} - b_{out} \times N0_3(t)\right) - v\mathrm{MAX\_NO_3} \times \frac{N0_3(t)}{N0_3(t) + k\mathrm{NO_3}} \times B(t)$$

$$\frac{dN0_2(t)}{dt} = \left(a_{in} \times N0_{2,in} - b_{out} \times N0_2(t)\right) + \beta \times \left(c \times f\mathrm{NO_3} + f\mathrm{NO_2}\right) \times \left(1 - \frac{q_0}{Q(t)}\right) \times B(t)$$
$$- v\mathrm{MAX\_NO_2} \times e^{(-\phi \times N0_3(t))} \times \frac{N0_2(t)}{N0_2(t) + k\mathrm{NO_2}} \times B(t)$$

$$\frac{dQ(t)}{dt} = v\mathrm{MAX\_NO_3} \times \frac{N0_3(t)}{N0_3(t) + k\mathrm{NO_3}} - \beta \times \left[c \times \left(\begin{matrix} v\mathrm{MAX\_NO_3} \times \\ \dfrac{N0_3(t)}{N0_3(t) + k\mathrm{NO_3}} \end{matrix} \right) + \left(\begin{matrix} v\mathrm{MAX\_NO_2} \times e^{(-\phi \times N0_3(t))} \times \\ \dfrac{N0_2(t)}{N0_2(t) + k\mathrm{NO_2}} \end{matrix} \right) \right]$$
$$+ \left(1 - \frac{q_0}{Q(t)}\right) + v\mathrm{MAX\_NO_2} \times e^{(-\phi \times N0_3(t))} \times \frac{N0_2(t)}{N0_2(t) + k\mathrm{NO_2}} - \mu_{MAX} \times \left(1 - \frac{q_0}{Q(t)}\right) \times Q(t)$$

$$\frac{dB(t)}{dt} = -b_{out} \times B(t) + \mu_{MAX} \times \left(1 - \frac{q_0}{Q(t)}\right) \times B(t)$$

Table 1: Summary table of model State Variables and Parameters

State variables	Definition (units)
NO_3	Nitrate in medium (μmol NO_3^- L^{-1})
NO_2	Nitrite in medium (μmol NO_2^- L^{-1})
Q	Nitrogen quota (μmol N cell^{-1})
B	Biomass (cell mL^{-1})
Parameters	**Definition (units)**
a_{in}	Input Dilution rate in chaemostat systems (day^{-1})
b_{out}	Output Dilution rate in chaemostat systems (day^{-1})
$NO_{3,in}$	Concentration of nitrate supply (μmol NO_3^- L^{-1})
$NO_{2,in}$	Concentration of nitrite supply (μmol NO_2^- L^{-1})
$v\mathrm{MAX\_NO_3}$	Maximum per-capita nitrate uptake rate (μmol NO_3^- cell^{-1} day^{-1})
$k\mathrm{NO_3}$	Nitrate half-saturation constant (μmol NO_3^- L^{-1})
c	Conversion coefficient from nitrate to nitrite (μmol NO_2^- ×(μmol NO_3^-)$^{-1}$). Set at c=1
β	Maximum proportion of per-capita nitrate and nitrite uptake released as nitrite (0≤ β ≤1) (unitless)
$v\mathrm{MAX\_NO_2}$	Maximum per-capita nitrite uptake rate (μmol NO_2^- cell^{-1} day^{-1})
ϕ	Nitrate inhibition for nitrite uptake (μmol NO_3^- L^{-1})$^{-1}$
$k\mathrm{NO_2}$	Nitrite half-saturation constant (μmol NO_2^- L^{-1})
q_0	Per-capita minimum nitrogen quota (μmol N cell^{-1})
Q_{init}	Per-capita initial nitrogen quota (μmol N cell^{-1})
μ_{MAX}	Growth rate at infinite nutrient storage (day^{-1})

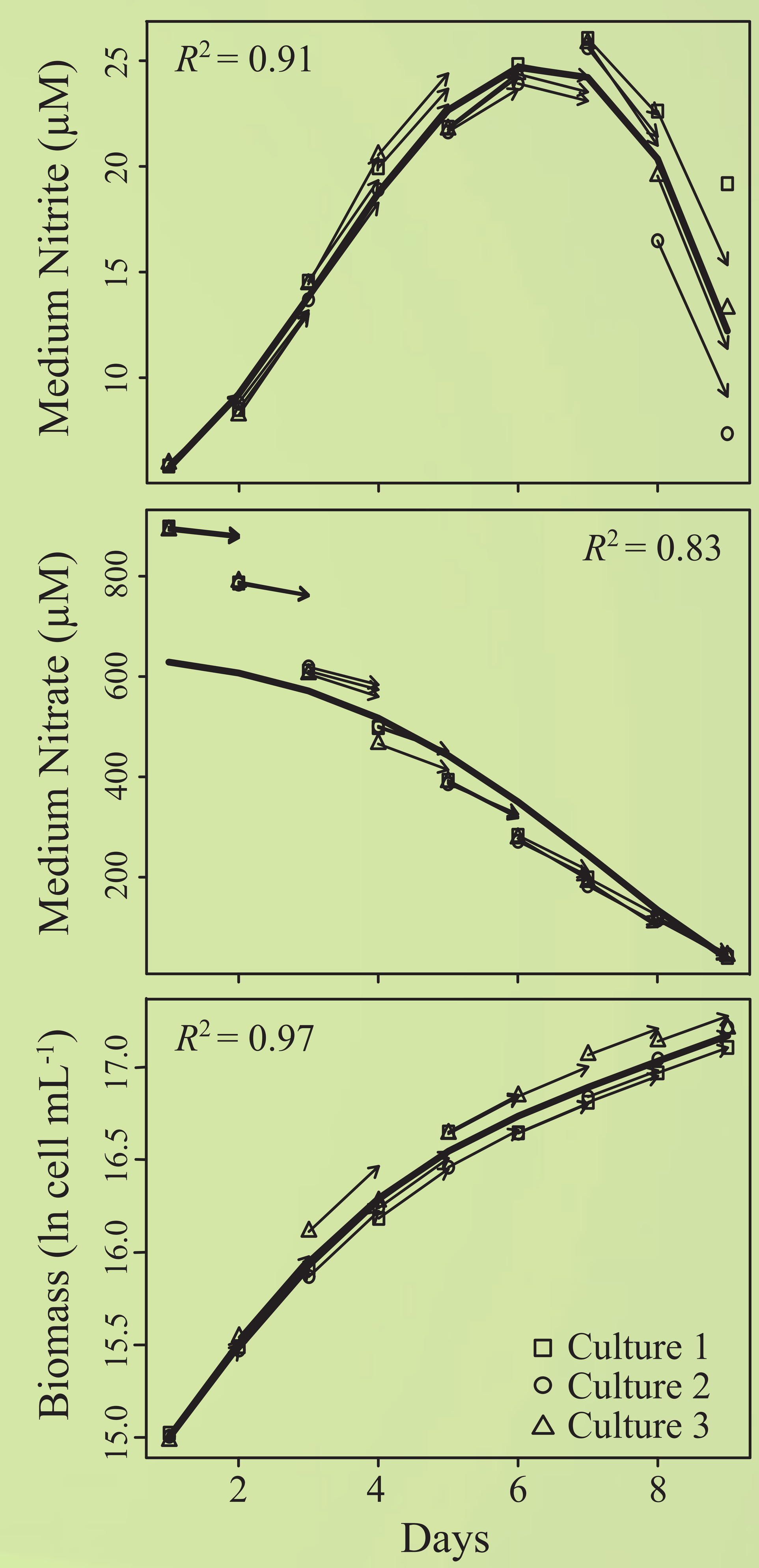

Figure 1: Dynamics for medium nitrite and nitrate, and biomass for three batch cultures of *Picochlorum atomus.* Phytoplankton continuously uptake nitrate and cells actively excrete nitrite to avoid cytotoxic effects of internal nitrite build up. Conversely, under nitrate limiting conditions, phytoplankton can directly take up nitrite and use it as an alternative nitrogen source. The *solid line* shows the best-fit model with observation error. Because this model assumes that the noise in the data is dominated by observation error, predicted values at time *t*+1 are calculated from the predicted values at time *t*, and thus the best-fit trajectory is a smooth line. The *arrows* show the best-fit model with process error. Because the process-error model assumes that the noise is dominated by real biological variability, the observed values at time *t* (base of the arrows) are used to obtain predict values at time *t*+1 (arrow heads; 'one-step ahead' prediction).

RESULTS and DISCUSSION: The model accurately characterizes the dynamics of nitrite uptake and excretion, nitrate uptake and assimilation efficiency, and population growth for the three cultures of *Picochlorum atomus* reared in batch culture. The model also characterizes the dynamics of three other phytoplankton species very well (results not shown: see Malerba et al. in press for details). This relatively simple model successfully captures a broad range of qualitatively different nitrate and nitrite dynamics, and provides insight into alternative explanations for nitrite utilization patterns that have been observed in previous work. Our approach provides a foundation for a more comprehensive understanding of the role of nitrite dynamics of phytoplankton in natural and engineered systems.

Source: Malerba, M. E.,Connolly, S. R., Heimann K., Nitrate - nitrite dynamics and phytoplankton growth: Formulation and experimental evaluation of a dynamic model. Limnology and Oceanography, *in press.*

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